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Hassan Qudrat-Ullah *Editor*

Managing Complex Tasks with Systems Thinking

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Fazeelat Begum (my mother) and Saira Bano (my mother-in-law)

Preface

We live in a complex world. A world where we face wicked problems that defy simple solutions. Have you ever wondered how to deal with complex problems that seem to have no easy solutions? How to understand the causes and consequences of dynamic phenomena that affect our lives and our planet? How to design effective interventions that can create positive change in the world?

If you have, then you are not alone. I have been asking myself these questions for a long time, and I have found systems thinking to be a powerful tool for answering them. Systems thinking is a way of understanding and solving complex problems by looking at the interrelationships and feedback loops among the elements of a system. It helps us to see the big picture, identify leverage points, and design effective interventions.

Systems thinking is not a new concept. It has been around for decades, and it has been applied in various fields such as engineering, management, biology, ecology, psychology, sociology, and education. However, systems thinking is not widely taught or practiced in our society. Most of us are trained to think analytically, breaking down problems into smaller pieces and solving them one by one. This approach works well for simple problems, but it fails for complex problems that require a holistic and systemic perspective.

My journey with systems thinking began when I was a graduate student at the University of Bergen, Norway, where I learned about system dynamics, a powerful method for modeling and simulating dynamic systems. I was amazed by how system dynamics could capture the essence of complex phenomena such as population growth, energy systems, epidemics, climate change, and business cycles. I decided to pursue my Ph.D. in decision sciences with a focus on system dynamics methodology (NUS Business School, National University of Singapore) and applied it to the study of complex dynamics of sustainable fisheries.

Since then, I have been teaching and researching systems thinking for over two decades, and I have witnessed its power and potential in addressing some of the most challenging issues of our time, such as climate change, health care, education, digital transformation, and social justice. I have also learned from many experts and practitioners who have generously shared their insights and experiences with me.

In this book, I have compiled some of the most recent and relevant theoretical and methodological advancements in systems thinking, as well as their applications in various fields. The book covers topics such as systems engineering, participatory modeling, behavioral economics, value networks, learning analytics, problem-solving skills, gender inequality, digital access, IT professional shortage, water management, land inequality, biosecurity, sustainability science, and healthcare policy.

The book is intended for anyone interested in learning more about systems thinking and its applications. It can be used as a supplementary textbook for undergraduate and graduate courses on systems thinking, system dynamics, or systems engineering. It can also be used as a reference book for researchers, consultants, managers, policymakers, educators, and students who want to apply systems thinking in their work or study.

I hope this book will inspire you to adopt a systems thinking mindset and apply it to your own complex tasks. I also hope it will contribute to the advancement of systems thinking as a discipline and a practice that can help us create a better world.

I would like to thank all the authors who contributed their chapters to this book. They are all leading scholars and practitioners in their respective fields, and they have provided valuable insights and examples of systems thinking in action. Some of them are my colleagues and collaborators who have worked with me on various projects over the years. Some of them are my mentors and role models who have inspired me with their vision and passion. Some of them are my friends and peers who have supported me with their feedback and encouragement. I am grateful to all of them for their contributions to this book.

I would also like to thank the reviewers who provided constructive feedback and suggestions for improving the quality of the book. Their comments helped me to refine the structure and content of the book and to ensure its coherence and consistency. Their expertise and experience added value to the book and enhanced its credibility.

Finally, I would like to thank my family and friends who supported me throughout this project. They gave me the motivation and confidence to pursue this ambitious endeavor. They also gave me the balance and perspective to enjoy life beyond work. They are my source of joy and inspiration. Dr. Anam Qudrat's weekly discussions kept me going in unparallel ways.

Toronto, Canada Hassan Qudrat-Ullah
June 2023

Overview

This book aims to fill this gap by providing an accessible and comprehensive introduction to systems thinking and its applications in various domains. The book is divided into eight parts:

- Part I: Introduction to Systems Thinking and Its Applications—This part provides an overview of systems thinking, its history, principles, methods, and tools. It also introduces some of the most influential thinkers and practitioners in the field of systems thinking.
- Part II: Theoretical and Methodological Advancements—This part presents some of the most recent and relevant theoretical and methodological advancements in systems thinking, such as systems engineering, participatory modeling, behavioral economics, value networks, and causal loop diagrams.
- Part III: Applications of Systems Thinking in Education—This part explores how systems thinking can be applied in education to foster problem-solving skills and creativity among students, enhance the student learning experience through learning analytics and interactive multimedia, and address gender inequality and promote an equitable environment for women in scientific vocations.
- Part IV: Bridging the Digital Gap with Systems Thinking—This part examines how systems thinking can be used to improve access, equity, and decision-making in the digital age, and to navigate the IT professional shortage with system thinking.
- Part V: Addressing Agricultural Issues with Systems Thinking—This part investigates how systems thinking can be used to address agricultural issues such as water management, land inequality, biosecurity adherence, and sustainable plastic contents recycling.
- Part VI: Sustainability Science and Systems Thinking—This part discusses how systems thinking can be used to study sustainability science topics such as climate change, energy systems, epidemics, endangered species, and public perception of the Canadian oil sands.
- Part VII: Dealing with the Complexity of Healthcare Systems—This part demonstrates how systems thinking can be used to deal with the complexity of healthcare

systems topics such as healthcare policy decisions, production and distribution of N95 masks, demographic effects of endangered species, and HIV/AIDS epidemic in China.

- Part VIII: Finally—This part concludes the book by summarizing the main points and providing some suggestions for further reading, learning, and future research.

Contents

Part I
Introduction to Systems Thinking and Its Applications

Chapter 1
Introduction: Managing Complex Tasks with Systems Thinking

Hassan Qudrat-Ullah

Abstract Decision making in highly uncertain and dynamic business environments is an essential activity in any organization. How can we improve human decision making and performance in complex tasks? This book argues that the systems thinking approach can provide a powerful and practical answer to this question. This chapter presents the case for this book and provides an overview of its content.

Keywords Organizational tasks · Human cognitive capacity · Feedback · Systems thinking · Complex systems · Climate change · Healthcare · Education · Digital technologies · Agriculture · Sustainability · Causal models · System dynamics

1.1 Introduction

Decision making is a fundamental and essential activity in any organization. However, many organizational tasks are complex and require more than just intuition and experience to handle them effectively. These tasks involve multiple interdependent decisions, nonlinear and simultaneous feedback loops, delays, and dynamic behavior that make them difficult to comprehend and predict. Moreover, these tasks are often influenced by various uncertainties and disruptions that can affect the outcomes and performance of the decisions. Therefore, human decision makers face many challenges and limitations while dealing with these complex tasks.

Some of the challenges and limitations that human decision makers face in complex tasks include bounded rationality, escalation of commitment, time constraints, uncertainty, and biases (Emmerling & Rooders, 2020; Pliner, 2020; Verywell Mind, 2020). Bounded rationality refers to the fact that human cognitive capacity is limited and cannot process all the information and alternatives available in a complex task (Verywell Mind, 2020). Escalation of commitment refers to the tendency to continue investing in a failing course of action despite negative feedback or evidence (Verywell Mind, 2020). Time constraints refer to the pressure

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to make decisions quickly without sufficient deliberation or exploration of options (Emmerling & Rooders, 2020). Uncertainty refers to the lack of reliable or complete information about the task, the environment, or the consequences of the decisions (Pliner, 2020). Biases refer to the systematic deviations from rationality or objectivity that affect human judgment and decision making (Verywell Mind, 2020).

These challenges and limitations can lead to suboptimal or erroneous decisions that can harm the performance and outcomes of the organization. Therefore, it is important to find ways to overcome or mitigate these challenges and limitations by applying the systems thinking approach. The systems thinking approach can help human decision makers to expand their perspective, consider multiple viewpoints, test their assumptions, learn from feedback, and design effective solutions for complex tasks (Pliner, 2020).

How can we improve human decision making and performance in complex tasks? This book argues that the systems thinking approach can provide a powerful and practical answer to this question. Systems thinking is a way of thinking that focuses on the whole system and its interactions, rather than its parts and their properties. Systems thinking helps us to understand the structure and behavior of complex systems, identify the root causes of problems, design effective solutions, and evaluate their impacts. By applying the systems thinking approach, this book demonstrates how we can deal with various complex organizational tasks in different domains, such as climate change, healthcare, education, digital technologies, agriculture, and sustainability

This book features various causal models that represent the structure and dynamics of complex tasks. Causal models are graphical tools that show how the variables in a system are connected by causal links and feedback loops. Causal models help us to visualize and communicate the logic and assumptions behind our decisions, test our hypotheses and scenarios, and learn from our experiences. This book shows how we can use causal models to build and test the effectiveness of decision-aiding solutions, such as policies, strategies, interventions, or tools, that can improve human decision making and performance in complex tasks.

This book also presents practical insights that can help us to make better decisions while dealing with complex tasks. These insights are derived from the analysis and simulation of the causal models and the decision-aiding solutions. These insights can help us to understand the behavior and consequences of our decisions, avoid common pitfalls and biases, anticipate potential risks and opportunities, and achieve our desired goals and outcomes.

To provide some unique theoretical perspectives and innovative systems thinking-based solutions for our increased understanding and better decision making in complex tasks, ***Managing Complex Tasks with Systems Thinking: Practical Insights for Better Decision Making***, we issued the call for contributions in this volume. Specifically, we sought help from the system dynamics modeling and systems thinking community. Consequently, several different examples of theoretical perspectives and innovative causal-loop-modeling-based applications, with a common unifying goal of "improving decision making in complex, dynamic tasks" are provided in this volume.

1.2 Methodology

We used various channels to disseminate our call for contributions on "*Managing Complex Tasks with Systems Thinking: Practical Insights for Better Decision Making*," such as social media platforms and professional networks, including the "Systems Thinking Group" at Linkedin. We also advertised the call for chapters on the message boards of some international conferences related to the topic. In addition, we invited our colleagues from different universities, research institutes, and business organizations to contribute. We received twenty-three long abstracts of two to three pages each as an expression of interest. Our review panel conducted an iterative screening process and selected eighteen chapters to invite for final submission. We applied a double-blind review process to all eighteen chapters that we received from the contributors. We compiled the feedback from the independent reviewers and sent it to the authors for them to address the issues and incorporate the suggestions. All eighteen chapters passed the final stage of acceptance. We edited the final versions of these eighteen chapters and included them in this volume.

1.3 Research Categories

We used a thematic approach to organize our contributions to this book. We grouped the chapters into eight categories according to the structure of the book. The first category, this one, introduces and previews "Managing Complex Tasks with Systems Thinking: Practical Insights for Better Decision Making". The second category explores four unique theoretical and methodological perspectives for improving organizational decision making, such as A Systems Engineering Framework for Reliability Assurance of Subsea Oil and Gas Production Systems, Improving the Strategy for Scientific Vocations in Colombia through Participatory Modeling Based on System Dynamics, Bringing Behavioral Economics into System Dynamics: Some Challenges, Solutions, and a Path Forward, and From Value Networks to Causal Loop Diagrams: Strategic Preparation for Designing Systemic Interventions in Organizations. The third category showcases three unique applications of systems thinking in the education sector, such as Learning Analytics and Interactive Multimedia Experience in Enhancing Student Learning Experience: A Systemic Approach, Fostering Problem-Solving Skills and Creativity in Latin America Primary Schools through System Dynamics, and Exploring Gender Inequality and Practical Solutions for an Equitable Environment for Women in Scientific Vocations. Next, the fourth category: Bridging the Digital Gap with Systems Thinking comprises two empirical contributions, namely (i) Using System Thinking for Improved Access, Equity, and Decision-Making in the Digital Age and (ii) Navigating the IT Professional Shortage with System Thinking: Practical Insights for Better Decision Making.

The fifth category focuses on the innovative applications of systems thinking in the agricultural domain and includes three contributions: (i) Leveraging IoT and System

Dynamics for Effective Cooperation in Solving Social Dilemmas in Water Management, (ii) Exploring the Systemic Causes of Land Inequality with Systems Thinking, and (iii) Biosecurity Adherence Using Cooperation Mechanisms: Leveraging System Thinking for Effective Strategic Organizational Biosecurity Decision Making. Next, the sixth category, the leading role of systems thinking in addressing the issues related to "sustainability" illustrates through two distinct chapters: (i) Review on Sustainable Plastic Contents Recycling in Bangladesh: A System Dynamics Approach, and (ii) The Potential Impact of ESG Spending on Public Perception of the Canadian Oil Sands. The seventh category demonstrates exceptional strength of the systems thinking approach through four state-of-the-art research contributions in the healthcare area, such as Improving Healthcare Policy Decisions with Systems Thinking: An Experimental Study, Understanding the Process of Production and Distribution of N95 Mask with a Systems Thinking Approach, Endangered Species-A Broad Look at Their Demographic Effects with Systems Thinking, Understanding the Dynamics of the HIV/AIDS Epidemic in China with System Dynamics. Finally, the last category concludes by highlighting the way forward for enhancing systems thinking practice.

1.4 Unique Theoretical and Methodological Perspectives

This book section, Category/Part II of this book, explores four exciting and innovative "Theoretical and Methodological perspectives to understand and solve some of the most urgent global challenges we face today, such as climate change, economic instability, sustainability challenges, and supply chain disruptions". We show how systems thinking and causal loop modeling, also known as soft system dynamics, can help us see the big picture and find effective interventions.

1.4.1 Achieving Reliability Assurance of Subsea Oil and Gas Production Systems

Offshore oil and gas production and supply systems are complex and expensive projects that need to operate reliably and safely. In Chap. 2, "**A Systems Engineering Framework for Reliability Assurance of Subsea Oil and Gas Production Systems**," Sirous Yasseri explains how to use a systems engineering approach to ensure the reliability of these systems. He begins by introducing the challenges and opportunities of subsea oil and gas production systems, and the importance of reliability assurance for these systems. He then argues that (i) high availability is essential to recover the large investment, (ii) the costs of intervention and revenue loss can be very high if the equipment fails, and (iii) therefore, the reliability of the production system must be verified and validated by reliability analyses and testing.

He describes how to connect the client's reliability needs to the system's performance, and how to specify the best strategies and procedures for verification and validation, taking into account all the factors that affect the system's availability, such as maintenance costs, intervention requirements, downtime, and possible expansion needs. He also shows how to use reliability analyses, testing, and risk analysis methods to manage the project risks and ensure the robustness and resilience of the production system. He enhances the system engineering V-model with reliability assurance requirements to achieve sustained operation. He illustrates his framework with a case study of a subsea oil and gas production system in the North Sea. For the readers of this book, this chapter provides a comprehensive and practical framework for ensuring the reliability of subsea oil and gas production systems using a systems engineering approach.

For the readers of this chapter: Do you want to learn how to use a systems engineering approach to ensure the reliability of offshore oil and gas production systems? If so, you need to read Chap. 2 of this book. It will show you how to connect the client's reliability needs to the system's performance, and how to specify the best strategies and procedures for verification and validation. It will also show you how to use reliability analyses, testing, and risk analysis methods to manage the project risks and ensure the robustness and resilience of the production system. You will learn from a case study of a subsea oil and gas production system in the North Sea. Don't miss this opportunity to learn how to use a systems engineering framework for the reliability assurance of subsea oil and gas production systems.

1.4.2 Designing Effective Strategies for Scientific Vocations

Designing and implementing strategic decisions and policies for fostering scientific vocations is a crucial issue for any country's development. In Chap. 3, "**Improving the Strategy for Scientific Vocations in Colombia through Participatory Modeling Based on System Dynamics**," Jorge et al. show how to use Participatory Modeling Based on System Dynamics (PM-SD) to tackle this challenge. In this chapter, they introduce the concept and benefits of PM-SD, which is an approach that combines System Dynamics and Participatory Modeling to help improve decision-making in complex systems by involving stakeholders, institutions, and citizens in the process. They apply PM-SD to the case of Santander, a Colombian department, where they aim to increase science vocations among children and adolescents. They build on previous studies that indicate the positive impact of PM-SD on stimulating interest and engagement in STEM fields and offer valuable insights and lessons learned for similar initiatives in Colombia or elsewhere.

They describe their project, which uses PM-SD as a methodology to implement a participatory and sustainable strategy for promoting scientific vocations. The project includes the development of research projects, support for teachers, and the creation of spaces for scientific dissemination. The project also evaluates the impact of the intervention on the participants using various indicators and methods. They present the results and findings of their project, which show that PM-SD has contributed to enhancing science vocations in Santander.

They discuss the challenges and opportunities for decision-making in complex systems and suggest practical considerations and strategies for applying System Dynamics and Participatory Modeling. They also explain how to identify the relevant stakeholders, institutions, and citizens for effective decision-making, and how to facilitate their participation and collaboration throughout the process.

They highlight the potential of Systems Thinking and Participatory Modeling to improve decision-making in complex systems, stressing the importance of collaboration among stakeholders, institutions, and citizens in achieving this goal. By using these approaches to enhance science vocations in Colombia, this chapter illustrates how Systems Thinking can be used to address real-world challenges. They also provide recommendations and suggestions for future research and practice in this field.

Overall, this chapter illustrates how Systems Thinking and Participatory Modeling Based on System Dynamics can help improve decision-making in complex systems, with a focus on enhancing scientific vocations in Colombia.

For the readers of this chapter: Do you want to learn how to design and implement strategic decisions and policies for fostering scientific vocations in your country? If so, you need to read Chap. 3 of this book. It will show you how to use Participatory Modeling Based on System Dynamics (PM-SD), an innovative approach that combines System Dynamics and Participatory Modeling, to involve stakeholders, institutions, and citizens in the decision-making process. You will see how PM-SD can help you tackle the challenge of increasing science vocations among children and adolescents, using the case of Santander, a Colombian department, as an example. You will also learn how to evaluate the impact of your intervention using various indicators and methods. You will discover the benefits and challenges of PM-SD, and get practical tips and strategies for applying it to your context. Don't miss this opportunity to learn how to use Systems Thinking and Participatory Modeling to improve decision-making in complex systems and promote scientific vocations in your country.

1.4.3 On the Fusion of Economics and System Dynamics

In Chap. 4, "**Bringing Behavioral Economics into System Dynamics: Some Challenges, Solutions, and a Path Forward**," Souleymane et al. propose a novel way to integrate behavioral economics and system dynamics to better understand and solve complex and dynamic problems in these turbulent times. They claim that system dynamics models can benefit from incorporating structures from behavioral economics that capture how human decision making influences system behavior. They explain that system dynamics models are used to study how complex system structures cause problematic system behaviors, and that behavioral economics models are used to study how human behavior deviates from rationality and affects economic outcomes. However, they also acknowledge the challenges and opportunities of merging these two disciplines, especially regarding the representation of time. They explain that system dynamics models use continuous time, while behavioral economics models use discrete time, and that both approaches have advantages and disadvantages depending on the context and the purpose of the model.

They illustrate their arguments with examples from Samuelson's multiplier-accelerator model, Allen's cobweb model, and three methods for discounting future benefits (exponential, quasi-hyperbolic, and hyperbolic). They show that the discrete and continuous versions of these models can produce similar or different dynamics, depending on the parameters and initial conditions of the models. They also show that the choice of time representation matters for transparency and insight, as some models are easier to understand and interpret in discrete or continuous time. They conclude with some suggestions for turning system dynamics models into games for experimental economics, and for creating a catalog of behavioral economics structures that can be used by system dynamists to enrich their models. They also discuss the implications and limitations of their approach and provide directions for future research in this field.

For the readers of this chapter, (i) it presents a novel and promising way to bring behavioral economics into system dynamics and shows how this can help improve decision-making in complex systems, (ii) it demonstrates the challenges and opportunities of merging these two disciplines, especially regarding the representation of time, (iii) it provides practical examples and suggestions for applying this approach to real-world problems, and (iv) it contributes to the advancement of both behavioral economics and system dynamics and opens new avenues for research and practice in this field.

1.4.4 Connecting the World Networks and the World of System Dynamics

Continuing with the thrust of Sect. 1.4.3, Fabian H. Szulanski and Hassan Qudrat-Ullah, in Chap. 5, "**From Value Networks to Causal Loop Diagrams: Strategic Preparation for Designing Systemic Interventions in Organizations**," introduce an innovative methodological framework for designing effective and systematic interventions in organizations. They show how to connect two different conceptual worlds: the world of value networks and the world of causal loop diagrams. They demonstrate how to link the world of interdependent value flows to the world of interdependent causal relationships between variables. They present a pragmatic methodology that is new to the strategic management community. They also provide some examples of how to apply this methodology. This is a significant advancement over the previous practice of analyzing value networks and causal loop diagrams separately, without an integrative perspective. Their methodology will help strategic management practitioners and researchers to design a systemic intervention by changing the system's structure causal loop diagrams, based on the information from a value network diagnosis. This will open new possibilities for more strategic management academic and professional writing.

Overall, if you, the readers of this book, are interested in learning how to design effective and systematic interventions in organizations, you will find this chapter very useful and insightful. You will learn how to connect two different conceptual worlds: the world of value networks and the world of causal loop diagrams. You will discover a new and pragmatic methodology that will help you link the interdependent value flows and causal relationships between variables. You will also see some examples of how to apply this methodology to real-world problems. This chapter will give you a significant advantage over the previous practice of analyzing value networks and causal loop diagrams separately, without an integrative perspective. This chapter will enable you to design a systemic intervention that will change the system's structure causal loop diagrams, based on the information from a value network diagnosis. This chapter will open new possibilities for more strategic management academic and professional writing.

1.5 Innovative Applications of Systems Thinking

In this section: Parts III to VII of this book, we will see how systems thinking can help us solve complex and dynamic problems in various domains, such as education, technology, agriculture, sustainability, and healthcare. Systems thinking is a way of understanding the interrelationships and patterns of behavior in a complex situation. It helps us see the part of the iceberg that's beneath the water, and find effective interventions that address the root causes of the problem. Systems thinking can also help us grasp the interconnectedness of our world and the impact of our actions on others. In this section, we will learn from the experiences and insights of experts who have applied systems thinking to their fields of work. We will also discover how systems thinking can help us prepare for the future and cope with uncertainty. Chapters 6–19 in these sections will demonstrate how systems thinking is a powerful tool for innovation and problem-solving that can benefit individuals, organizations, and society as a whole.

1.5.1 Part III: Applications of Systems Thinking in Education

In this section, readers can see how the systems thinking approach enhances our understanding and addresses the key issues in the education sector. Specifically, will show how the systems thinking approach has helped the decision makers in addressing critical issues, for example, gender inequality, promoting creativity and problem-solving skills, and learning analytics in formal educational programs.

1.5.1.1 Learning Analytics

In Chap. 6, "**Learning Analytics and Interactive Multimedia Experience in Enhancing Student Learning Experience: A Systemic Approach**," Jorge et al. present a unique application of causal loop modeling, a prominent tool of the systems thinking approach. They explain how Learning Analytics (LA) is a feedback loop process that collects and analyzes data from learning activities designed by teachers. These data are then used to provide recommendations to improve the learning experience in a continuous cycle. LA has been integrated into multimedia systems that are oriented to user experience, and the design of Interactive Multimedia Experiences (IME) can include LA to enhance the learning experience and collect data. However, they point out that the effectiveness of LA in improving students' learning experiences is still unclear, as different studies have reported mixed results. Therefore, they call for more research to evaluate the impact of LA tools on student retention.

They argue that it is important to consider the relationship between multimedia elements and performance, including the quantity and quality of multimedia features and how they match with learners' needs and abilities. They stress the need to investigate how multimedia elements can engage users and influence their learning outcomes.

In their chapter, they propose to identify the key feedback loops that link the LA process with IME in multimedia projects. They aim to develop a dynamic hypothesis that explains how the learning experience is related to user experience and teacher enthusiasm. They describe how researchers and teachers will collaborate to identify reference modes, variables, and feedback loops that connect the Learning Experience with the User Experience. By doing this, they claim that we can better understand and improve students' learning experiences by using LA tools and multimedia elements effectively in IME.

For the readers of this chapter: If you are interested in learning how to use Learning Analytics and Interactive Multimedia Experience to enhance the student learning experience, you will find this chapter very useful and insightful. You will learn how to use causal loop modeling, a prominent tool of the systems thinking approach, to identify the key feedback loops that link the learning process with the user experience. You will also discover how to use data and multimedia elements effectively to engage users and improve their learning outcomes. This chapter will help you apply a systemic approach to design and evaluate multimedia projects that enhance the student learning experience.

1.5.1.2 Fostering Problem-Solving Skills and Creativity

In Chap. 7, "**Fostering Problem-Solving Skills and Creativity in Latin America Primary Schools through System Dynamics**," Jorge et al. show how systems thinking can help primary-school students in Latin America develop problem-solving skills and creativity. They argue that there is a growing need to foster these skills among students to prepare them for the complex challenges of today's world. They explain how system dynamics can help educators create an integrated learning environment that enhances students' analytical and creative abilities to deal with complex issues.

They describe how educators can use collaborative teaching strategies such as visualization, structured dialogue, problem-solving activities, and simulations to create a dynamic and interactive learning experience that fosters critical thinking, problem-solving, and teamwork. They emphasize that this approach requires clear communication, problem-understanding, creative and critical thinking, and evaluation of solutions. They also highlight the importance of creating an environment that supports collaboration, creativity, openness to new ideas, and interaction. They suggest that by empowering students to tackle localized problems, educators can create leaders in problem-solving and improve learning and development outcomes for Latin American students and communities.

For the readers of this chapter: If you are interested in learning how to use system dynamics to foster problem-solving skills and creativity in primary-school students in Latin America, you will find this chapter very useful and insightful. You will learn how to use collaborative teaching strategies and system dynamics models to create a dynamic and interactive learning environment that enhances students' analytical and creative abilities. You will also discover how to create an environment that supports collaboration, creativity, openness to new ideas, and interaction. This chapter will help you prepare students for the complex challenges of today's world and improve learning and development outcomes for Latin American students and communities.

1.5.1.3 Fostering Problem-Solving Skills and Creativity

In Chap. 8, "**Exploring Gender Inequality and Practical Solutions for an Equitable Environment for Women in Scientific Vocations**," Jorge Valencia and Martha Massey tackle the important issue of gender inequality in the higher education sector. They argue that despite advances in science and education, women still face barriers and biases that limit their participation and leadership in decision-making roles. They suggest that systems thinking can help us understand and address the complex causes of gender inequality and devise realistic strategies and solutions. They present a dynamic hypothesis of gender inequality that identifies four feedback loops, each with four cycles of reinforcement that create and maintain structural inequality between men and women in science. They propose a multifaceted approach that targets the different feedback loops and the structural factors that influence social inequalities, such as unconscious bias, gender stereotypes, and access to resources. They emphasize that achieving gender equality and equal opportunity is essential for building a more equitable and inclusive scientific community and that systems thinking can help us take a comprehensive approach to address gender inequality and move towards a more just and equitable society.

For the readers of this chapter: If you are interested in learning how to use systems thinking to address the issue of gender inequality in the higher education sector, you will find this chapter very useful and insightful. You will learn how to identify and target the feedback loops and structural factors that create and maintain gender disparities in science. You will also discover how to devise and implement realistic strategies and solutions that promote gender equality and equal opportunity in the scientific community. This chapter will help you apply systems thinking to create a more equitable and inclusive environment for women in scientific vocations.

1.5.2 Part IV: Bridging the Digital Gap with Systems Thinking

In this section, two exceptional contributions demonstrate how the systems thinking approach can help us understand and tackle the key challenges in the technology sector. Specifically, they show how the systems thinking approach has enabled the decision makers to address a critical issue of our times: the widening digital gap.

1.5.2.1 Improving Access, Equity, and Decision-Making in the Digital Age

In Chap. 9, "**Using System Thinking for Improved Access, Equity, and Decision-Making in the Digital Age**," Jorge Valencia and Martha Massey address the important issue of the widening digital gap, a pressing challenge for many communities worldwide. They argue that AI technology can offer a unique solution to this challenge by enhancing digital literacy, promoting access to information and resources, and facilitating personalized learning experiences. They show how machine learning algorithms, natural language processing, and other AI-driven technologies can be used to provide more effective and efficient training that is customized to individual needs and learning styles.

They also explain how AI tools can provide more accessible and relevant information to individuals regardless of their level of digital competence. They suggest that by using AI tools to improve digital literacy, promote access to information and resources, and facilitate personalized learning experiences, we can create a dynamic feedback loop that helps close the digital gap. They claim that this feedback loop can lead to a cycle of empowerment, where the accumulation of knowledge and resources reinforces the ability to learn and acquire more resources. Finally, this chapter provides recommendations on how to use AI tools ethically and responsibly to address the digital gap.

For our readers of this chapter, If you are interested in learning how to use system thinking and AI technology to address the issue of the widening digital gap, you will find this chapter very useful and insightful. You will learn how to use machine learning algorithms, natural language processing, and other AI-driven technologies to enhance digital literacy, promote access to information and resources, and facilitate personalized learning experiences. You will also discover how to create a dynamic feedback loop that helps close the digital gap and leads to a cycle of empowerment. You will also get recommendations on how to use AI tools ethically and responsibly to address the digital gap. This chapter will help you apply system thinking and AI technology to improve access, equity, and decision-making in the digital age.

1.5.2.2 Addressing IT Professional Shortage

How can you solve the IT professional shortage with systems thinking? This is the question that Jorge et al. answers in Chap. 10, "**Navigating the IT Professional Shortage with System Thinking: Practical Insights for Better Decision Making**." They reveal the root causes of the IT talent gap and how to overcome them with a holistic and strategic approach. They show you how to use systems thinking to understand the interconnections and feedback loops that affect the IT job market, and how to leverage them to your advantage. They share real-world examples of organizations that have successfully applied systems thinking to attract, retain, and develop IT professionals.

They also offer practical insights and recommendations for improving your decision-making and addressing the IT professional shortage in your organization. Finally, they emphasize the need for a systemic vision of digital competencies and skills to close the digital talent gap and foster a more resilient digital economy. They claim that this chapter will help you to adopt systems thinking mindset and solve the IT professional shortage with confidence and creativity.

For the readers of this chapter: Do you want to solve the IT professional shortage with systems thinking? If so, you need to read Chap. 10 of this book. It will show you how to identify and address the root causes of the IT talent gap, and how to use systems thinking to improve your decision-making and strategy. You will learn from real-world examples of organizations that have successfully applied systems thinking to their IT challenges. You will also discover how to develop a systemic vision of digital competencies and skills that will help you close the digital talent gap and strengthen the digital economy. Don't miss this opportunity to learn how to solve the IT professional shortage with systems thinking!

1.5.3 Part V: Addressing Agricultural Issues with Systems Thinking

In this section, you will discover how the systems thinking approach can help you to deal with some of the most pressing challenges in the agriculture sector of the economy. You will learn from three innovative chapters how the systems thinking approach has enabled the decision makers to tackle the issues of water management, land inequality, and biosecurity. You will see how the systems thinking approach can help you to understand and address the complex interactions and feedback loops that affect these issues. You will also gain practical insights and recommendations for applying the systems thinking approach to your agriculture challenges.

1.5.3.1 Solving Social Dilemmas in Water Management

Water management is a complex and challenging issue that requires cooperation among various stakeholders. But how can we achieve such cooperation in a world of competing interests and scarce resources? This is the question that Beatriz Marin and Jorge Valencia answer in Chap. 11, "**Leveraging IoT and System Dynamics for Effective Cooperation in Solving Social Dilemmas in Water Management."** They reveal how the Internet of Things (IoT) and System Dynamics can be used as powerful tools to enhance stakeholder cooperation in water management. They show you how to use IoT and System Dynamics to model and simulate the complex dynamics of water systems, and how to use this information to communicate, learn, and build trust among stakeholders. They share a practical approach to solving social dilemmas in water management, with a focus on sugarcane production for panela, a crop that consumes a lot of water. They show you how to use IoT to collect and share real-time data, and how to use this data to collaborate and optimize water use. They also explain how their approach can be applied to other cases of water management, with examples of agent-based models, conflict management practices, game theory, and mathematical models. This chapter will help you to understand how IoT and System Dynamics can help you to solve the social dilemmas in water management, and how to use them to create more inclusive and collaborative policies that promote equitable and sustainable water use in various contexts.

For the readers of this chapter: Do you want to learn how to use IoT and System Dynamics to solve the social dilemmas in water management? If so, you need to read Chap. 11 of this book. It will show you how to use these tools to model and simulate the complex dynamics of water systems, and how to use this information to enhance stakeholder cooperation. You will learn from a practical approach to solving water management issues, with a focus on sugarcane production for panela. You will also discover how to apply this approach to other cases of water management, with examples of different models and practices. Don't miss this opportunity to learn how to use IoT and System Dynamics to create more inclusive and collaborative policies that promote equitable and sustainable water use in various contexts.

1.5.3.2 Understanding the Dynamics of Land Inequality with Systems Thinking

How can we solve the problem of land inequality with systems thinking? This is the question that Martha Galvis and Jorge Valencia answer in Chap. 12, "**Exploring the Systemic Causes of Land Inequality with Systems Thinking**." They show how land inequality is a complex and systemic issue that affects the quality of life of many people, especially the poorest. They reveal how cooperation can be used as a powerful tool to address land inequality, by analyzing the actors involved and their roles and interests. They demonstrate how cooperation can lead to more equitable and efficient public policies and community-led solutions that meet the needs of vulnerable populations. They also show how cooperation can improve stakeholder communication and understanding, leading to better bargaining and fairer regulations. They also discuss other relevant factors, such as economic interests and international initiatives, and how they influence the problem of land inequality. They conclude by highlighting the importance of a systemic analysis to understand and combat land inequality. This chapter will help you to learn how to use systems thinking and cooperation to solve the problem of land inequality in various contexts.

For our interested readers: Do you want to learn how to use systems thinking and cooperation to solve the problem of land inequality? If so, you need to read Chap. 12 of this book. It will show you how to use systems thinking to understand the complex and systemic nature of land inequality, and how it affects the quality of life of many people. It will also show you how to use cooperation to create more equitable and efficient public policies and community-led solutions that meet the needs of vulnerable populations. You will learn from examples of how cooperation can improve stakeholder communication and understanding, leading to better bargaining and fairer regulations. You will also discover how other factors, such as economic interests and international initiatives, influence the problem of land inequality. Don't miss this opportunity to learn how to use systems thinking and cooperation to combat land inequality in various contexts.

1.5.3.3 Dynamics of Adherence to Biosafety Procedures

How can we use cooperation mechanisms to improve biosecurity adherence? This is the question that Cindy Daza-Ríos and Jorge Valencia answer in Chap. 13, "**Biosecurity Adherence Using Cooperation Mechanisms: Leveraging System Thinking for Effective Strategic Organizational Biosecurity Decision Making**," the final chapter of this section.

They present a dynamic hypothesis that uses a model to explain how people decide to cooperate or not in biosafety procedures, based on social dilemmas. They explain how social dilemmas are situations where individual and collective interests are in conflict, and how they can affect biosecurity adherence. They also describe the different types of cooperation mechanisms, such as rewards, punishments, communication, and reputation, and how they can influence people's decisions. They aim to provide conceptual and methodological frameworks that help strategic decision making in organizations, as well as the development of institutional policies that improve the culture and communication among stakeholders. They show how these frameworks and policies can help to align individual and collective interests and to foster a sense of responsibility and trust among stakeholders. They also seek to reduce the negative environmental impacts and the effects on the quality of life of workers and other stakeholders that could be affected by microorganisms that pose a biological hazard that must be properly managed, contributing to corporate sustainability. They discuss the challenges and opportunities of managing biological hazards in different contexts, such as health care, agriculture, and biotechnology. They conclude by highlighting the importance of using system thinking and cooperation mechanisms to enhance biosecurity adherence in various contexts.

For the readers of this chapter: Do you want to learn how to use system thinking and cooperation mechanisms to enhance biosecurity adherence? If so, you need to read Chap. 13 of this book. It will show you how to use a model to understand how people decide to cooperate or not in biosafety procedures, based on social dilemmas. It will also show you how to use different types of cooperation mechanisms, such as rewards, punishments, communication, and reputation, to influence people's decisions. You will learn how to use conceptual and methodological frameworks to help strategic decision making in organizations, and how to develop institutional policies that improve the culture and communication among stakeholders. You will also discover how to reduce the negative environmental impacts and the effects on the quality of life of workers and other stakeholders that could be affected by biological hazards. Don't miss this opportunity to learn how to use system thinking and cooperation mechanisms to enhance biosecurity adherence in various contexts.

1.5.4 Part VI: Sustainability Science and Systems Thinking

In this section, you will learn how the systems thinking approach can help you to tackle some of the most pressing challenges of our time: sustainability-sustainable consumption and production of products and services in different parts of our world. You will benefit from two unique and innovative empirical studies that cover the plastic industry and the oil sand industry, and show how the systems thinking approach can be used to solve complex issues that we face. You will see how the systems thinking approach can help you to understand and address the interconnections and feedback loops that affect these industries, and how to leverage them to create more sustainable solutions. This section will show you the strength and utility of the systems thinking approach in solving complex sustainability issues.

1.5.4.1 Plastic Contents Recycling

In Chap. 14, "Review on Sustainable Plastic Contents Recycling in Bangladesh: A System Dynamics Approach", Mohammad Shamsuddoha and Mohammad Abul Kashem present an innovative application of systems thinking to an important sustainability issue related to the plastic industry. They argue that the increasing use of plastics has caused environmental and sustainability problems and that scholars have explored the feasibility of plastic content recycling. They acknowledge that plastic contents are harmful, but that they need to be removed and reused or recycled to protect the environment and society. They point out the uncertainty of the economic viability of plastic recycling, as well as the challenges of finding the best, most affordable solution and the expertise to handle it, in Bangladesh. They claim that the initiatives are not effective, and even inappropriate, without enough support from the government or the non-profit sector. They use a System Dynamics method to develop a causal loop diagram that assesses the current state of plastic recycling and sustainability challenges. They also suggest efficient techniques for collecting, sorting, and valuing recyclables to create a sustainable environment for a densely populated country.

They further claim that the System Dynamics approach used in this study helps to identify feedback loops by drawing causal loop diagrams that show relevant variables and solutions for the plastic recycling industry. They offer summary recommendations for improving plastic recycling, such as building a robust infrastructure, promoting education and awareness programs, and developing policies that encourage sustainable practices. They conclude that a System Dynamics model, a reverse and circular economy can help to transform plastic waste into valuable resources to achieve sustainable development goals.

For the readers of this chapter: Do you want to learn how to use systems thinking and a System Dynamics model to improve plastic recycling and sustainability in Bangladesh? If so, you need to read Chap. 14 of this book. It will show you how to use a causal loop diagram to assess the current state and challenges of plastic recycling, and how to suggest efficient techniques for collecting, sorting, and valuing recyclables. It will also show you how to use a System Dynamics model, in a reverse and circular economy to transform plastic waste into valuable resources and achieve sustainable development goals. Don't miss this opportunity to learn how to use systems thinking and a System Dynamics model to create a sustainable environment for a densely populated country.

1.5.4.2 Public Perception of the Canadian Oil Sands

In Chap. 15, "The Potential Impact of ESG Spending on Public Perception of the Canadian Oil Sands", Saroj et al. explore the perceptions of people regarding sustainability and the Canadian Oil Sands. They argue that the Oil Sands in Alberta, Canada, which has the fourth-largest oil reserves in the world, is undergoing transformational change due to national and global pressure for greenhouse gas abatement. They assert that for the Oil Sands industry to survive, it must achieve a 'new normal', where it operates within a framework of increased environmental, social, and regulatory governance (ESG) standards. They claim that a key factor for achieving this 'new normal' is the perception of the industry by various stakeholders, which must be neutral or positive. They propose four metrics that influence the perception of the industry: First Nations, the Environmental Lobby, Investors, and the General Public. They claim that these metrics are influenced by both exogenous and endogenous factors that are linked, creating behaviors that can be studied using system dynamics.

They present a System Dynamics (SD) model to analyze the effects of reinvesting profits from Oil Sands into ESG spending on public perception. They focus on a specific case of oil production using mining and in situ drilling methods and examine the emissions, land use, water use, wildlife, and fish impacts, and well-being of First Nations people in Northern Alberta. They show how ESG spending can improve these impacts and influence the perception of environmentalists and First Nations people. They also examine the economic aspects of oil production, such as prices, profits, royalties, taxes, jobs, and productivity. They show how these aspects affect the perception of investors and the general public.

They report that their major findings evaluate perception as a complex and synergistic combination of well-being values: "economic well-being, social well-being, and environmental well-being", as well as specific sub-values related to emissions, wildlife, fish, land, and water. They highlight the importance of investor perception, which is central to the well-being of the industry.

They further claim that their SD model could inform practical ESG policy approaches for the Oil Sands industry in Canada, which could convince First Nation people and the country at large to support its survival. They suggest that their model could also be adapted for other countries where Oil Sands are explored. They recommend that the industry make a concerted effort to reach "net-zero emissions by 2050" to improve its perception by many of its stakeholders. They suggest that their quantitative model of stakeholder perceptions fills a crucial methodological gap in studying Oil Sands

For the readers of this chapter: Do you want to learn how to use system dynamics and ESG spending to improve public perception of the Canadian Oil Sands? If so, you need to read Chap. 15 of this book. It will show you how to use a System Dynamics model to analyze the effects of reinvesting profits from Oil Sands into ESG spending on various stakeholders, such as First Nations, environmentalists, investors, and the general public. It will also show you how to use ESG spending to improve the environmental, social, and economic impacts of oil production, and how to achieve net-zero emissions by 2050. Don't miss this opportunity to learn how to use system dynamics and ESG spending to create a sustainable future for the Oil Sands industry in Canada and beyond.

1.5.5 Part VII: Dealing with the Complexity of Healthcare Systems

How can systems thinking help us tackle some of the most urgent and complex challenges in healthcare? In this section, we present four inspiring and innovative examples of applying systems thinking to diverse and critical issues in healthcare. We use causal loop modeling to explore the supply chain dynamics of N95 masks during the COVID pandemic, the policy design for HIV/AIDS prevention in Canada, the health and sustainability of endangered species, and the dynamics of HIV/AIDS transmission in China. These examples demonstrate the power and potential of systems thinking for addressing healthcare problems holistically and systemically.

1.5.5.1 Dynamics of the Logistics of N95 Mask

In Chap. 16, "Understanding the Dynamics of the Logistics of N95 Masks with Systems Thinking," Hassan Qudrat-Ullah applies systems thinking approach to investigate the dynamics of the production and distribution of N95 masks. He explains that a supply chain refers to a system of activities and structures that an organization uses to transform the inputs into outputs for the customer. The process starts with the production and ends with the delivery to the final user, and all the steps in between are connected and coordinated to achieve the desired output. He contends that the supply chain involves the inventory and movement of materials for the production process, as well as the management policies that regulate the different flows. Supply chain management is the smooth and efficient management of the flow of goods and services from their source to their destination through various channels. In this chapter, he examines the production and distribution of N95 masks in Canada. An N95 mask is a protective device that health professionals wear during surgical procedures. It helps to trap the bacteria in liquid droplets from the user's mouth and nose to prevent transmission to others. Activities such as coughing, sneezing, breathing, and speaking can release bacteria that may infect a person undergoing surgery. He explores how different raw materials are assembled into finished products in the production line, and how they are transported through various modes of transportation to the users in Canada.

For the readers of this chapter: Do you want to learn how to use systems thinking to solve the toughest healthcare problems? In this book, you will discover four amazing stories of systems thinking in action for healthcare. You will explore the secret power of causal loop modeling for understanding and improving the dynamics and feedback loops of healthcare systems. You will learn how to see the big picture and the details of healthcare problems, and how to address them holistically and systemically. You will also enhance your skills and knowledge in systems thinking and healthcare management, and become a systems thinker and a healthcare leader.

1.5.5.2 Improving Healthcare Policy Decisions

How can we design better policies and rules to prevent and treat HIV/AIDS in Canada? In Chap. 17, "**Improving Healthcare Policy Decisions with Systems Thinking**." Hassan Qudrat-Ullah uses a system dynamics simulation-learning environment, SIADH-ILE, to teach and train healthcare professionals and policymakers on HIV/AIDS management. He collects data from action experiments in real educational settings, using the SIADH-ILE program, a questionnaire, and qualitative feedback from the participants. He evaluates the effectiveness of using Interactive Learning Environments (ILEs) in the classroom. He finds that a combined approach for HIV/AIDS prevention and treatment leads to fewer deaths from HIV/AIDS. He also finds that the participants strongly support the scenario-based SIADH-ILE training. He suggests that: (i) an integrated approach is needed for HIV/AIDS policies and programs in both public and private sectors, and (ii) training with debriefing-based simulations such as SIADH-ILE can improve the decision making skills of health policymakers and authorities who are fighting against HIV/AIDS.

For the readers of this chapter: Do you want to learn how to design better policies and rules to prevent and treat HIV/AIDS in Canada? In this chapter, you will discover how a system dynamics simulation-learning environment, SIADH-ILE, can help you understand and improve HIV/AIDS management. You will see how SIADH-ILE can teach and train healthcare professionals and policymakers on how to use a combined approach for HIV/AIDS prevention and treatment. You will also learn how SIADH-ILE can enhance your decision making skills and help you fight against HIV/AIDS. You will find out how SIADH-ILE has been tested and validated in real educational settings, using data from action experiments, a questionnaire, and qualitative feedback from the participants. You will gain insights and tools for improving healthcare policy decisions with systems thinking.

1.5.5.3 Dynamics of Endangered Species

How can we protect endangered species from extinction? In Chap. 18, "**Understanding the Dynamics of Endangered Species with System Dynamics Approach**," Hassan Qudrat-Ullah uses systems thinking to analyze the dynamics of conservation efforts for endangered animals. He explains the concept of endangered species and the importance of saving them for the balance and diversity of life on Earth. He uses a system dynamics model to simulate the scenarios of conservation and no conservation for these species. He shows how conservation can help them recover from the threats of habitat loss, climate change, poaching, and human-wildlife conflicts. He also discusses the challenges and limitations of conservation strategies, some of which are controllable and some of which are not. He suggests that we need to adopt a systemic and holistic approach to conservation, taking into account the interrelationships and feedback loops among the various factors that affect the survival and well-being of these species. He also emphasizes the role of education and awareness in promoting conservation values and actions among the public and policymakers.

For the readers of this chapter: Do you want to learn how to protect endangered species from extinction? In this chapter, you will discover how systems thinking can help you understand and improve the dynamics of conservation efforts for endangered animals. You will see how a system dynamics model can simulate the scenarios of conservation and no conservation for these species. You will also learn how to adopt a systemic and holistic approach to conservation, taking into account the interrelationships and feedback among the various factors that affect the survival and well-being of these species. You will find out how to overcome the challenges and limitations of conservation strategies, some of which are controllable and some of which are not. You will also gain insights and tools for promoting conservation values and actions among the public and policymakers.

1.5.5.4 Dynamics of the HIV/AIDS Epidemic in China

How can we understand and prevent the HIV/AIDS epidemic in China? In Chap. 19, "**Understanding the Dynamics of the HIV/AIDS Epidemic in China with System Dynamics**," Hassan Qudrat-Ullah and Fabian Szulanski use systems thinking to analyze the HIV/AIDS spread and prevention in China. They use data from the Chinese CDC website and Unaids China to inform their analysis. They give a historical overview of the HIV epidemic in China since 1985 when the first case was detected in a foreigner. They explain how the epidemic has evolved and affected different population groups. They model the main modes of transmission: sexual contact, injecting drug use, and mother-to-child transmission. They identify the factors that influence the transmission rates and the behaviors of the infected and at-risk individuals. They also model the effects of medical interventions such as PEP and HAART on reducing HIV infection and mortality. They show how these interventions can improve the quality and length of life of the infected people and prevent new infections. They review the testing and prevention programs that China has implemented to achieve the UNAIDS 90–90–90 targets and curb the epidemic. They evaluate the effectiveness and challenges of these programs and their impact on the epidemic dynamics. They simulate the dynamics of HIV/AIDS under different scenarios using a system dynamics simulation model and compare the results using time graphs. They illustrate how different policies and interventions can affect the future course of the epidemic. They suggest some policy recommendations to address the HIV/AIDS epidemic in China, based on their analysis and simulation results.

For the readers of this chapter: Do you want to learn how to understand and prevent the HIV/AIDS epidemic in China? In this chapter, you will discover how systems thinking can help you analyze the HIV/AIDS spread and prevention in China. You will see how a system dynamics model can model the main modes of transmission and the effects of medical interventions on reducing HIV infection and mortality. You will also learn how to simulate the dynamics of HIV/AIDS under different scenarios and compare the results using time graphs. You will find out how to evaluate the testing and prevention programs that China has implemented to achieve the UNAIDS 90–90–90 targets and curb the epidemic. You will also gain insights and tools for suggesting policy recommendations to address the HIV/AIDS epidemic in China.

1.6 Part VIII: *Finally and a Way Forward*

In Chap. 20, "**Finally and A Way Forward**." Hassan Qudrat-Ullah concludes this book by highlighting how the systems thinking approach can enable us to enhance our decision making and performance in complex tasks.

1.7 Concluding Remarks

In this chapter, we have given you an overview of our book, its methodology, and its contents from Part I to Part VIII. We have summarized the main learning outcomes and insights that you can expect from each chapter of this book. We have also explained how we have organized the chapters into eight categories according to the structure of the book. These categories are Introduction of Systems Thinking and its Applications, Theoretical and Methodological Advancements, Applications of Systems Thinking in Education, Bridging the Digital Gap with Systems Thinking, Addressing Agricultural Issues with Systems Thinking, Sustainability Science and Systems Thinking, Dealing with the Complexity of Healthcare Systems, and Conclusion. We hope that this overview has sparked your interest and curiosity to read the rest of the book and to learn more about systems thinking and its applications in various domains. We also hope that this book will inspire you to apply systems thinking to your problems and challenges and to become a systems thinker and a leader.

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Part II
Theoretical and Methodological Advancements

Chapter 2
A Systems Engineering Framework for Reliability Assurance of Subsea Oil and Gas Production Systems

Sirous F. Yasseri

Abstract Capital projects, such as deepwater offshore oil and gas production systems (SPS), require a large investment, thus high availability to recover the investment is vital. The costs of intervention (recovery of failed equipment, repair, and replacement) and the loss of revenue will add to the problem. Thus, the reliability of the production system must be assured by reliability analyses and testing. A Systems Engineering (SE) approach is described in this chapter that links the client's reliability needs to the system's performance, hence permitting the specification of appropriate strategies and procedures for verification and validation while accounting for all constraints, including the costs of maintenance, possible intervention requirements, and downtime, and relates these to the equipment performance that is needed to achieve the desired availability of the SPS. In addition, the possibility of constructing the field in stages and expanding it as needs arise must also be considered. It is shown how to relate the equipment performance to the Client's requirements. The procedure described in this chapter can also assist with project risk management by blending the reliability analyses, testing, and various risk analysis methods for the system verification and validation procedures. The system engineering V-model is augmented by reliability assurance requirements to assure sustained operation by ensuring the robustness and resilience of the production system.

Keywords Subsea production system (SPS) · Capital projects · Reliability assurance. Systems engineering · Verification · Validation & testing · Qualification & certification · Failure mode effect critically analysis · Hazard identification · Hazard of operation · Mean time to failure · Mean time to repair · Mean time between failures

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Abbreviation

CAPEX	Capital Expenditure
ConOps	Concept of Operations
CR	Client Requirement
EFAT	Extended Factory Acceptance Test
FE	Finite Element
FAT	Factory Acceptance Test
FFP	Fit-For-Purpose
FFS	Fit-For-Service
FMECA	Failure Mode Effect Critically Analysis
HAZID	Hazard Identification
HAZOP	Hazard of Operation
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MTBF	Mean Time Between Failures
OPEX	Operation expenditure
RAM	Reliability, Availability, and Maintainability
SAT	Site Acceptance Test
ROV	Remotely Operated Vehicle
SPS	Subsea Production System
TRL	Technology Readiness Level
V&V	Verification & validation

2.1 Introduction

The petroleum industry requires a detailed comprehensive framework for delivering high reliability and availability systems. "*Reliability is taken as the probability that a system will operate satisfactorily under specific operating conditions for a given time. System maintainability is defined as the ability of a system to be operable without failure for a given duration in the future, and the system can be restored easily if a breakdown occurs*" (Rausand & Høyland, 2004). A system is considered 'not available' if it is shut down for unplanned or planned maintenance or component failures since the outcome is the same. "*The reliability analysis is used to judge a system's maintainability. Reliability, in turn, is dependent on the system architecture, material selection as well as design details; and it is only achievable if the availability is at its highest level*" (MIL-HDBK-217 Rev. F, 1995).

"*Performing System reliability, availability, and maintainability (RAM) analyses early in the phases of a project development provides a metric for comparison of alternative architectural concepts*" (Yasseri & Bahai, 2018). At the concept generation time (Yasseri, 2012), several functional architectures are considered, it is useful at this phase to model the functional components, as rough building blocks, without reference to their physical properties for an early estimate of the reliability using historical data. Functional architecture is an idealized abstraction of a system, which identifies functional elements without a precise description of their physical properties and their implementation.

The client decides on the desired target reliability level of the system, which is used by the designers for the allocation of reliability requirements for every piece of equipment (it may also include software) as a target. Then the system engineer's objective is to demonstrate "*by examination and provision of evidence that the hardware (as well as software) meets the Client's specified requirements for the intended use*" (DNVGL-RP-A203, 2019). For novel hardware, the failure data is likely to be non-existent or insufficient, thus tests may be essential to enhance confidence in the reliability of results.

Reliability can also be affected by an ill-defined specification or mismatch between specification and design. Bad manufacturing processes, unsuitable materials, poor installation, inadequate or irrelevant tests, and incorrect use of the system will also influence the system's performance. These lead to the estimated performance, which is demonstrated by analyses, to be different from the actual performance of the as-built system. Other explanations are "*emergent behavior, undetected faults, unanticipated operating conditions, unanticipated failure mechanisms & their causes, epistemic and aleatory uncertainties*" (Pecht, 1993). Unforeseen and unexpected operational conditions are because of insufficient or incorrect specifications, user errors, or as a result of incorrect implementation changes due to inadequate change control management and lack of oversight. A scenario-based approach and what-if analyses can help to minimize the impact of any uncertainties. The "*results of functional failure analyses and testing, are complemented by field experience obtained from observation of proven technologies as well as physics-based analyses*" (Viola et al., 2012).

A reliability analyst who uses only generic historical data, (e.g., OREDA, 2009), to determine the probability of mechanical failures cannot account for the impact of design errors and poor manufacturing on reliability. It may be incorrectly assumed that all errors will be detected and rectified during the development of the system. Thus, "*the reliability predictions based only on historical data is not highly dependable, and hence must be augmented by other types of analyses and tests*" (Feiler et al., 2012). It is not realistic to assume that modern fabrication methods and material qualities are the same as they were in the past.

The equipment reliability may even change from project to project. Components that are designed to perform a specific functionality by different manufacturers could have different failure modes and routes to failure. V&V and testing must be used to fill the knowledge gap.

A more dependable framework is needed for validating and qualifying a system, economically and quickly, rather than "test and test again until time and budgets are exhausted". The objective is to outline a methodology for the detection of all types of errors early in the Development Phase and to '*furnish the system with good quality attributes, such as high performance, safety, sufficient reliability, resilience,* *robustness, and defensible (adequate installation security)* (Yasseri & Bahai, 2018). It is prudent to build resilience into the system at the design stage to counter unforeseen, undetected, and emergent behavior. It is also crucial to assure that unavoidable, undetected, and unanticipated failure modes are managed by a well-organized and robust risk management plan during the operational phase. This framework aims to identify failure modes at the architectural level, the approach is also can deal with issues that are not easy, or possible, to test unless the whole system has been installed.

A framework for achieving a reliable SPS is described in this chapter. A parallel V is proposed which shadows the SE's V-model (see Fig. 2.18). This ties the reliability assurance to the system development process efforts and minimizes downtimes by embedding robustness and resilience into the system. The framework enables the delivery of reliable systems while respecting all constraints and requirements. The subsea battery limit in this chapter is from the down-hole valve to the seabed production equipment, to the topside equipment, (and possibly, to an onshore receiving terminal), in their operational environment employing the notion of "Fit-For-purpose".

2.2 System Thinking in SE

A system is an assembly of components and linkages, and linkages allow the system's components to interact with each other (Fig. 2.1). How components of a system are arranged, interact, and influence each other determines the property of that system. A collection of components, without linkages and relationships, does not make a system.

Accordingly, a system is a set of objects ate are organized in a specific way, with a certain relationship between the objects that work together in some manner to perform a function (the purpose). Systems can accomplish tasks that would be impossible if the same elements were put together in random order, or if there is

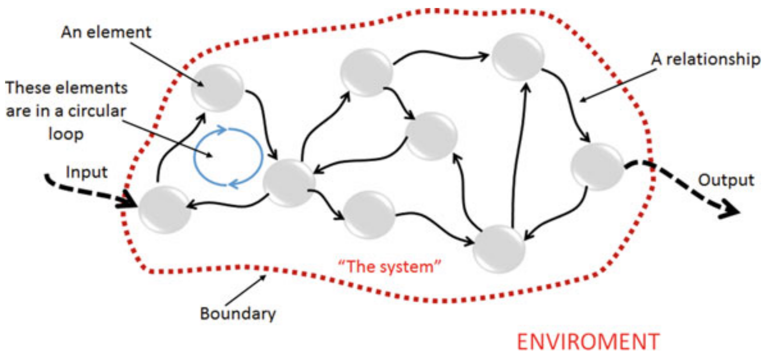

Fig. 2.1 A system consists of three elements: components, linkages, and relationships

no logical relationship between them. Humanity benefits continually from various clever ways of putting together the resources that provide us with food, transportation, education, goods, and services.

The characteristics of a system are (Fig. 2.1):

- ***Purpose***: A system can only be visioned when it has a clear purpose and provides a desired function. This purpose usually governs the arrangement of elements, their connectivities, as well as the strength of their relationship and the interactions between the system and its environment.
- **Boundaries**: The boundary determines the extent of influence of a system. The boundary stops where the impact of the environment on the system becomes marginal, and vice versa. Judgments as to where the boundary lies, are necessary constituents of the Systems Thinking.
- ***Coherence***: (A sense of belonging). Every interaction within a system must be coherent.
- ***Emergence***: A characteristic of systems is that they cannot be identified solely by their parts. This wholeness causes behaviors to emerge that are known as emergent characteristics.
- ***Hierarchy***: Any system should consist of at least three levels of hierarchy; System of systems (SoS), systems, and sub-systems, which determine how changes at one level can influence other levels.
- ***Sub-systems***: These are the parts of the system that must interact to achieve a balance to the purpose of the system. A sub-system or a component is a system the vendor.
- ***Environment*****:** All things not included in the system that may affect its purpose. Some aspects of a system's environment may be closely associated with the system, while other aspects are less relevant or unrelated.

The "*systems thinking focus is on relationships between the system's elements, (not on the elements as unrelated objects), objectives (not the structure), the whole (not its constituent parts), the context (rather than the contents) of a system, and patterns*" (Royal Academy of Engineering, 2014). Engineers for a long time have taken any complex system (like a transportation system), separated it into its parts, and then tried to manage each part as best as they can. Parts could in the context of transportation refer to different means of transport (road, rail, air, etc.), hardware, or people. If that was done, engineers believed that the system would behave well. "*Thinking in systems requires shifts in perception, which lead to diverse ways to perceive, and different ways of organizing a system*" (Edson, 2008). "*It is possible to improve the performance of many system's components and yet disable or destroy the system in its entirety*" (Senge, 1990).

2.3 System Architecture

"*System Architecture is an abstraction of the vision of how a system should hang together, which is an arrangement of its components and their relationships to each other and the environment*" (Sillitto, 2014). The system architecture is used as a plan (blueprint) for the definition of subsystems and components, their design, manufacture, and integration with the system's operational environment so that the elements of the installed system will work in unison to deliver the intended functionality.

A system architecture is presented at two levels of abstraction hierarchy, which are known as functional and physical. The first level is the functional architecture, which is also known as the "conceptual design", it is still an abstract view of the system but may have more details (Yasseri & Bahai, 2018). In software engineering, another layer is added between these two and call it the logical architecture. In this chapter functional and logical architectures are used interchangeably.

The functional architecture is a representation of the system independent of suppliers, and equipment is named by its functions. Each piece of equipment is represented by a box and identified by its function. At this early stage of development, what a component must deliver is known but its physical properties (dimensions, sizes, footprint, material, weight, and so forth) are not known until more definitions are added by identifying suppliers and deciding which equipment to procure. This takes place in the next phase of the project development.

Equipment manufactured by two different suppliers delivers the same function, but their physical properties are quite different. Two pieces of equipment designed and manufactured by two suppliers will share many common functional characteristics, but they will have many different physical characteristics. A component in the functional architecture represents its function (what it does), but some properties, and interfaces may be similar to a range of products supplied by different vendors. The functional architecture remains static and independent of technologies and vendors and will provide a relatively stable baseline to proceed to the system design, vendor selection, and fabrications.

The lefthand side of Fig. 2.2 shows, a deepwater subsea system to deliver certain functionality (extract gas from six wells and send it to shore for preparing it for sale), consisting of several sub-functions. At this stage of hierarchy, the function of all equipment, their relationship & connectivity, and how they should communicate are defined, which are mostly diagrammatic and descriptive. This is to make sure that all required components are present and logic for their inclusion is well understood.

Several concepts are developed, prioritized, and the front runner is taken forward for greater definition. The physical architecture gradually evolves to the middle section of Fig. 2.2. The middle section of the drawing in Fig. 2.2 is similar to the lefthand side, but with more information, and "*there is a one-to-one relationship between the functional components and their physical realization.*" (Yasseri, 2014a). All major components of the physical architecture (middle part of Fig. 2.2) are defined by their physical properties, suppliers, position in the system, and relationship and communication between them. It must include all known data such as the concept of

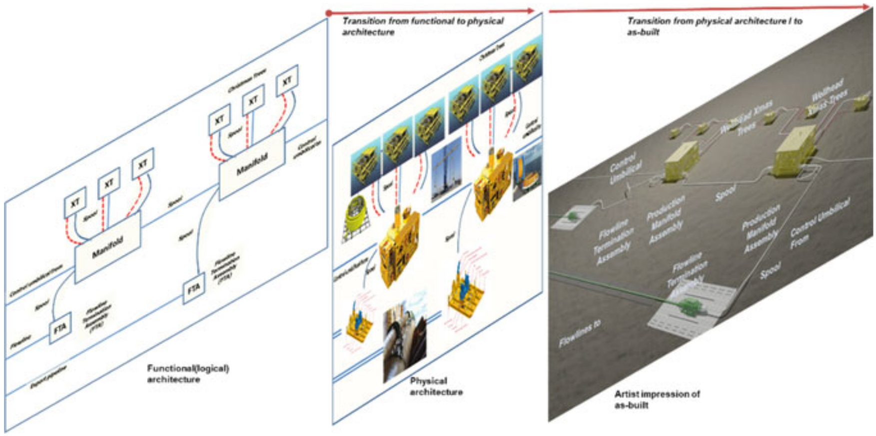

Fig. 2.2 A typical subsea system and its functional and physical architecture

operation (How the system should operate), system configuration, supplier's operating instructions, materials, and means of communication (flow of fluid, signals, and energy) & control. "*All physical constraints or limitations are also identified, e.g., physical solution for interfaces, fluid flow requirements, size (geometric compatibility), footprint, weight, and installation barges & cranes requirements are also decided*" (Yasseri, 2015b).

"*The functional architecture is a plan that enables each function of a system to be allocated to a physical component* (Fig. 2.2). *The functional design will remain almost unchanged, but the physical design will change throughout the lifecycle*" (Yasseri & Bahai, 2018). The choice of physical components is governed by the available suppliers and needs to improve or modify the installation during its lifecycle, and hence the physical system will be changed to suit the new conditions. Physical architecture would also change with the introduction of new capabilities (e.g., debottlenecking or expansion), new technologies (e.g., new control systems), hardware innovations, software upgrades, the necessity of replacing obsolete equipment (e.g., no spare is available), or acquiring a piece of equipment from a different vendor.

Figures 2.3 and 2.4 show examples of the functional architecture of two types of deepwater fields.

2.4 Phase-Gated-Incremental Commitment

The development of a project is a sequential process that takes several years from its inception to its completion. The time from the inception to decommissioning is known as the life cycle. Life cycle models vary according to the project's nature, purpose, use, and the procedures of the Client's organization. There are many forms

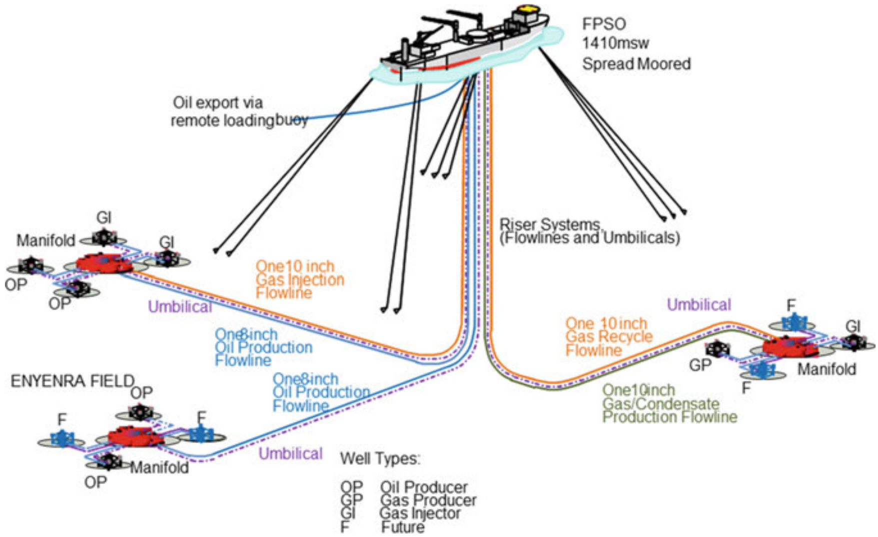

Fig. 2.3 A typical functional architecture of a deepwater development

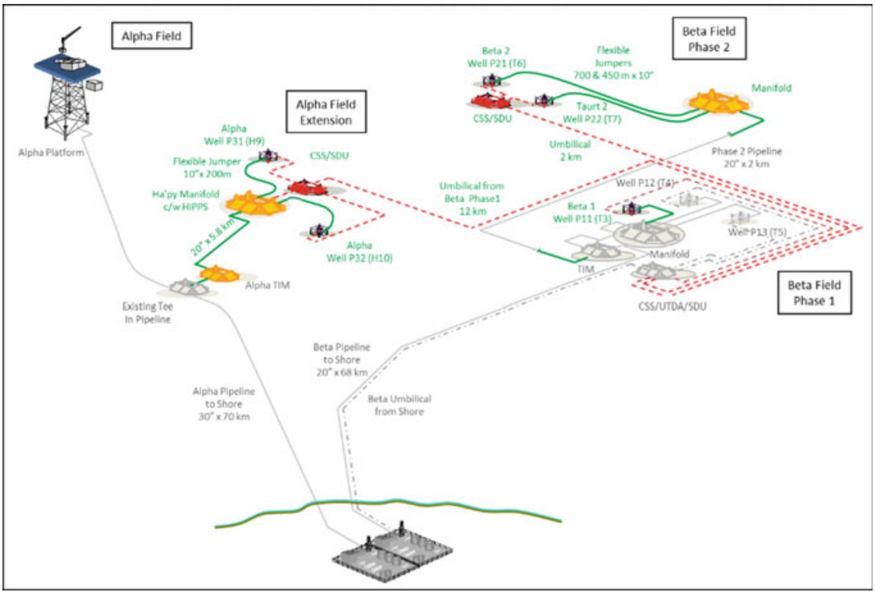

Fig. 2.4 A typical functional architecture of a satellite deepwater field. The produced oil and gas are transported via pipeline to an onshore terminal

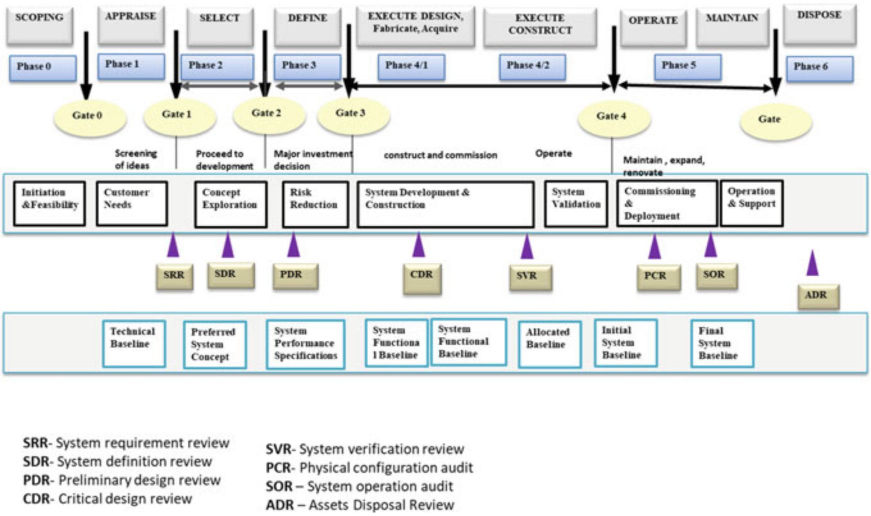

Fig. 2.5 A typical life cycle model with phase-gate and review milestones

of life cycle models, however, they all share a similar set of phases. The development life is divided into several phases (Fig. 2.5), and sometimes each phase is broken down into several stages—(some authors swap around phases and stages). "*Each phase has a distinct and definite purpose and position in the life cycle and represents an identifiable period in the life cycle of a system*" (ISO/IEC 15288, 2008). These phases also mark major milestones in the development process.

The subsea project life cycle begins with exploration and scoping (initiation)—(Phase 0)—the concession to explore by the government is excluded here. Phase 1 (the Appraisal Phase) focuses on identifying the Client's needs and objectives, exploring diverse ways of extracting the hydrocarbon, and transporting it to the shore. The focus of Phase 2 (the Select Phase) is identifying, refining, and verifying the system requirements, generating a few concepts with enough detail for decision-making, choosing a front-runner, and taking it to Phase 3 (the Define Phase) for more definition. Afterwards, the project progresses to Phase 4 (the Execution Phase), Phase 5 (the Operations Phase), and finally to Phase 6 (decommissioning or retiring). A life cycle model shows how early choices would impact what can be done further along a project's life cycle, thus enabling sensible trade-offs, and can beneficially influencing its viability.

Commitment to the capital investment in any large complex project is incremental. The lifecycle approach enables one to commit to the project incrementally (*incremental commitment*). This is achieved by inserting gates between phases. The gates are milestones and key decision-making points of the project development. The gate enables sponsors to review progress, decide on the commercial and technical viability of the project, and whether it is logical to proceed to the next stage by committing more funds. Phase-gated processes (Fig. 2.5) allow the timely accrual of required information for the decision-makers.

Each phase is designed to collect specific information or meet specific goals (Table 2.1). There is a major *review gate* at the end of each phase, where the Client's team gets the opportunity to assess whether the phase objectives are met and decide if and how the project should continue. Reviews are a formal means that allow project sponsors to control risks (commercial and technical) and monitor changes in the project scope. Based on the deliverables and decision criteria for the phase, sponsors can also validate the business case. This is an external review by the executive sponsor, stakeholders, and others who were not involved with the design.

At each gate, Project managers and sponsors should review the following:

- Identify and manage risk in each phase.
- Whether the phase met its objectives.
- Approve any changes in scope or schedule since the last gate review.
- Abandon the project, or proceed (with or without modification in scope).

The criteria for successful gating are:

- Gates must control decisions, not activities. Deliverables, decision criteria, and decision-makers must be clearly defined.
- Division of the project into a suitable number of phases that are structured, scalable, simple, and adaptable.
- The gate must be for transitioning a project to the next phase and must logically be a milestone in the development process.

2.5 Fitness-For-Service

The notion of Fitness-For-Service (FFS) and Fit-For-Purpose (FFP) is promoted to assess a system's or a product's suitability for service-i.e., it does the job. Two phrases of FFS and FFP are used interchangeably in this chapter. These phrases are used to mean that a system, based on rational reasoning, is suitable for a specified purpose. The poof can be qualitative as well as quantitative. If a system is poorly assembled, sustained some damage, or is not suitable for its intended purpose, then it is considered as not 'Fit-For-Purpose'. That is the system cannot reliably deliver what is expected of it; either it fails frequently, or it doesn't function as it is supposed to. For example, if a component is '*bolted on*'—(added as an afterthought)—to a system to enhance the system somehow (e.g., to become more reliable or safer), but the add-on component does almost nothing, then that component is not FFP, meaning quality, is decided based on FFP (or FFS). This means that quality is not a system's intrinsic property; but is assessed in the context of what it must deliver (namely if it provides the required functionality). For instance, hardware cannot be judged to be of a 'high quality' product, because the quality is an attribute of the relationships among the system's components and the purpose for which a component is inserted into a system. But a product can be judged as 'low quality' because it can be shown that it

Table 2.1 Activities in the design phases of a large capital project

Appraise: • Feasibility and economics Studies • Alignment with business strategy • What are the project drivers? • Is there a viable opportunity to pursue? • Engage with regulators
Select: • Develop a few concepts (options) and prioritize • Develop an initial cost estimate and schedule for each option • Compare options focusing on risk, economics, and uncertainties (trade-offs) • Recommend a preferred option. Provide improved cost estimate, schedule, and production forecast
Define: • Develop the selected option with enough details and planning requirements to enable freezing the scope • Alignment with business strategy • What are the project drivers? • Refine, costs, schedule, and production estimates • Vendor assessment & Selection • Contacts for long lead items • Inform Regulator
Execute: • Detail engineering • Procurement • Testing (Factory, quayside assembly, installed assemblies and Integration) • Site support • Project management and System engineering • Accounting • Document control & management • Submit the 'Formal Safety Case' to obtain permit • Sparing policy
Operate: • Evaluate installation against requirements • Revise RAM studies • Personal training • Support the hand over team • Check the system's performance • Plan sparing • Intervention policy

is not good for any use. The purpose of a system (its function), and the quality that is needed for delivering the stated function, must be well-defined such that to enable one to make a judgment on the system's quality. It is difficult to imagine a purpose for a subsea control system that cannot perform emergency shutdown in an orderly manner and as safely as reasonably practicable within an acceptable time. Some systems may have many functionalities (purposes), and over time, some original functionalities may not be needed anymore. The systems' envisioned operating conditions (normal and abnormal) and the system's intended purpose are coupled and must be completely identified and well-defined, leaving no room for interpretation.

With the notion of "Fitness-For-Purpose", one can judge, as well as question, the completeness, and relevance of the defined purposes to ensure compliance and possible enhancement. FFP equates quality with the fulfillment of a specification or stated objectives. The intention is to validate a system for its intended use, nothing less or more. There may be multiple purposes such as safety, reliability, availability, or some specific quality requirements (possibly all), which are requested by the client. Thus, FFP is a practical concept for assuring a system meets quality, measured against the client's requirement. This definition gives the impression that '*value for money*' is a synonym for Fitness-for-Purpose, however, neither affordability nor cost-effectiveness criteria are necessary elements of FFP.

The notion of Fitness-For-Purpose has emerged as a guide to direct efforts toward an installation with zero faults (i.e., no downtime). The ultimate measure of perfection is 'zero faults', which is an excellent goal but achieving it is impractical. Perfection is meaningless If a system does not deliver the required service.

Proving a system is 'Fitness-For-Service' requires gathering many kinds of evidence, which involves collecting data while the system development is in progress. Such evidence includes reviews, V&V of requirements and design, using the analytical methods, simulation, and particularly test results to support justifiable confidence in the as-built system.

Generally, a 'claim' is made that a piece of equipment is FFS, then the claim is qualified by assembling relevant evidence (Yasseri, 2015a) that supports "the equipment would function within defined limits and with a sufficient confidence level" (Woody et al., 2014). Such confidence is assured by prototyping, simulation, physics-based analyses (analytical and numerical), reliability analysis methods (FMECA, RAM, etc. (see e.g., IAEA, 2001), risk assessments, visual inspection, and of course testing.

2.6 State of Practice

Classification societies have published recommended practices and guidance notes on the qualification of subsea production systems. For example, API-RP-17N (2023) and API-RP-17Q (2023), DNVGL-RP-A203 (2019), Bureau Veritas-NI525 (2020), ABS (2017), and Lloyds Register (2017). Figure 2.6 shows the DNVGL-RP-A203 (2019) procedure. API recommendations are similar with some variations (Fig. 2.7).

The primary target of these codes of practice and guidance notes is "New Technology", but their definition of new technology is quite wide and includes almost everything if the site is greenfield and even includes some brownfield sites. The term "'Technology' in these codes refers to a piece of "*equipment that uses a physical law' to satisfy a purpose*". They recommend that both the underlying physics and equipment be qualified. For example, if existing topside equipment is modified for the subsea application (i.e., marinized), it must be qualified. Generally, if no new

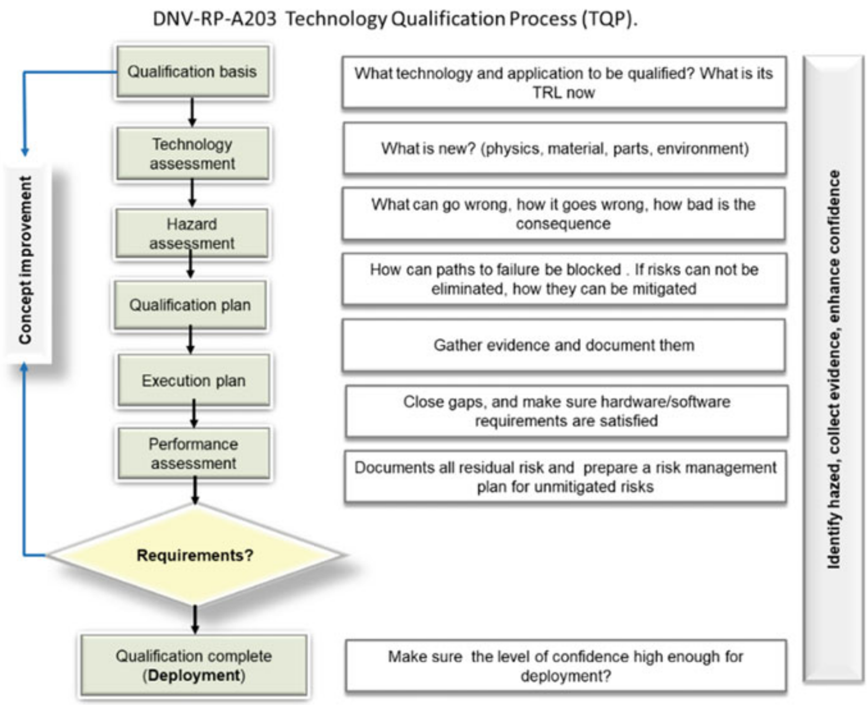

Fig. 2.6 DNVGL-RP-A203 (2019), Technology qualification process (TQP)

physics is involved, then it is only required that the equipment be qualified for its new working environment (effects of corrosion, marine fouling, etc.).

These codes, require reliability analyses to be conducted in Phase 1 for the entire system, with a level of detail that is commensurate with the definition of the system at that phase. The stated purposes to do so are:

- Identify possible design weaknesses.
- Compare and contrast alternative designs, architecture, equipment, materials, etc.
- Estimate costs at each phase of the lifecycle, with sufficient accuracy necessary for the decision-making.
- Perform availability assessments and check if the architecture would meet the client’s target.
- Define requirements, procedures, tooling, and required results for performing reliability testing.
- Specify sparing requirements and sparing policy.
- Probable intervention needs, its practicality, and intervention tooling & methods.

More than one reliability analysis method must be used to tease out all failure modes. Another tool to be used together with reliability methods to mitigate technical risks is the Technology Readiness Level (TRL).

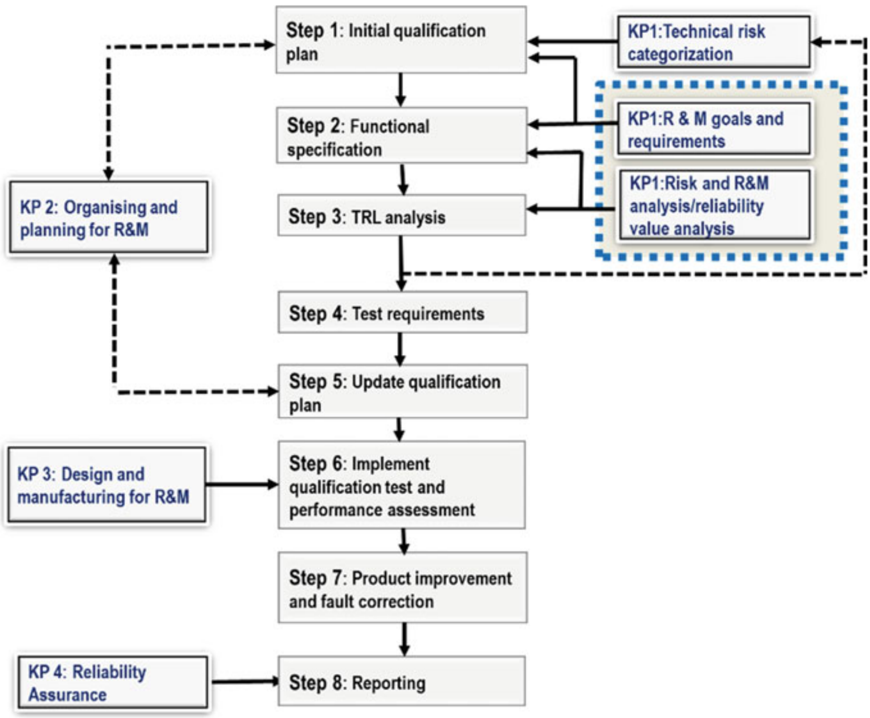

Fig. 2.7 API-RP-17N (2023) Technology qualification process flow chart

DNVGL-RP-A203-2019 and API-RP-17N-2023 recommendations define "*technology as 'new' when it is not used (i.e., its suitability is not proven) in a similar field under similar conditions*". Thus, if Commercial Off-The-Shelf technology (COTS) is used in an environment that was not used before, it must be considered new, but not unknown. This implies that the TRL of every subsea equipment for a new field at best, at TRL = 5, (Yasseri, 2013).

2.7 Systems Engineering V-Model

Systems Engineering (SE) provides processes for developing a system that can satisfy the client's requirements and needs against the background of conflicting constraints. "*SE is an all-encompassing integrative activity, which encourages and coordinates the collaboration of several disciplines, to deliver a coherent operable system that is not dominated by the perspective of any single discipline*" (NASA, 2007). INCOSE (2015) gives this definition: "*SE is an iterative process of top-down sequential synthesis and development to produce a system that meets, (in a near-optimal manner), the full range of the client's requirements*".

SE does not deal with the physics of the problem but provides processes, which can be employed to meet both the client's business needs and the technical requirements in engineering the system. System Engineering processes have been successfully applied for many purposes such as (NASA, 2007):

- ***Definition of systems of systems***—identification of system(s) that satisfies the client's needs.
- ***Development of system requirements***—development of conceptual architecture, concepts trade-offs, configuration management during development, and system integration.
- **Validation, verification—**operability evaluation and acceptance tests, sparing policy, and planning for maintaining the system over the whole lifecycle, including interventions, expansion, and refurbishment.

The process starts left-hand side of the SE's V-Model (Fig. 2.8) with the definition of the ConOps and the client's operational needs. Namely how the system is supposed to operate and function. Then the system is deconstructed (decomposed) into functional components or subsystems and components, for the ease of managing its development. The aim of breaking down a system into its constituent components is to create a logical chain by linking the operational needs to system requirements, to the specification of subsystems, then to the specifications for their integration, and then to acceptance testing. Moving along the left-hand side of the V one can partition the system hierarchy into functional, and physical collections of components which can be designed by the discipline experts and tracked to the logical conclusion. The use of conceptual models early in the project development is encouraged by SE processes to gain insights into the technical feasibility of a concept. A better understanding of the client's requirements enhances the chance of succeeding in delivering what the client asked for. The V-model allows concurrent activities.

The horizontal line, in the middle of the "V" in Fig. 2.8, depicts the handover of the design activities to the specialized disciplines, or engineers, who specialize in specific engineering disciplines, to produce the physical system. The position of this dividing line determines the overlap between discipline engineers and the systems engineer engaged in the integration processes. The horizontal line as drawn shows a modest overlap; a total separation is not implied. Interface management and some integration and qualification activities take place during the design.

The right-hand side of the V-model depicts the integration, Verification & Validation, and qualification activities. Integration involves the assembly of parts into components, the assembly of components into subsystems, the assembly of sub-subsystems into higher-level subsystems, and the assembly of subsystems into the final system. These parts, components, and assemblies must be qualified which could involve testing of the newly assembled sub-subsystems to check their compliance with the requirements; this process is known as verification (Grady, 2007). After verifying the system against the system requirements, the system must be validated.

The V diagram graphically shows how the design activities flowed down from system requirements to functional design, and finally to the physical design in an iterative loop of interrelated activities. Several factors, such as technology selection

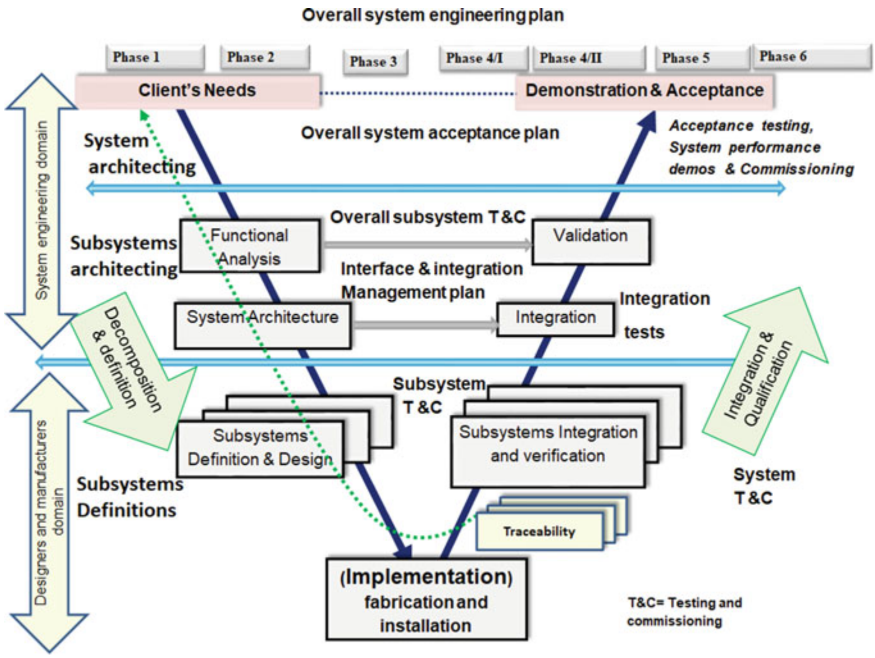

Fig. 2.8 Systems engineering V-model

(Yasseri, 2012), degree of standardization, hardware interface requirements, as well as the choice of concept would influence the nature and the level of iteration and possibility of concurrent engineering (Yasseri & Bahai, 2019).

2.8 Primary Loops of Development Process

The V-model requires that a system be decomposed into functional subsystems, which can be designed with fewer complications. This allows subsystems to be designed and fabricated in parallel (concurrent engineering) according to verified and validated system specifications developed in the previous phase. The SE processes allow the concurrent development of subsystems of a large system which accelerates the project development by involving many disciplines concurrently and encourages the engagement of vendors.

The V-model breaks down system definitions into three separate loops (Fig. 2.9). These three main loops, (Fig. 2.8), are the three main loops in the system development. The first loop is the design loop which deals with components, assemblies, and subsystems. If the system is a modular type, then the subsystem design and verification can be done in parallel. The installation '(implementation) takes place

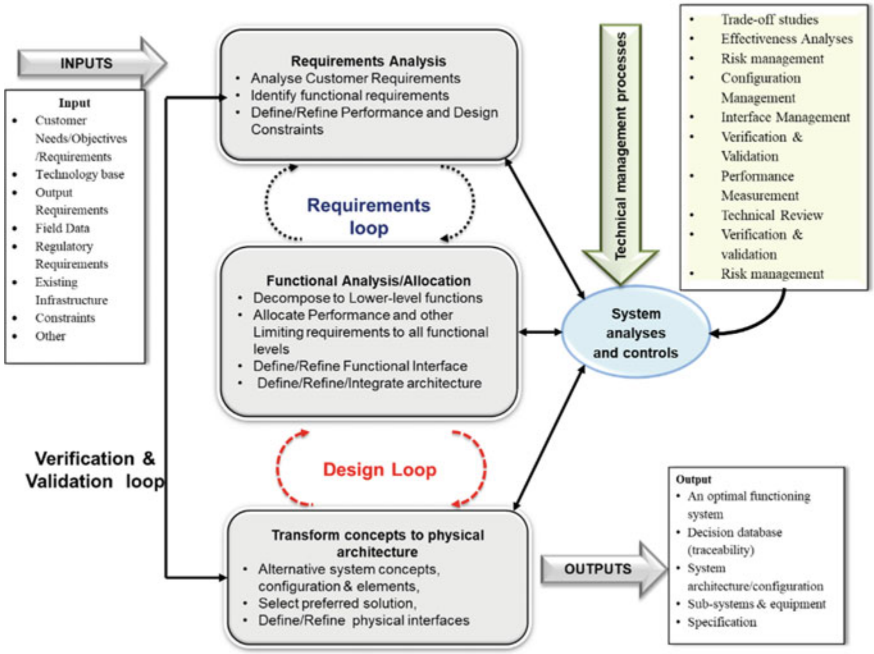

Fig. 2.9 Three loops of the development process-Left-hand side of the V-model (adapted from NASA, 2007)

at the bottom of the V, which is a collection of many 'parallel Vs', which are equal to the number of subsystems that are inserted into the system.

"*The Systems Engineering Processes are iterative, which is applied top-down sequentially by system engineers to decompose a complex system into manageable parts, for which an expert can be found. The client's goals, requirements, and needs are described in a set of top-level system requirements that are input for the next level of decomposition*" (NASA, 2007). A complex system is decomposed sequentially to several levels. At each level, more definitions are added, and performance requirements cascaded down. This process leads to nested loops (Fig. 2.9) indicating the repetitive nature of the process. "*The loops are the **requirements loop**, **design loop**, **verification loop,** and **control loop**. It also includes **input** & **output** definitions*" (NASA, 2007). "*These loops link **requirement analysis, functional analysis & functional allocation,** and **synthesis***" (see NASA, 2007 for more details).

The ***Inputs*** are the customer's requirements, objectives, needs, and the list of all constraints. The design process starts with understanding the client's needs and wants, the system operating environment and the battery limit. Before searching for a concept, it must be determined if the client's inputs are primary requirements or nice-to-have features (wants). Separating needs from wants allows the system engineer to concentrate on needs as the primary objectives and define a system that satisfies requirements rather than the implementation of the directed by the client's wants.

Requirements analysis is the elicitation and validation of the client's requirements and needs, which is the basis of the system's functional and performance requirements. The client's requirements are translated into the system requirements, namely what and how the system must function. Development starts by translating the Client's need into a set of agreed requirements, from which the system requirements are established. The system requirements are then flowed down to establish requirements for subsystems and equipment. "*Parts, assemblies, and subsystems are successively qualified against their requirements*" (Bahill & Henderson, 2005).

Functional Analysis & Allocation's purpose is to allocate functions and performance requirements to lower-level subsystems, which defines the system successively to its lowest level. "High-level *system requirements are flowed down for allocating them to subsystems and components. Defining allocated functions in adequate detail provides design specifications and verification criteria to support the development of the entire system*" (INCOSE, 2015). Functional and performance requirements for lower-level subsystems must be tied to higher-level requirements. Functional analysis and allocation activity will ensure consistency of the requirements and may require another iteration of the requirement's analysis. This is the ***Requirements Loop,*** which is iterative.

Synthesis defines the property of the hardware that makes subsystems, which leads to the complete description of the physical architecture. Every hardware (part) must support at least one of the functional requirements, however, several functions can be delivered by a single part.

Design Loop is the process of inspecting and assuring that the functional architecture leading to the physical system can deliver the desired functionalities at the desired performance levels. The ***design loop*** allows the revisiting of how the system would function and if it is desirable to optimize the system further.

The verification Loop is for verifying if the solution satisfies the requirements. System requirements at each level of the hierarchy must be verified. During the functional analysis and allocation baseline documents are developed which define how every requirement must be verified. As each component is integrated into the system, it is verified for compliance with all higher-level requirements. Visual inspection, demonstration, simulation, or test are used for the verification. Verification strategies and plans are to support the requirements. Validation is a system-level activity in which the system performance is compared with the requirements.

2.9 Requirement Analysis

The quality of a product only has meaning if it fulfills the service provider's needs. If a piece of equipment performs well the function for which it is inserted into a system, then it is considered as a quality product (i.e., Fit for Service), Thus "*what the system* must deliver, its performance and availability" must be defined (FAA, 2008). "*Requirements are linked to ConOps* via *traceability matrix*", (INCOSE,

2015) and "*cascaded down into requirements for subsystems, sub-subsystems, and components*" (Hull et al., 2002).

System requirements are defined for two operational conditions:

- The capabilities under normal operational regimes, which specifies the expected behavior, and desired performance.
- Desired expected behavior during upset conditions (abnormal conditions) i.e., the required resilience and survivability (robustness), and how to control the system during an upset condition and return it to normal operation.

The first loop of product development (Fig. 2.9) is about the requirements that define what is required of a system and its purpose. How well a system must fulfill its functions, or how well it must suit its purpose, which is an indication of how good the system is.

Requirements engineering is the systematic effort to collect, verify, specify, agree, validate, and manage the client's needs and goals while considering the user's interaction with the system, technical issues, and economic & business concerns. These envelop the whole lifecycle, involving dispersed teams of specialist engineers and several supply chains over many regions for a few years. Thus, requirements that are complete, verified, and stable are important tasks of systems engineers, since all design activities are cascaded from the high-level requirements.

The following three concepts are helpful when dealing with large capital projects:

- **Abstraction**: i.e., seeing the big picture, not details. The functional architecture is an abstraction of the system's functions without much detail.
- **Decomposition**: i.e., decrypting a system into its subsystems and components, so that they can be studied in isolation by relevant engineers. A system is decomposed along the line of suppliers' specialization. In decoupling between parts no decomposition is perfect, however, it enables the identification of specialist engineers and competent suppliers.
- **Projection**: i.e., an understanding of how the system should work (a perspective of view of the system) and describing only the pertinent aspects. While constituent (decomposed) components are designed independently, they share a common mission (purpose) as members of one system.

Requirements analysts use these concepts to decide what requirements are necessary and sufficient and how to satisfy them. The system engineer by abstraction, decomposition, and projection reduces a complex problem to its simplest form and investigates if existing solutions or off-the-shelf items can be used. Ideally, the decomposition must be directed toward components (or solutions) that already exist, which can be used albeit with some modifications. However, adopting existing solutions and off-the-shelf items could require substantial work to integrate them into a system in a different context.

"*Each requirement may impact many parts of a system and may need several test cases to verify it*" (INCOSE, 2015). The integration of a system with its environment and user interaction are also requirements.

There are two types of requirements (NASA, 2007):

- Functional requirements define the system's purposes, i.e., what services it provides and how.
- Non-functional requirements address the practicalities, which is how the system must operate and, the regulations and standards that must be obeyed. Other attributes cannot be expressed as functions—for example, the installation security, reliability maintainability, and availability.

Non-functional requirements may also include the following:

- Can the system be expanded, or adapted to suit new conditions?
- Can the system be fabricated in existing construction yards?
- Can the system be broken down to suit road and sea transportation restrictions?
- Can the system be installed using existing barges and lifting capabilities?
- Can the system be shut down fast in an emergency and startup with a reasonable effort and time?
- Are human–machine interfaces suitable and are users' access acceptable?
- Are suitable materials, skill sets, and manufacturers available? and
- any other constraints.

2.10 Concept of Operations (ConOps)

The operation (ConOps) document (Fig. 2.10) describes how the system should operate (Frittman and Edson (2010) and GOES-R, 2020). According to IEE (1362 and 1220), "*the ConOps is a "user-oriented document", that describes how a system will be used, and includes: who will use it; when they will use it; how they will use it, and for what purpose they will use it*."

The ConOps document defines the user's needs and expectations for the system developer, the procurement team, and the other stakeholders. ConOps establishes a shared understanding among all stakeholders. The ConOPs document (Fig. 2.10) is prepared at the beginning of the requirements analysis, describing what the system should do (not how it will do it) and its rationale (why). It should also identify any critical, top-level performance objectives and requirements as well as the system rationale. The human–machine interface must also be defined.

The primary considerations are (GPO, 2005):

- The client's team must be involved.
- The ConOps must be mature as the project moves through the project lifecycle.
- Must allow performing "what if" analysis.
- Should help to reach a consensus before the requirements process begins.

The principal function of ConOps is to have a collective understanding among all stakeholders regarding the expected functionality and level of expected performance. It is also used to describe/define some of the high-level concepts in support of detailed engineering, installation, integration, verification, and validation processes.

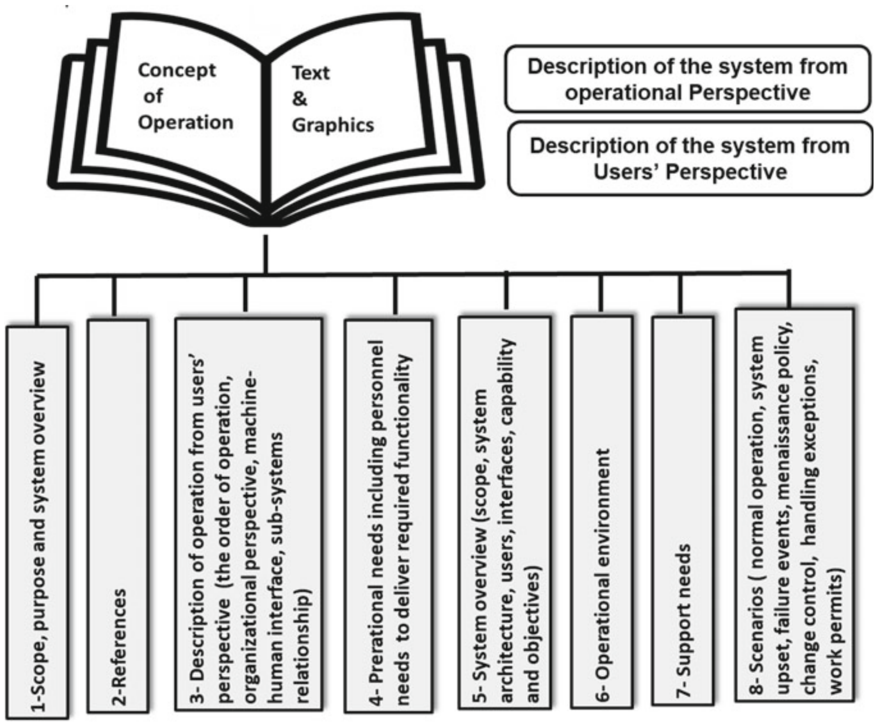

Fig. 2.10 Content of the ConOp document

2.11 Baselining

Paraphrasing Barry Boehm "*Constructing an installation from a specification is like walking on the water—It is safer if it is "frozen"*.

A design, product, or procedure at the end of a phase is called a "baseline", provided it has been reviewed and agreed upon, and then that level of progress is frozen. Any change thereafter can only take place through the project's formal change control management. A design that is baselined becomes the basis for the next stage of improvement evolving toward the final stage of development. For example, a System Requirement Specification (SRS) is frozen (i.e., baselined) to move to the next phase of development as a basis for completion. Once a design (or product) is baselined then no change can take place haphazardly, thus providing a stable reference for further improvement.

Thus, a baseline is a frozen picture of the design evolution at a specific time (generally the project's milestone point) in the system development lifecycle, signaling the end of a phase. It becomes a basis for improvements under change control management in the following phase, and hence it needs to be a stable reference for design

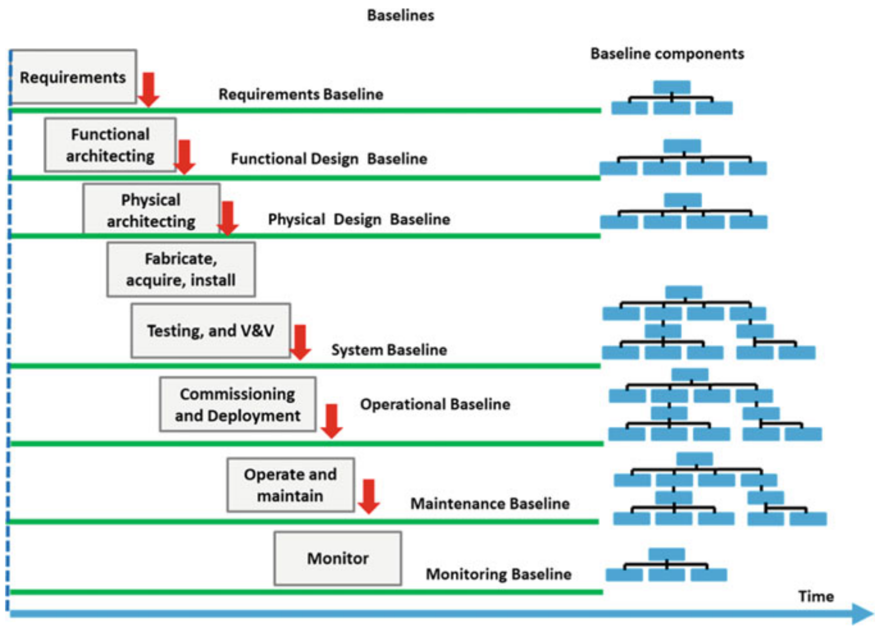

Fig. 2.11 Specifying a baseline

evolution. The objectives are to mitigate the vulnerability of all key deliverables to haphazard uncontrolled changes.

Figure 2.11 shows a typical baseline waterfall, which includes.

2.12 Requirements Traceability

"*The purpose of requirements traceability* (Fig. 2.12) *is to ensure every low-level requirement is linked to the higher-level requirements*" (Dick, 2002, 2012), however, some high-level requirements may impact many low-level requirements. Everything should be traceable from requirement specifications to design documents, interface control documents, and down to test procedures for acceptance. "*It is important to establish the link between requirements, design specifications, and supporting data for design (known as the design basis) since providing the original context in which a requirement was defined enables any future modification of the requirement to be checked to see if the originally defined constraints are still controls*" (Königs et al., 2012).

The traceability aims to create consistent links between test cases, user requirements, and project specifications. It should be possible to consistently cross-reference between components and system requirements, namely the functionality of any equipment is traceable to the client's requirements. For this purpose, the Client's

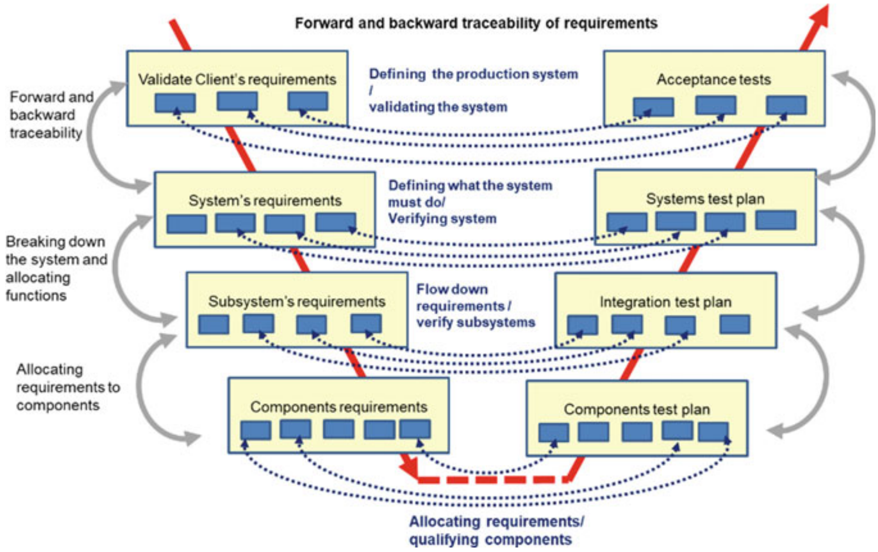

Fig. 2.12 Requirements traceability (see also Fig. 2.8)

requirements are assigned a distinct identification number for designation, which enables referencing.

Each client's requirement is tied to at least one system requirement, and vice versa. The system engineer enters these links in the tracing matrix to demonstrate that all client requirements have been considered. This is also used to show the completeness of the system specifications and the correspondence between the technical implementation and the requirements. The tracing matrix is also used for the compilation of the test plans to demonstrate that all requirements have been tested.

The primary purpose is to establish links between V&V tests and system requirements (Fig. 2.12). After cascading down higher-level requirements to equipment appropriate test plans are defined to verify whether the system will meet requirements. The following three items must be considered:

- If the Client's requirements and needs are accounted for
- All components are necessary, and in combination are sufficient, for adequately meeting the client's needs.
- The test plans will unambiguously verify them.

The circular traceability links enable precisely assessing what will be impacted if a requirement changes, and if there is a choice to avoid the proposed change.

Figure 2.13 gives an example of the decomposition of a system requirement into many component requirements. The two essential sufficient and necessary conditions are:

- **Sufficient**: if the compiled low-level requirements are sufficient? and
- **Necessary**: if every low-level requirement is necessary?

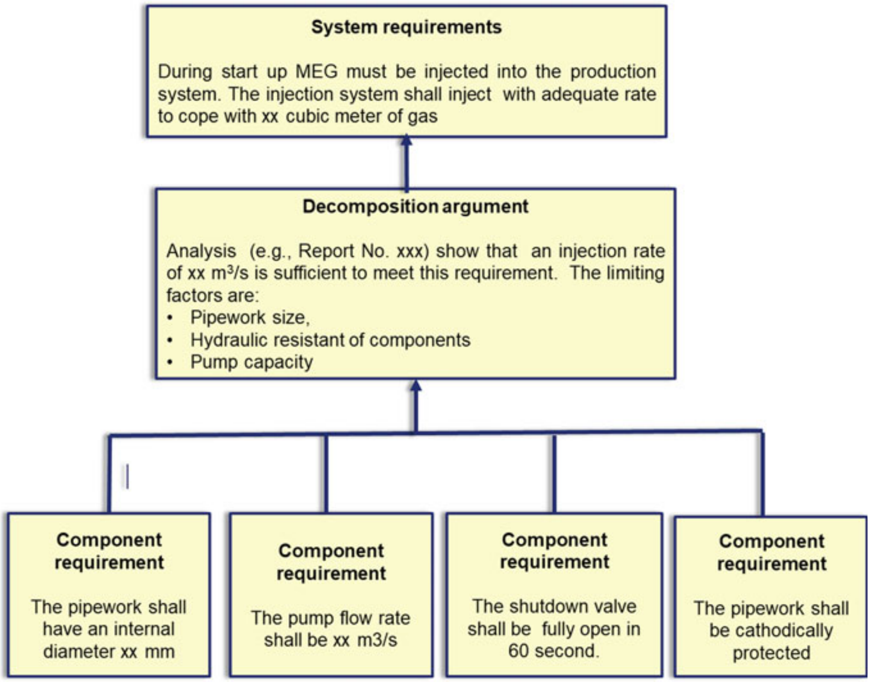

Fig. 2.13 Tracing requirements through a satisfaction relationship

2.13 Reliability Assessment for Assurance

The reliability of any modern equipment that is well-designed and manufactured, with materials that are suitably chosen, and tested is generally very good. However, in practice, several items are bundled together to make an assembly, hence the assembly's reliability is lower, and the Mean Time to Failure (MTTF) for the assembly would be shorter because there is more equipment that may fail. The Choice of architecture based on reliability can help to optimize MTTF.

Reliability, Availability, and Maintainability (RAM) analyses are used to obtain a functional architecture with the most advantages, considering all constraints. There is a multitude of methods such as MTBF (Mean Time Before Failure), MTTR (Mean Time to Repair), and the Reliability Block Diagram (RBD) that can be used to achieve the client's goals within reason (Fig. 2.14). These techniques are used to determine the most promising functional architecture for a field. At the early phase of development, historical failure data, (OREDA, 2009) is employed to estimate the availability of a system in pursuit of meeting the project's target availability.

At the physical design phase, the supplier and the client's failure database become available, and they are added to the historical data for a more accurate estimation of system reliability. The primary tool to capture all probable failure modes, their

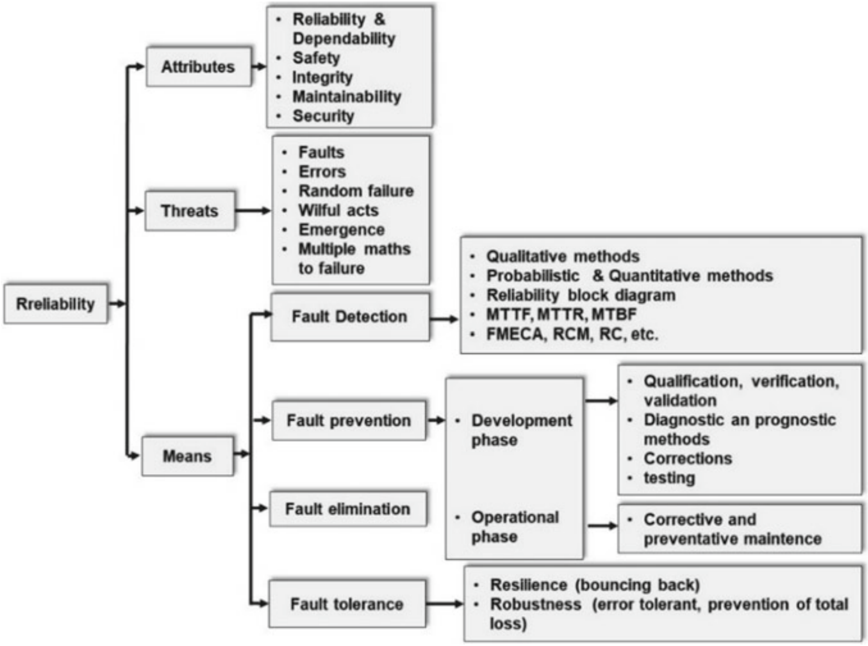

Fig. 2.14 Components of reliability analysis

effects, and criticality is FMCA (the Failure Modes, Effects, and Criticality Analysis). The Define Phase is a suitable time to perform the first FMECA and should be revisited in the Execution Phase when the physical architecture is almost complete. The aim is to identify the weaknesses and potential failure modes, rank them, assess their criticality, and suggest design modifications to avoid them, and if modification is not possible then mitigate their effect. The level of detail of FMEA must be commensurate with the project development phase. It is challenging to undertake RAM analysis at an early phase of development since little is known about the physical system. Nevertheless, even a rough RAM analysis is useful in assessing if the target availability is achievable. Before performing the RAM analysis, a Systems Description Document must be prepared to enable a common understanding among system engineers and designers. The content of this document is a description of all components and their functions as well as their interfaces. This document also defines the expected level of performance for all components, which are used in the system's RAM analysis at the Define Phase.

The primary objective is to identify all possible ways that a system can fail to perform. "*A failure state results if one or more components malfunction (e.g., not performing well or exceeding their acceptable limit). The resulting state is called a fault or a failure mode*" (Rausand & Høyland, 2004). "A component may have several failure modes and each failure mode may have many causes, mechanisms, and effects" (Rausand & Høyland, 2004).

Early in the Define Phase, only suppliers of long lead items are selected and very few pieces of equipment are known with enough detail, it is useful to perform functional FMECA to identify potential failures for each function according to their hierarchy of functions, because a failure of a lower function leads to failure of a higher-level function. After Phase 4 when preferred suppliers are selected and the physical design has taken shape, an FMECA is performed for interfaces to verify compatibility across all interfaces of the system's components. Then specifications for equipment are prepared (Datasheet), and the preferred suppliers are invited to tender. Towards the end of the Define Phase vendors are selected and possibly contracts to supply are placed.

When contacts are placed for all hardware (the Execution Phase), a System Breakdown Structure (SBS) is constructed showing the hierarchy of components and subsystems, which is like the Function Trees Fig. 2.15. With the SBS as input, a detailed FMECA is performed to identify system failures based on the failure modes of lower-level components and step by step moving toward the higher levels in the functional components hierarchy. The FMECA is performed by posing the following questions (Rausand & Høyland, 2004):

- *Credible failure of each part, component, and assembly.*
- *Possible failure mechanisms of identified failure modes? And their possible effect.*
- *Is the failure on the safe or unsafe side? (The concept of a "fail-safe" system.)*

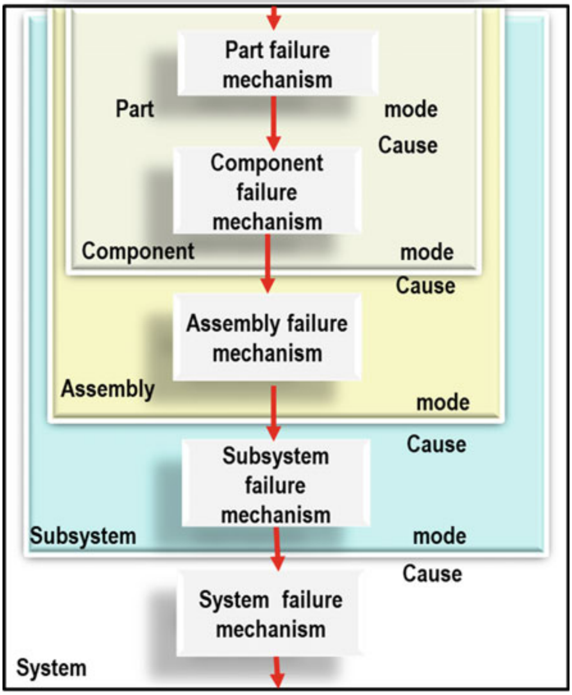

Fig. 2.15 Failure hierarchy (adapted from IEEE 1220)

- *How to detect failure?*
- *What provisions are provided to stop the failure progression or mitigate its effect?*

RAM analysis is deployed for verification and validation of the system's components at every level of evolving development (Using TRL as an indicator) and compared against the agreed client's operational requirements. Complications in manufacturing and system integration could lessen the system availability. Therefore, to offset the influence of manufacturing errors on the system availability, designers deliberately aim at availability above the agreed operational availability target, while addressing every manufacturing limitation.

2.14 Technology Readiness Level

Tests and simulations can only eliminate some of the uncertainties. The Technology Readiness Level (TRL) scale is another tool to manage technical risks. TRL is a useful tool for tracing the progress of technology toward readiness and maturity (API-RP-17N, 2023). However, *"TRL is not a measure of the quality of technology to be inserted into a system*" (API-RP-17N, 2023).

"*The TRL for a piece of existing equipment that is inserted in a new system is assumed to be at TRL = 4, or at best at TRL = 5*" (Yasseri, 2014b). The logic behind this decision is that a new subsea field is not the same as an old one; they are similar but not the same. Consequently, every piece of equipment must be qualified for use in the new environment and operational conditions.

The notion of TRL was advanced by NASA in the '70s. Later, NASA rehashed the idea and published this metric as a 9-point scale. Many industries have adopted NASA's 9-point TRL scale but modified it to suit their needs (Yasseri, 2013). Table 2.2 is adopted from API, which shows API's definitions alongside a NASA-type TRL. TRL = 1 in The NASA scale is a technology as a basic idea probably supported by basic science. The development is pushed along the TRL ladder until it reaches maturity, then readiness which is proven by working in its intended operating environment.

Table 2.3 shows processes that are used to reduce uncertainties of the technology during its development phase.

2.15 Verification and Validation

Components are tested for acceptance at the factory, known as Factory Acceptance Tests (FAT). Some components may require extended factory tests (EFAT). Tested components are delivered to the fabrication yard to produce bigger assemblies or modules for ease of transportation and installation. Modules are then transported to the quayside for integration. They are tested at quayside before installing them in their

Table 2.2 API definitions of TRLs and its equivalent NASA's scale (based on API-RP-17N, 2023)—(Yasseri, 2013)

	API 17N's TRL	API 17N's TRL	NASA type TRL	Development stage completed	Definition of the development stage
Concept	Initiation	0	1	Unproven concept (basic R&D, paper concept)	Basic scientific/engineering principles observed and reported; paper concept; no analysis or testing completed no design history
Proof-of-concept	Concept	1	2	Proven concept (as a paper study or R&D experiments)	(a) Technology concept and/or application formulated (b) Concept and functionality proven by analysis or reference to features common with/to existing technology (c) No design history; essentially a paper study not involving physical models but may include R&D experimentation
	Proof-of-concept	2	3	Validated concept (experimental proof of concept using physical model tests)	Concept design or novel features of the design is validated by a physical model, a system mock-up, or a dummy and functionally tested in a laboratory environment; no design history; no environmental tests; materials testing, and reliability testing are performed on key parts or components in a testing laboratory before prototype construction
Prototype	Integration	3	4	Prototype tested (system function, performance, and reliability tested)	(a) Item prototype is built and put through (generic) functional and performance tests; reliability tests are performed including reliability growth tests, accelerated life tests, and robust design development test programs in relevant laboratory testing environments; tests are carried out without integration into a broader system (b) The extent to which application requirements are met is assessed and the potential benefits and risks are demonstrated

(continued)

Table 2.2 (continued)

	API 17N's TRL	API 17N's TRL	NASA type TRL	Development stage completed	Definition of the development stage
	Demonstration	4	5	Environment tested (pre-production system environment tested)	Meets all requirements of TRL 3; designed and built as a production unit (or full-scale prototype) and put through its qualification program in a simulated environment (e.g., hyperbaric chamber to simulate pressure) or intended environment (e.g., subsea environment) but not installed or operating; reliability testing limited to demonstrating that prototype function and performance criteria can be met in the intended operating condition and external environment
	Commissioning	5	6	System tested (production system interface tested	Meets all the requirements of TRL 4; designed and built as a production unit (or full-scale prototype) and integrated into the intended operating system with a full interface and functional test but outside the intended field environment
Field qualified	Production	6	7	System installed (production system installed and tested)	Meets all the requirements of TRL 5; production unit (or full-scale prototype) built and integrated into the intended operating system; full interface and function test program performed in the intended (or closely simulated) environment and operated for less than three years; at TRL 6 new technology equipment might require additional support for the first 12–18 months
	Field-proven	7	8&9	Field proven (production system has been field proven)	Production unit integrated into the intended operating system, installed and operating for more than three years with acceptable reliability, demonstrating a low risk of early life failures in the field

Table 2.3 Uncertainty reduction at various levels of the TRL scale (adapted from Yasseri, 2015b)

Phase	API TRL	Development stage completed	Reduction of uncertainties
System validation	7	**Field Proven** SPS is field-proven (several months in operation)	Maintaining the aging system's reliability
	6	**System installed** SPS is installed and tested for operational requirements. Start of commissioning and hand over	Validating and commissioning of SPS using 'use cases' and the system's operational requirements
Technology verification	5	**System tested** Testing of SPS in its environment is complete	Validation testing; final RAM analysis of the as-built SPS
	4	**Tested in the operational environment** SPS is tested in its environment	Verification testing
	3	**Prototype tested** The system's functions, performance, and reliability are investigated	RAM analysis using the vendor's and cline's failure data
Concept validation	2	**Validated concept** Experimental proof of physics is performed using laboratory models	HAZID, HAZOP, FMECA, fault tree analysis, event tee analyses, Bow-Tie analysis
	1	**Fundamental concepts are demonstrated** Proof of concept as desk study or R&D by experimentation	What-if analysis, scenario building, logical architecture level reliability analyses; RAM analysis using generic data
	0	**Unproven concept** Basic ideas in research papers	Preliminary HAZID, HAZOP, FMECA, and Operability analyses

working environment and integrating them with the previously installed modules until the integration and verification of the entire 'as-built system' is complete, the entire system is tested and commissioned for handing it over to the client's team. When the entire system is installed on the seabed, and commissioning tests are complete, the responsibility of operation is gradually handover to the client's operations team. The handover includes providing support, devising a sparing policy, instructions for operation, operator training, and all other enabling items that assure the smooth running of the operation and maintaining the system in good working condition. During the handover period acceptance tests are organized by the client's team to confirm that the system complies with the client's requirements. The handover

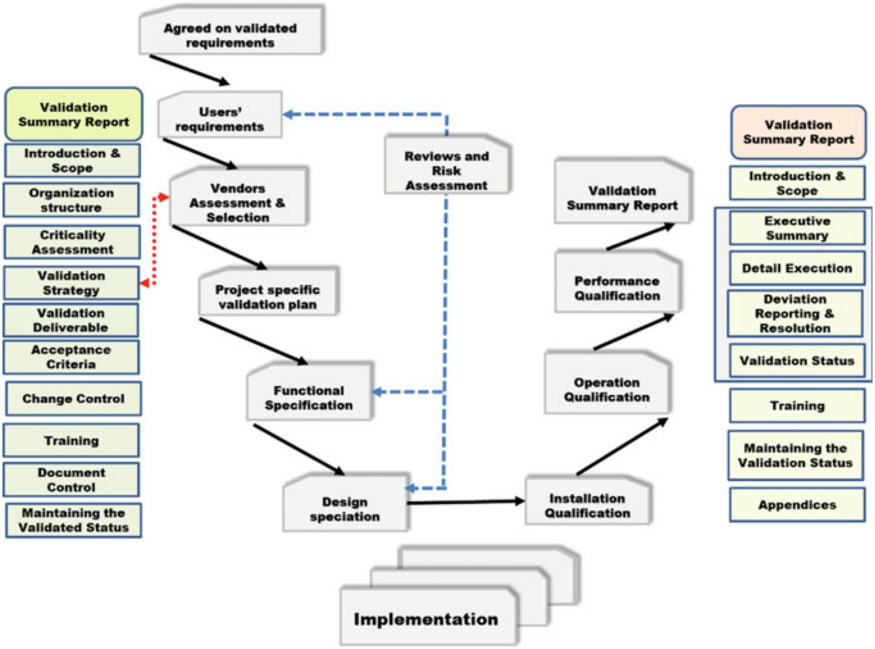

Fig. 2.16 V&V life cycle

period and warranty period are intended for a smooth transition of responsibilities from the primary contactor to the client's operation team. The entire process is called "Verification" and "Validation" (V&V), which are carried out through a myriad of tests at every stage of system integration (Fig. 2.16).

"*Verification and Validation procedures are used to confirm that a product, service, or system meets its defined specifications and judged it is FFS. Verification is a quality control process that is used to evaluate whether a product, service, or system complies with regulations, specifications, or conditions requested by the client at the beginning of the Development*" (Babuska & Oden, 2004). "*Validation is a quality assurance process for obtaining evidence that with a high degree of confidence proves a product, service, or system delivers the agreed specified requirements*" (Plant & Gamble, 2003). The ISO 9000 (2015) definition is based on the general field of quality and the focus is on providing "objective evidence" which proves that all requirements have been satisfactorily satisfied. According to ISO 26262 (2011), "*the validation is focused on providing proof that the system will meet its intended purpose.*" ISO defines the verification process in broad terms.

Figure 2.17 shows a possible flow diagram for the V&V activities. The process begins with reliability analyses and ends with V&V by testing, prototyping, simulation, and analytical approaches. The approved system's requirements are used to define the subsystems' requirements and specifications, which are then validated to

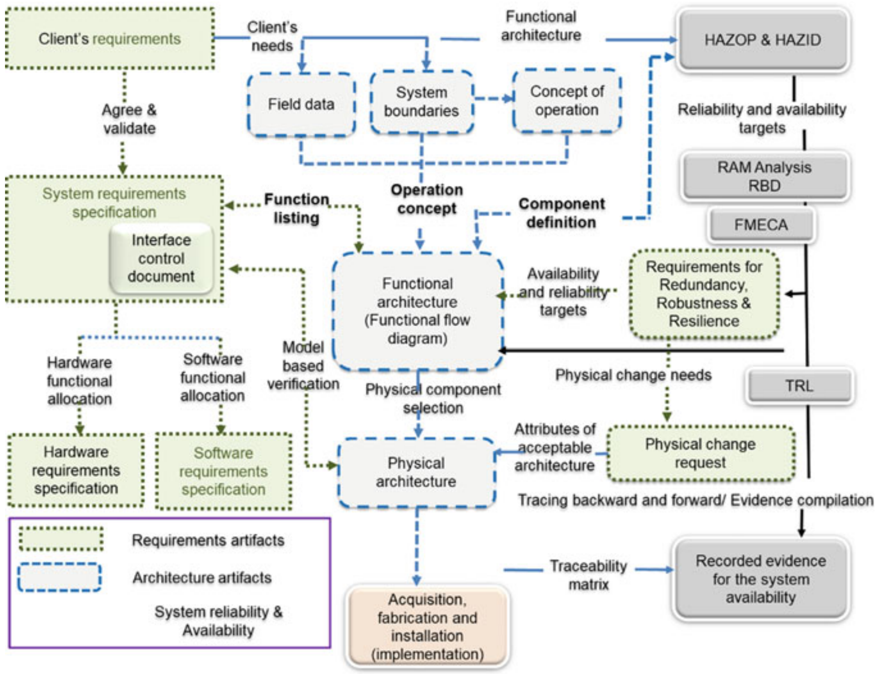

Fig. 2.17 A possible flow chart for verification and validation

assure that they are feasible, necessary, and exhaustive, in the light of the notion of 'necessary and sufficient' condition.

Tools are qualified but processes are validated according to this definition, qualification is considered as a subset of validation. All fasteners (rivets and nuts & bolts) including welding are considered tools for joining, but their FFS must be evaluated. In this respect:

- Fasteners, weldments, and materials as well as procedures using them are qualified as a tool for system building. They are procured from trusted suppliers and may be accompanied by a certificate of FFS. However, basic verification, based on the statistical sampling method, should be undertaken.
- Fasteners and weldments in assembled equipment must be validated to assure that they are capable enough to allow the equipment to fulfill its purpose. Results from the fastener's qualification tests are appended in the equipment's validation report.

The Verification and Validation strategy is a set of actions, consisting of tests, inspections, and trials. Each requirement may require several actions.

Each action must be:

- Suitable to check the requirements under consideration.

- Timely-implementation at an early phase is preferable.
- Describe the necessary testing tools.
- Define the successful outcome.

Verification & Validation, and qualification are used interchangeably in some literature. For example, IEC 61508 (2010), defines the qualification process to encompass V&V.

Figure 2.18 shows the V&V activities in parallel with the development processes. Any requirement may give rise to several verification tests at every phase of the evolving project. If a requirement is fulfilled by chance due to the beneficial effect of emergent behavior, such a chance event must be confirmed by tests at the level of emergent behavior.

Evidence for quality assurance is collected throughout the development phase utilizing a combination of testing and simulation. Validation solely based on tests or analytical methods would let some faults remain undetected. A balanced approach to confirm compliance has a high chance to control costs and enhance confidence in the system's performance. Simulation is preferable and testing is best used to fill the knowledge gap since simulation cannot detect manufacturing errors or visual inspection may not be suitable for accepting fabrication defects.

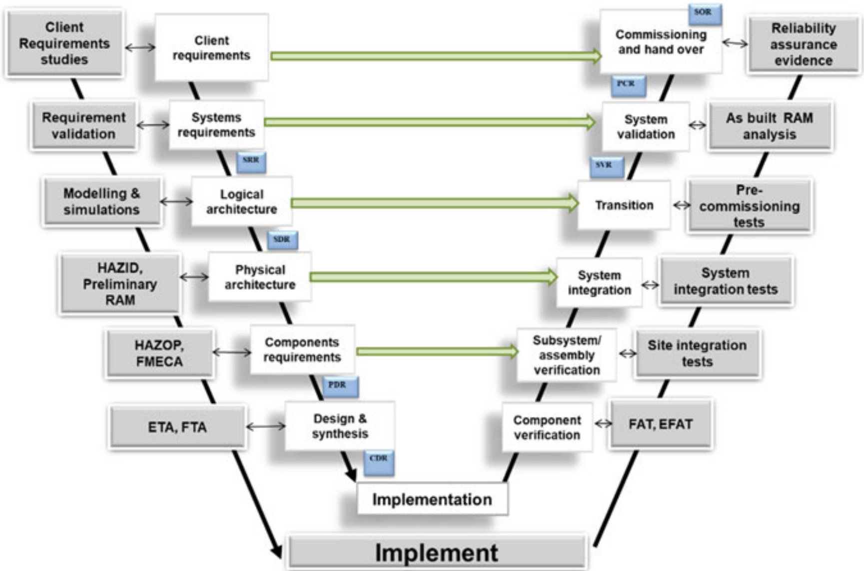

Fig. 2.18 The Qualification activities are shown in parallel with the development activities

2.16 Provision of Evidence

There are several methodologies for gathering evidence for supporting reliability assurance, and naturally, some overlap between them should be expected. Any chosen procedures (methods), and the depth and detail, are based on the "*need to know*" or "necessary and sufficient, and hence the choice depends on the problem at hand. There must be a purpose to gather information. Sometimes, evidence is collected for the design activities and hence is indispensable, since the design effort, however exhaustive, cannot reasonably detect all probable failures and their causes. The concept is founded on the principle of 'beyond a reasonable doubt', which is quite rigorous, not based on the balance of probabilities. However, reasonable doubt does not mean beyond all doubts. Sound engineering judgment is needed to avoid undertakings yielding little value. As a minimum two different methods should be used to detect all probable faults. A particular procedure, e.g., testing, may be necessary but is not sufficient (e.g., doing the same test twice), thus it must be complemented with another method to make sure that all faults are detected. Generally, simulations and analytical methods are used to lower the cost of testing needed for reliability assurance. Numerical approaches could replace the need for testing, for example when testing is almost impossible or very expensive. A few approaches that are in use for managing V&V are listed below:

Trust-based means that hardware is sourced from a trusted supplier or a design can be claimed to be compliant with codes and standards by the contractor, and it is taken on trust that the contractor's claim is valid. Generally, any claim involving analysis or simulation is verified by a trusted third-party verifier.

The certification approach means that a third party has witnessed the performance of the finished product during some specified tests and that the third party awarded a certificate of performance. The certificate approach is commonly used for mass-produced items based on a standard or specification. The certificate is the qualification of the production facilities, as well as assuring that prescribed standards (depending on the application area), are followed and the product meets all stated requirements which means the product is FFP. This approach is also used to validate the claim of a manufacturer/fabricator that an item as sold is "fit-for-Purpose". Representatives of a verifying consultancy witness tests organized by the manufacturer and issue a certificate of compliance for a particular application if convinced. For example, firewalls are qualified using this approach.

The current certification approach follows the prescribed process of an applicable standard. For example, IEC 61508 is designed for industrial purposes, ISO 26262 (2011) covers the automotive industry, and DO-178B/C (2012) focuses on software for airborne systems.

Competence Cost of compliance with ever-increasing requirements is not trivial. The capability to check weld quality demands management of personnel competence. ISO 3834:2008 defines the quality requirement for fusion welding, with an emphasis on the welder's competence and inspection, supervision, and testing personnel (ISO

3834, 2008, and AS/NZS ISO 3834 (2021). Thus, competence assurance (e.g., certified operators) is essential in delivering reliable systems, to assure the delivered product is FFP, and should remain so for its design life. Personnel competence assurance is set out in ISO 9001 clause 6.2.1. Inspectors are also required to have a certificate of 'competence' issued by an authority.

2.17 Acceptance Testing

The purpose of acceptance testing is to validate the system assuring that it will deliver the required functionalities; that is FFS. At the start of the project, all Client requirements, the system purpose, key capabilities, use cases, (ConOps & usage scenarios), level of performance to be achieved, and the system's acceptance criteria for validations are defined and documented. The *System Validation Plan* is produced and put under the change control process for monitoring to ensure that the test procedure (the verification plan) is relevant, up-to-date, and not changed without the approved change processes. "*The purpose of Test Plans is to demonstrate that a system satisfies the approved requirements*-i.e., FFS" (Engel, 2010)—Fig. 2.19

The Test Plans document is the overall testing strategy, which includes the general test procedures, what results are to be documented, and the procedures for dealing with test failures. The Test Plan will also include types of testing, describing the testing environments and tooling, the responsibility matrix, test equipment that will be used, and any other organizational procedures.

Test Protocols describe the specific testing requirements. Test Protocols are a collection of Test Cases (use cases) that validate a specific element of the system. Each test case includes the goal of the test, prerequisites, as well as acceptance criteria. Each test case is broken down into a series of steps. Each step includes detailed instructions, what result to expect, as well as the actual result, and what to document. The test procedures must have sufficient details so that a tester can perform the testing consistently without requiring interpretation.

The **Client Acceptance Criteria** are used for authorizing the shipment of parts, equipment, or assemblies that are tested and ready to be delivered to the Client site. That is, it is verified that the part, equipment, or assembly is constructed in a manner that has been defined by the flow-down of the client requirements and fabricated in a manner that meets the industry standards, good practices, and client standards. This is achieved by various procedures, such as using independent testers, witnessing the vendor's test, or on the trust base.

User Acceptance Testing (**UAT**)—for operational needs—describes testing to prove the fulfillment of what the user expects the system to deliver, and how the system must function. UAT documents provide pertinent information, data, the operating environment, acceptable processes, and the system's functionality to make tests meaningful, applicable, and repeatable. These tests are completed during the FAT (Factory Acceptance Test) as well as the SAT (Site Acceptance Test (SAT) (Rahimi, 2013). If a piece of equipment is developed by the vendor's subcontractor, then it

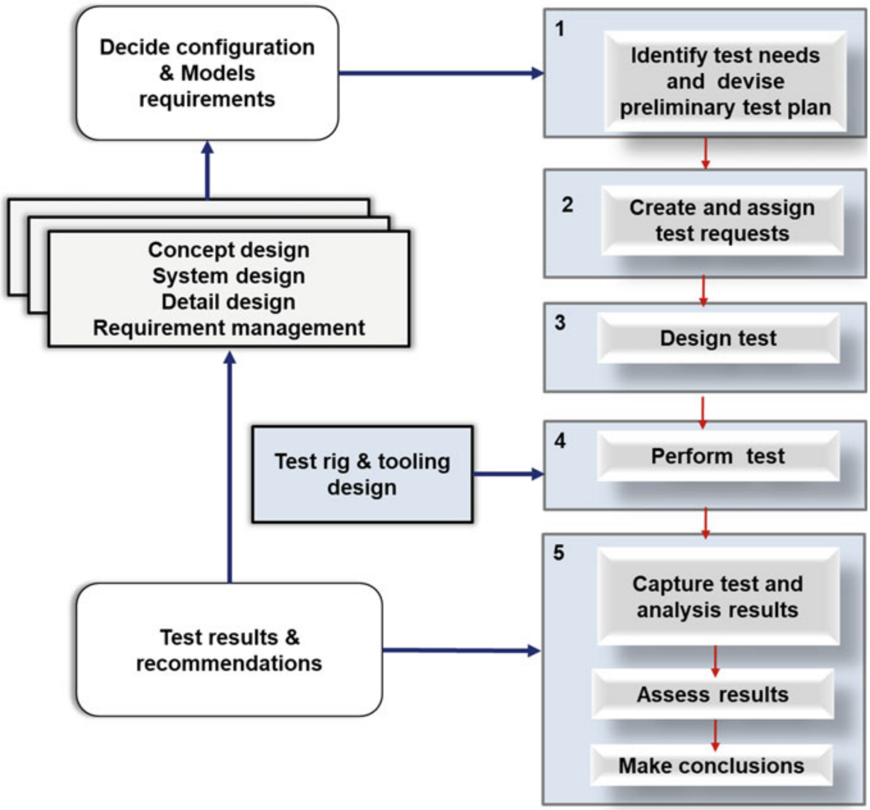

Fig. 2.19 Tests plan to demonstrate that a system meets requirements

must have a FAT and SAT plan associated with it and a certificate issued by the subcontractor.

FAT and UAT can be looked at as the partial commissioning and qualification of equipment, and systems, which must be done before shipping products to the Client's site. The vendor tests the product using the Client's approved test plans and specifications to show that the system is mature/ready to be shipped to the site. For most equipment and assemblies, FAT is the focus of collecting evidence to support the verification and validation of equipment or the assembly.

FAT and EFAT (Extended Factory Acceptance Tests) are done by the manufacturer, possibly witnessed by the client's representative, and results are documented for use in linking tests' results to the requirements in the traceability matrix. The traceability matrix must show that tests' results are linked to one or more requirements and hence no requirement is forgotten. Validated components are then assembled to make bigger assemblies or modules, and then they are tested to assure they will work together.

A complementary purpose of testing is to check whether all interfaces comply with specifications and also all constraints have been accommodated. The integration plan, which was produced earlier in the project development, defines the order of components integration towards constructing the whole system. The functionality of every subsystem at every stage of integration is checked against the relevant approved requirements and must be verified following the 'Subsystem Verification Plan.' Tests for the verification of component-level requirements are necessary because many systems' requirements are flowed down via several routes and levels of system decomposition (Yasseri, 2013). These efforts should ensure that the functionality of all parts of the system has been proven.

2.18 Insights and Implications for Practice

A practical framework was described for delivering reliable subsea production systems based on the system engineering processes. The objective is the assurance of uninterrupted operation and the robustness & resilience of the SPS. Although subsea production systems are used as a vehicle to explain the process, the method is equally applicable to the reliability assurance of any capital project (Okaro, 2017).

Reliability assurance is a useful framework, to build robustness and resilience into a system (e.g., security threats, Yasseri, 2019). Reliability assurance also relies on mitigative policies, such as using appropriate materials, corrosion & erosion protection, and prevention of accidents (e.g., dropped objects), other external hazards (e.g., boat impact, seismic event, storms, debris flow), geotechnical hazards (liquefaction, seabed movement), and so forth. The effectiveness of reliability assurance is judged by the availability of the system for continued operation when required.

The outlined method also supports the project's risk control management, and it is also aligned with the owner's strategic objectives. The described framework aims to achieve the following objectives:

- Meet the Client's needs and goals.
- Control the project cost and schedule.

The method starts with the client's requirements (needs and objectives). It was stated that each requirement shall be:

- *Traceable*—higher-level requirements are linked to one or more components' requirements
- *Unique*—it should be associated with a paragraph in a document with an identifier
- *Single*—it should not concern more than one issue.
- *Verifiable*—can be verified using approved project's verification procedures.
- *Unambiguous*—defined with an exact statement.
- *Correctly assigned* to applicable requirements, with unambiguous paragraph identifier.

A fundamental idea is that quality must be built into a system's components and processes at the start of development. The system design specifications must support the quality needs of all processes so that they can be judged as 'deemed' FFS. Reliability analysis will identify 'critical elements' of a system architecture, which then can be used to moderate the amount of testing. The term 'critical elements' means mitigation controls devices included during the design phase, which are hardware, not procedural controls. Risk analysis may also be used to identify critical elements.

A myriad of techniques is used for risk identification. HAZOP, HAZID, and FMECA are the most favored tools of hazard identification and assessment; all perform well in identifying failure modes. The original use of HAZID and HAZOP was to enhance system safety, but the reliability analysis also employs them.

It also emphasized the importance of tracing the requirements to their physical implementations (design solutions). It was shown how to translate the results of requirements analysis into the project-specific design requirements, from which technical specifications for equipment (data sheets) can be developed and used to prepare testing and acceptance criteria. Testing starts from the lowest level component, then progresses to assemblies and modules, and finally, the whole system is tested for compliance (Tehera et al., 2019)-The validation process.

Reliability and safety analysis address separate issues, but the safety-related system must be reliable, thus risk analyses are used for risk reduction and enhancement of the reliability of the safety system. Note that there are two sets of safety systems which are process safety and system safety; though both perform the same function but are independent of each other.

Designers should never intentionally create requirements and designs that result in the system operating at the "limit."; i.e., little or no margin. If a system is designed to meet performance specifications within an adequate margin, then it should be rare for the system to fail rapidly when excursions beyond normal operating conditions are minor. A key objective in developing a high-reliability system is, for the system to degrade gracefully without sudden, frequent failure, as well as OPEX, and unplanned intervention overrun.

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Chapter 3
Improving the Strategy for Scientific Vocations in Colombia Through Participatory Modeling Based on System Dynamics

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Abstract This chapter explores the use of Participatory Modeling Based on System Dynamics (PM-SD) as an approach for improving decision-making in complex systems. Drawing on previous studies that suggest the positive impact of PM-SD on promoting scientific vocations, this chapter applies the approach to the Colombian department of Santander as a means of enhancing science vocations among children and adolescents. Literature suggest the potential for participatory approaches to promote interest and engagement in STEM fields, and could provide valuable

The results presented in this paper are derived from the social intervention and research project entitled "Strengthening Scientific Vocations for Rural development in the Department of Santander," with the SIGP COD. 72457 and BPIN 2020000100025. Our study was funded by the Ministry of Science in Colombia and a consortium of universities, including the Universidad Autónoma de Bucaramanga, Universidad de Santander, and UniSangil. We are grateful to Policy Dynamics for their collaboration and support. Through the project's development, which focuses on strengthening scientific vocationsscientific vocations for rural development in the department of Santander, 120 research projects developed by children and adolescents belonging to elementary and middle school educational institutions will be supported, affecting 30 municipalities and 120 teachers. Likewise, the project proposes the development of 11 spaces for scientific dissemination in Santander and contemplates an impact evaluation that will allow the identification of its influence on the participants during the execution of the project over 24 months.

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insights and lessons learned for similar projects in Colombia or elsewhere. The project described in this chapter employs Participatory Modeling and System Dynamics as methodology to implement a participatory and sustainable strategy for promoting scientific vocations. The project involves the development of research projects, support for teachers, and the creation of spaces for scientific dissemination. The impact of the project on the participants will also be evaluated. The chapter discusses the challenges and opportunities for decision-making in complex systems and proposes practical considerations and strategies for implementing System Dynamics and Participatory Modeling. It also outlines methods for identifying the necessary stakeholders, institutions, and citizens for effective decision-making. Ultimately, the chapter highlights the potential for Systems Thinking and Participatory Modeling to improve decision-making in complex systems, emphasizing the importance of collaboration among stakeholders, institutions, and citizens in achieving this goal. By applying these approaches to the promotion of science vocations in Colombia, this chapter provides insights into how Systems Thinking can be used to address real-world challenges.

Keywords Participatory modeling · System dynamics · Complex decision making · Systems thinking · Science vocations · Colombia · Sustainable strategy · Equity · Rural development

3.1 Introduction

Decisions related to scientific vocations are complex due to the non-linear relationships within the system, including delays and counter-intuitive behaviors (Forrester, 1961; Sterman, 2000). This complexity is evident in the insufficient availability of scientific vocations to meet the demands of a knowledge-based economy (Besley et al., 2013a, 2013b). The challenge of addressing the talent gap in science and technology remains, and insufficient actions have resulted in complex problems related to the supply of goods and services, as well as the potential for communities to develop (Funtowicz & Ravetz, 1993). In this chapter, we focus on using systems thinking and participatory modeling based on system dynamics to improve complex decision-making in the context of promoting scientific vocations in Colombia. We present practical considerations and strategies for identifying stakeholders, institutions, and citizens necessary for effective decision-making, as well as for implementing participatory modeling and system dynamics. Our project in the department of Santander involves the development of research projects, support for teachers, and the creation of spaces for scientific dissemination, with the goal of enhancing science vocations among children and adolescents. By emphasizing collaboration among

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stakeholders, institutions, and citizens, we aim to create a sustainable strategy that fosters creativity, equity, and rural development, and enables the appropriation of knowledge in the areas of agroindustry, biodiversity, and biotechnology. The potential of systems thinking and participatory modeling to improve decision-making in complex systems highlights the importance of promoting scientific vocations and the development of a knowledge-based economy.

Science vocations have a crucial role to play in promoting sustainability, as recognized by the United Nations' Sustainable Development Goals (SDGs) (Millar & Searcy, 2020). For example, the SDGs aim to conserve coastal and marine areas, expand scholarships for developing countries, improve water and sanitation management, and promote responsible consumption and production. Citizen science is one way science vocations can contribute to sustainability, as citizens can use their time and technology tools to contribute to scientific discovery and governance (Millar & Searcy, 2020; Kenyon et al., 2020). Lastly, improving science education and scientific literacy worldwide is essential for sustainability, as it requires a focus on science education and scientific literacy for the broader society (Gülhan 2023; Millar & Searcy, 2020;). In summary, science vocations are essential for promoting sustainability through citizen science, ODS promotion, and science education.

Scientific vocations have the potential to make significant contributions to promoting sustainability, as recognized by the United Nations' Sustainable Development Goals (SDGs) (Millar & Searcy, 2020). However, maintaining the availability of these vocations in a sustainable manner remains an area where literature is limited. The SDGs highlight the role of science in achieving sustainable development, with specific goals aimed at conserving marine areas, expanding vocational training, and scientific programs in developing countries, and improving water and sanitation management (Millar & Searcy, 2020).

One approach to promoting sustainability through scientific vocations is citizen science, which involves the participation of citizens in scientific discovery through observations, analysis, and technology tools (Kenyon et al., 2020); Millar & Searcy, 2020).

Improving science education and scientific literacy is also critical in promoting sustainability. Traditional science education has focused primarily on pre-vocational training for future scientists and has relied on methods familiar to twentieth-century scientists. However, for sustainability, it is necessary to improve science education and scientific literacy of society worldwide (Gülhan, 2023; Millar & Searcy, 2020).

While there is limited literature on maintaining scientific vocations in a sustainable manner, it is acknowledged that science vocations can play a vital role in promoting sustainability through citizen science, development promotion, and improved science education and scientific literacy. Achieving sustainable development will require a concerted effort from all sectors of society, including the scientific community, and ensuring the sustainability of scientific vocations will be crucial in this endeavor.

This chapter presents a novel approach to addressing complex issues in science vocations through participatory modeling combined with system dynamics. We begin by providing an overview of the current state of and challenges related to the sustainability of vocations and equity. We then introduce the concept of participatory modeling, explain how it can be used to engage stakeholders and develop a shared understanding of complex systems. Next, we describe the method used to combine participatory modeling with system dynamics and the rationale for this approach. We then present the results of the participatory workshops, including insights gained by the participants and the developed models. Finally, we discuss the implications of our findings for science vocation policy and practice and provide conclusions and recommendations for future research in this area.

3.2 Background

Participatory approaches have been utilized in various ways for urban development and empowerment strategy, including Rapid Rural Appraisal and Participatory Rural Appraisal (Re-Visit ART Participatory Art Model for Transforming Place Identity in Urban Villages of Indonesia, 2022). Additionally, participatory and dialogic pedagogical methodologies have been used for education for social change and adult learning (Foster et al., 2005). The SMART framework has integrated citizen science, community-based participatory research, and systems science for population health science in the digital age (Katapally, 2019). Participatory research has been proposed as a means of community empowerment (Williams, 2005), and participatory science is commonly used in citizen science (Gaudet, 2017). However, despite the use of participatory models in various fields, there is no specific evidence linking science vocations to participatory modeling and strategy.

The recruitment of young people to pursue careers in science is a concern among scientists (Ho, 1927), as it is critical to promote sustainability in scientific vocations. To address this issue, the National Research Council has prepared "Career Pamphlets" to inform young people about opportunities in various scientific fields (Ho, 1927). However, effective vocational guidance must be based on scientific investigations into the personnel of the vocations (Ho, 1927).

Schools also have a crucial role in promoting scientific vocations by designing teaching-learning strategies that involve all stakeholders (Dopico & Armstrong, 2021). Such strategies can enhance students' interest in science and cultivate their scientific thinking, which can lead to a greater likelihood of pursuing scientific vocations. Decision-making is critical to promoting sustainability in scientific vocations, and this can be achieved through scientific investigations, vocational guidance, and designing effective teaching-learning strategies.

In higher vocational colleges, promoting sustainability in engineering mechanics can be achieved by applying teaching reform flexibly (Wang et al., 2022). Incorporating sustainability concepts and principles into the curriculum and teaching methods can help achieve this reform. For example, introducing real-life scenarios and case studies that illustrate the importance of sustainable practices in engineering mechanics can help students appreciate sustainability in scientific vocations.

Promoting sustainability in scientific vocations requires effective decision-making through scientific investigations, vocational guidance, and designing effective teaching-learning strategies. Incorporating sustainability concepts and principles into the curriculum can help cultivate a greater appreciation for sustainability in scientific vocations.

3.3 Applying Systems Thinking to Improve Complex Decision Making

Participatory modeling combined with system dynamics have been shown to be a useful tool for decision-making in environmental and sustainability decisions. Research has found that incorporating participatory modeling and system dynamics can facilitate decision-making in various contexts. For example, Olivar-Tost et al. (2020) found that participatory modeling and system dynamics can be useful in evaluating and prioritizing green projects in Colombian post-conflict communities. Similarly, Stave (2002) suggests that system dynamics can improve public participation in environmental decisions by providing a framework for structured deliberation and a more transparent and participatory educational framework.

Furthermore, Falconi and Palmer (2017) argue that participatory system dynamics modeling can involve stakeholders in the conceptualization, specification, and synthesis of knowledge and experience into a useful model for addressing dynamic complexity of socio-ecological problems. Videira et al. (2017) also suggest that participatory modeling system dynamics can help decision-makers by involving stakeholders in the decision-making process and providing a framework for structured deliberation and education.

Besides the potential benefits of participatory modeling and system dynamics in promoting sustainability and environmental decisions, there is currently limited evidence of their use in promoting new science vocations. Further research and application of participatory modeling and system dynamics in the context of promoting sustainability in scientific vocations are necessary, based on the literature and the experience in the field.

Science, technology, and mathematics education play a crucial role in the economic development and self-reliance of any country. This is particularly true for developing countries like Nigeria and Nepal, where technical and vocational education and training (TVET) is seen as a means of enhancing productivity, reducing poverty, and developing human resources capable of contributing to the country's prosperity.

STEM (Science, Technology, Engineering and Mathematics) education and vocational training are critical components of a country's development strategy. By aligning education and training programs with the needs of the labor market, and providing specialized training and continuing education opportunities, countries can ensure that their workforce is equipped with the necessary skills and knowledge to succeed in their chosen professions.

Identifying the necessary stakeholders, institutions, and citizens for effective decision-making is crucial for the successful implementation of scientific vocation programs. Through participatory modeling, all relevant parties can be involved in the decision-making process, ensuring that the program aligns with the needs and goals of the community. Teachers involved in the formation of scientific vocations can offer valuable insights into the challenges and opportunities associated with such programs. Their participation in the decision-making process can help ensure that the program is tailored to the needs of the students and the community.

The participatory modeling methodology allows all actors involved in the process of scientific vocations to participate. In this chapter, we will present the participation of teachers involved in the formation of scientific vocations in the department of Santander, Colombia. In future stages, the participation of students and professional advisors of projects that students develop as part of their scientific vocations is also planned. Other possible participants include educational administrators, designers of public policies related to science and technology education in Colombia, mayors, governors, entrepreneurs, parents, and the community as a whole. Each of these groups plays a fundamental role in understanding and comprehending scientific vocations and how to maintain a sustainable number of scientific vocations to contribute to sustainability in various social and economic fields.

In addition to teachers, other stakeholders such as educational administrators, policy designers, mayors, governors, entrepreneurs, parents, and the community as a whole, can provide important perspectives and support for scientific vocation programs. By involving all relevant parties in the decision-making process, the program can be designed and implemented in a way that is sustainable, effective, and inclusive.

To ensure the success of scientific vocation programs in Colombia, it is important to maintain a sustainable number of scientific vocations. This requires a collaborative effort from all stakeholders to support and encourage students to pursue scientific vocations. Through participatory modeling and involving all relevant parties in the decision-making process, the scientific vocation programs can be designed and implemented in a way that meets the needs of the students and the community, leading to a sustainable and successful outcome.

Engaging students in scientific vocations is a crucial challenge for educators and policymakers, as it can lead to a more equitable distribution of students in science-related fields. The study of scientific literature reveals various types of experiential learning, gaming, and virtual reality that can be used to motivate and interest both male and female students in science-related fields. Furthermore, scientometric analyses can reveal how gender and culture perceptions affect interest in scientific vocations, providing insight into areas that require further research, educational interventions, or policy-making to reduce gender-based disparities in these fields.

One of the issues related to scientific vocations is the disparity between rural and urban areas in terms of resources, opportunities, attitudes, academic performance, and occupations. Several studies have reported on this topic, including Mupezeni (2018), Astalini (2020), Kryst (2015), and Alasia (2005). Mupezeni (2018) found that inadequate school facilities, lack of support, mentorship, and equipment impacted rural learners' activities. Astalini (2020) determined significant differences in the attitudes of students in rural and urban areas. Kryst (2015) reported that students attending rural schools had lower science scores, and this rural disadvantage increased between 1995 and 2011 in some countries. Alasia (2005) found that managerial and professional occupations were more concentrated in urban regions, whereas the intensity of unskilled occupations was more prominent in rural regions. These differences may affect the concentration of scientific vocations in rural areas compared with urban areas.

Understanding the concentration of scientific vocations in rural and urban areas is crucial in creating effective policies that aim to promote scientific vocations equitably. The literature shows that disparities exist between rural and urban areas in terms of resources, opportunities, and attitudes, which can affect the concentration of scientific vocations in these areas. Addressing these disparities requires a comprehensive understanding of the unique challenges faced by rural students and the development of targeted interventions to overcome them.

In the quest to make science vocations more accessible and equitable, researchers have explored various approaches to engage students in science-related fields. By studying the scientific literature, experiential learning, gaming, and virtual reality have been identified as potential tools to increase student motivation and interest in science (Cavanagh et al., 2016). Additionally, researchers have found that changing teaching methodologies and introducing current and relevant scientific topics could make science vocations more sustainable (Dopico, 2017).

Encouraging young adolescents to pursue careers in science has also been suggested as a way to promote sustainability in science vocations (Tai, 2006). Furthermore, fostering a positive science identity and shifting the culture of academic science could lead to more equitable outcomes in science-related fields (Hackett, 1990; Stets, 2017).

However, despite efforts to promote inclusivity in science vocations, gender-based disparities continue to persist. Studies have found that girls often have fewer experiences in science than boys, which can contribute to greater gender gaps in certain fields (Kahle, 1983). In addition, masculine cultures, lack of experience, and low self-efficacy have been identified as contributing factors to greater gender divides in fields such as computer science, engineering, and physics compared to other subjects like biology, chemistry, and mathematics (Cheryan, 2017).

Another factor contributing to inequality in science vocations is the scarcity of scientific vocations in rural areas. Research has suggested disparities between rural and urban areas in terms of resources, opportunities, attitudes, academic performance, and occupations (Alasia, 2005; Astalini, 2020; Kryst, 2015; Mupezeni, 2018). These differences may influence the concentration of scientific vocations in rural areas compared to urban areas.

In summary, by exploring the scientific literature, researchers have identified various approaches to engage students in science-related fields and make science vocations more sustainable. However, gender-based disparities and differences between rural and urban areas in terms of resources and opportunities continue to be factors contributing to inequality in science vocations. Further research, educational interventions, and policy-making may be needed to address these challenges and promote inclusivity in science-related fields.

This study aimed to investigate the effects of participatory modeling combined with system dynamics in workshops on science teachers' mental models of sustainability and equity in scientific vocations. This study seeks to answer two research questions: what strategies do science teachers use to promote equitable access to scientific vocations and their sustainability, and how do System Dynamics and Participatory Modeling workshops contribute to understanding sustainability and equity in scientific vocations?

By analyzing the existing literature and interviewing science teachers, this study hypothesizes that participating in these workshops will enhance teachers' understanding of scientific vocations and effective strategies for increased sustainability, as well as advance equity and inclusion practices. Moreover, this study aims to analyze the potential effects of changing strategies on the sustainability of scientific vocations by employing participatory modeling with the archetypes of overshoot, collapse, and privilege.

3.4 Method

The methodology of System Dynamics is widely used in various fields, including engineering, economics, and social sciences (Sterman, 2002). The underlying idea is that systems consist of interconnected parts that influence each other over time, and System Dynamics uses computer models to simulate the behavior of these systems and test different policies and scenarios (Forrester, 1987). At the core of System Dynamics is the concept of feedback loops, which create cause-and-effect cycles that can lead to complex and unpredictable behaviors (Wolstenholme, 1982). In the case of scientific vocations, System Dynamics can be used to study the interactions between human behavior, technological changes, and natural forces that shape the dynamics of science vocations.

We have several participatory methods to consider. For example, Group Model Building (GMB) is a participatory approach that brings together stakeholders to develop a model to address a complex problem (Rouwette et al., 2002). This collaborative process involves a facilitator who guides the group through exercises to elicit information about the problem and develop a shared understanding of the key variables that influence the system (Hovmand, 2014). The group develops a visual model, typically using causal loop diagrams or stock and flow diagrams, which can be used to explore different scenarios and test different interventions.

One of the key advantages of GMB is that it promotes consensus-building among stakeholders by ensuring that everyone's voice is heard and perspective is taken into account (Rouwette et al., 2002). This can help build trust and improve communication in complex, multi-stakeholder environments.

Using a combination of System Dynamics and Participatory Modeling, this study aims to improve the promotion of scientific vocations by identifying, analyzing, and visualizing possible interactions between different elements of the system. Participants, including teachers, students, parents, and policymakers, can gain a better understanding of the opportunities available in science and appreciate the complexity of the problem. Through group discussions led by experts and knowledgeable individuals, action plans can be created and refined to increase awareness and information about scientific vocations, ultimately leading to an increase in their promotion.

The integration of System Dynamics and Participatory Modeling provides a powerful tool for analyzing and improving the sustainability and equity of scientific vocations. By providing a holistic approach that considers the interactions between various elements of the system, this methodology can help stakeholders gain a deeper understanding of the problem and create effective strategies to promote scientific vocations.

The use of participatory system dynamics is an effective method for decision-making, especially when promoting scientific vocations. To test the hypotheses, an exploratory study was conducted, which involved both qualitative and quantitative research techniques. This included a comprehensive review of the scientific literature on System Dynamics and Group Modeling workshops, a modeling workshop with a small sample of science teachers, and a series of semi-structured questions to explore teachers' experiences with the workshops.

The methodology of the workshops included six major steps. The first step was identifying the problem, followed by gathering information and data on the target audience and social context. The third step involved understanding the root cause of the lack of promotion of scientific vocations, leveraging group model building and system dynamics. The fourth step was defining measurable goals and objectives that should be prioritized, while the fifth step involved formulating a plan and strategy for promoting scientific vocations. Finally, the sixth step involved developing an action plan to implement the strategy successfully.

3.5 Results: Enhancing Scientific Vocations in Colombia Through PM-SD

Initially, workshops were conducted with teachers in Bucaramanga, San Gil, and Barrancabermeja, identifying strategic resources and modes of reference around narratives about the sustainability of scientific vocations. The data obtained were used to apply fundamental concepts of system dynamics, such as feedback cycles, delay, and counter-intuitive behavior. The results were then confronted against two fundamental structures, representing the inequality between groups and the overshoot and collapse of strategic resources around training in scientific vocations.

By following these steps and applying system dynamics and group modeling, science teachers can better equip students with the skills needed to engage in scientific vocations. Thus, it is essential to involve stakeholders, institutions, and citizens in this process to ensure the sustainability and equity of scientific vocations in the community.

In a participatory workshop, teachers from various schools in Bucaramanga were asked to share their insights into the success of their students in scientific vocation training. This exercise was inspired by a keynote address given by Prof. Sterman at the 2022 International Systems Dynamics Conference in Frankfurt, Germany (Sterman, 2022).

The teachers' responses were analyzed and graphed to better understand the factors that contribute to individual and collective success in scientific vocation training. Figure 3.1 shows that teachers identified a range of factors, including student motivation, teacher quality, availability of resources, and parental support, as important contributors to success.

Interestingly, many teachers also highlighted the importance of systemic factors, such as the quality of the educational system and government policies that support scientific education. This suggests that success in scientific vocation training is not solely dependent on individual factors, but is also influenced by broader social and political factors.

During the participatory workshop in Bucaramanga, teachers were asked to provide explanations for their students' success in scientific vocation training. The responses were recorded and analyzed, and the findings are presented in Fig. 3.1. The graph depicts the key variables that the teachers identified as being crucial for explaining individual and collective success.

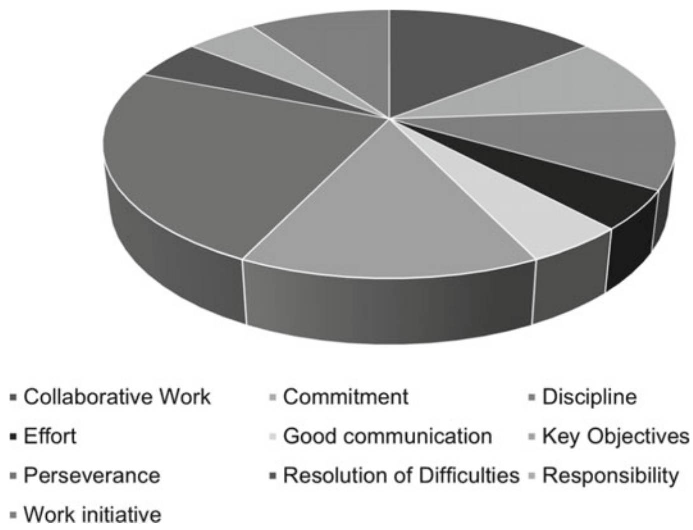


Fig. 3.1 Responses provided by the teachers in Bucaramanga regarding explanations of individual and collective success

Figure 3.1 shows that several variables were identified as being important for success. These variables include perseverance, chasing key objectives, effort, commitment to initiative, communication ability, responsibility for collaborative work, and problem-solving capability. These variables were deemed important for both individual and collective success.

The identification of these variables can provide valuable insights for designing educational programs aimed at promoting scientific vocation training. By focusing on these key variables, educators can create curricula that help students develop the skills and attributes necessary for success in science-related fields. Furthermore, these findings can help educators tailor their teaching methods to address the identified variables, potentially leading to improved outcomes for students.

Overall, the responses provided by the teachers in Bucaramanga provide valuable insights into the factors that contribute to success in scientific vocation training. By taking these factors into account, educators can develop more effective educational programs that equip students with the necessary skills and attributes for success in science-related fields.

In Fig. 3.2, we see the responses of the teachers in Bucaramanga to the question of what they believe to be the best explanation for individual and group success. The options given were either the environment or individual decisions. Interestingly, the majority of the teachers chose individual decisions as the best explanation for success, which is in line with the findings of Prof. Sterman's keynote address at the 2022 International Systems Dynamics Conference in Frankfurt, Germany (Sterman, 2022). His research found that individuals tend to attribute success more to their own decisions and actions than to factors such as their environment.

This result highlights the importance of teaching students the value of taking ownership of their actions and decisions in order to achieve success in scientific vocation training. By empowering students to take responsibility for their own learning and development, educators can help them build the necessary skills and mindset to succeed in the field of science. Additionally, this result underscores the importance

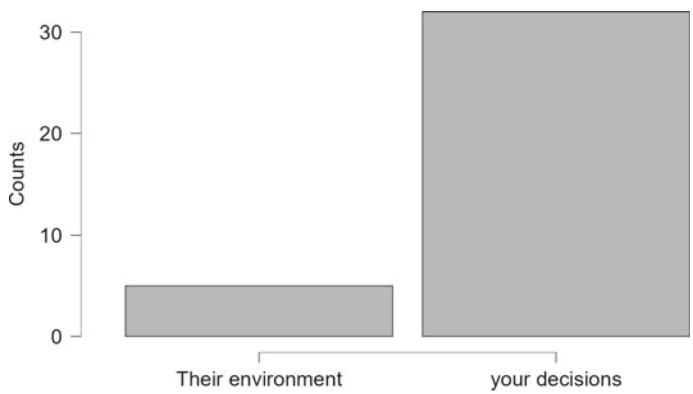


Fig. 3.2 The teachers provided the best explanation for individual and group success

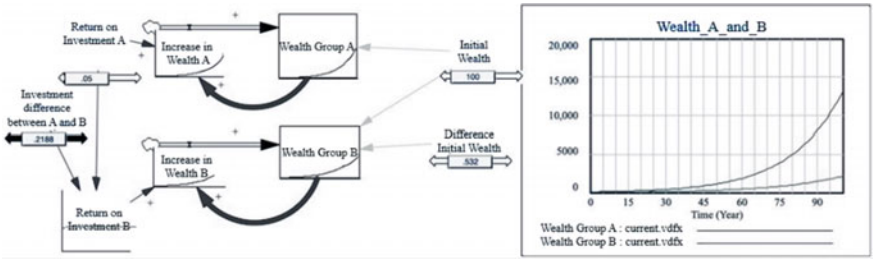


Fig. 3.3 The Inequality archetype is based on Sterman (2022)

of fostering a growth mindset among students, where they believe that their abilities can be developed through dedication and hard work, rather than being fixed traits that are predetermined by genetics or other external factors (Dweck, 2006).

In Fig. 3.3, we presented the teachers with an archetype of inequity based on Sterman's work on privilege (Sterman, 2022). The structure consisted of two levels with corresponding feedback loops and a simulation graph, which demonstrated how differences in initial values of group levels and the speed of accumulation can lead to increasing disparities in resource accumulation rates and, therefore, inequities.

By presenting this archetype, we aimed to raise awareness among the teachers that both individual decisions and the environment play a crucial role in shaping opportunities for scientific vocation formation. Our goal was to evaluate whether the teachers could grasp this concept and identify intangible resources that contribute to inequities in the classroom.

Through their understanding of the archetype, we hoped that the teachers could propose strategies to reduce the gap in scientific opportunity formation. By recognizing how the environment of scientific vocation formation could generate inequities, they could take steps to level the playing field and ensure that all students have equal access to scientific training and education.

In Fig. 3.4, we can see the responses of the teachers when asked about the fundamental strategic resources that create differences in the performance of groups in scientific and vocational callings. The results revealed that several resources were identified as unevenly distributed, which explains the performance gap between different groups. Some of the key resources mentioned were adequate classrooms, availability of work time, training of two teachers, financial resources, good family environment of the students, technological resources, minimum conditions of well-being, motivated teachers, institutional support, study plans, and alliances. This highlights the importance of addressing these disparities to ensure that all students have access to the necessary resources to succeed in scientific and vocational pursuits. By identifying these resources, we can work towards developing strategies that promote equity and reduce the performance gap between different groups.

In Fig. 3.5, we see the responses of the teachers when asked about the resources that could impact the development process of scientific vocations. The teachers identified several key resources, including economic, technological, and cultural resources, as

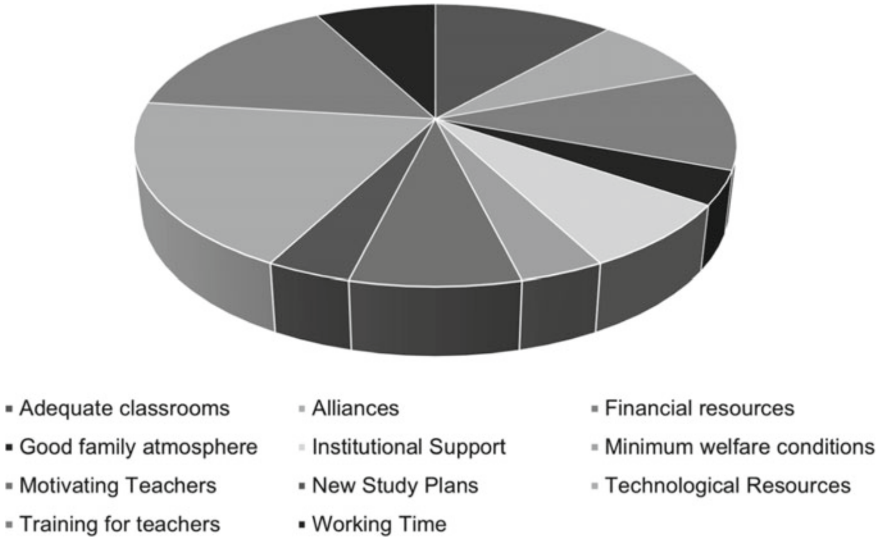


Fig. 3.4 The teachers answered about the fundamental strategic resources that are unevenly distributed and that create differences in the performance of one group compared to another group around the scientific and vocational callings

well as interpersonal relationships, teacher motivation, and having the right places. These resources were seen as crucial to the development and success of scientific vocations among students. This is in line with previous research that has identified these resources as important factors in the formation of scientific and vocational callings (Herrera, 2018; Ortiz & Vélez, 2020).

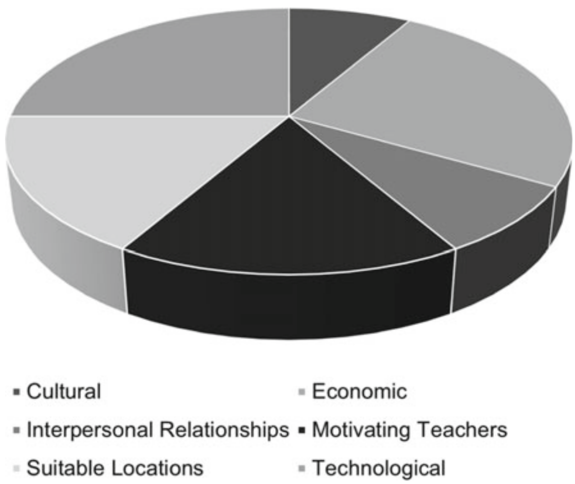


Fig. 3.5 Teachers' answers regarding resources may affect their intergroup performance in scientific vocations

The recognition of the importance of these resources highlights the need for policies and initiatives that ensure equal access to them, particularly for underprivileged students who may not have the same opportunities to develop scientific vocations. By addressing these resource disparities, we can work towards a more equitable and inclusive educational system that promotes the development of scientific vocations and reduces the performance gap between different groups.

In Fig. 3.6, we can observe the responses of the teachers when asked about tangible resources that affect the formation of scientific vocations, generating gaps. The results show that technological resources, financial resources, and classroom availability were the most significant tangible resources identified by the teachers. These findings align with previous studies, which have shown that access to resources such as technology and financial support can have a significant impact on the development of scientific vocations, particularly for underrepresented groups (National Academies of Sciences, Engineering, and Medicine, 2018). Therefore, it is essential to ensure that these resources are distributed equitably to reduce the gap in scientific opportunity formation. In addition to tangible resources, it is also important to consider intangible resources, as they play a significant role in the development of scientific vocations. These resources will be discussed in the next section.

The teachers were also asked to identify intangible resources that could affect the formation of scientific vocations and generate gaps. Their responses indicated that variables such as motivated teachers, willingness to engage in research, discipline, effort, recursive leadership, ability to develop interpersonal relationships, creativity, perseverance, and innovation were among the intangible resources that affected the performance of scientific vocations (see Fig. 3.7). These findings are consistent with previous research that has identified non-cognitive factors such as grit and growth mindset as important predictors of academic success (Duckworth & Gross, 2014; Dweck, 2006). Therefore, it is important to recognize and cultivate these intangible

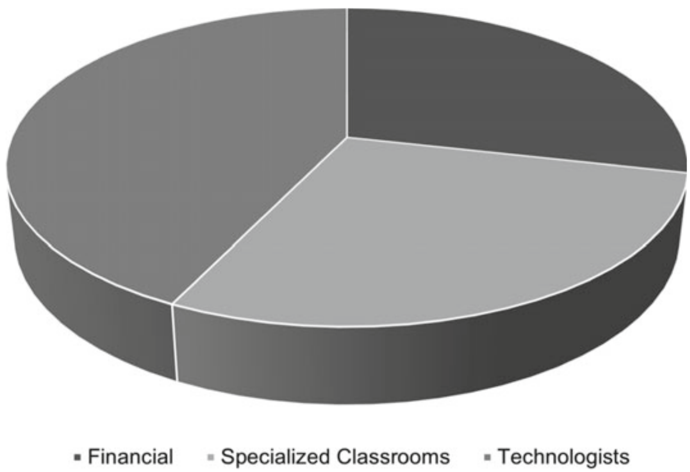


Fig. 3.6 Teachers' answers about tangible resources in scientific vocation activities

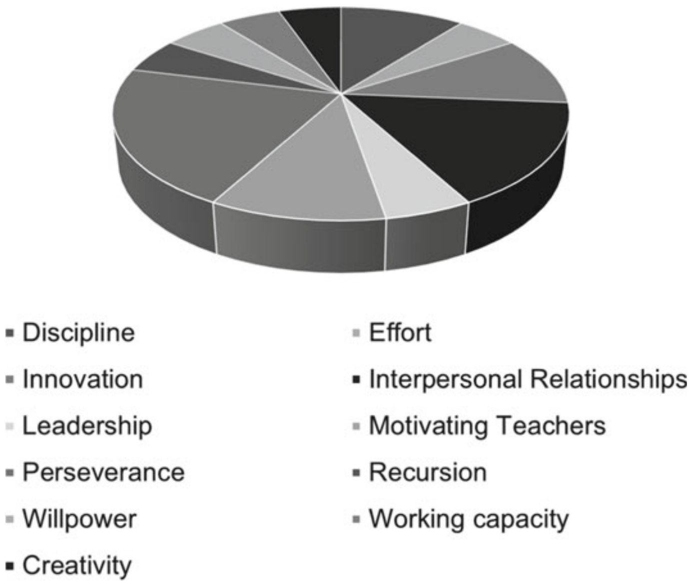


Fig. 3.7 Teachers' answers to intangible scientific vocation resources

resources in students to promote the formation of scientific vocations and reduce gaps in performance.

In addition to identifying specific tangible and intangible resources that affect the formation of scientific vocations, the teachers were also asked to consider the reference mode of these resources. Figure 3.8 shows their responses, indicating that the most commonly mentioned reference modes for tangible resources were "technological resources" and "financial resources," while for intangible resources, the most commonly mentioned reference modes were "motivated teachers" and "willingness to work in research."

This insight provides important information for designing interventions to reduce gaps in scientific vocation formation. For instance, addressing the availability of technological resources and financial resources may be necessary to address gaps related to tangible resources, while promoting teacher motivation and providing opportunities for research may be crucial to addressing gaps related to intangible resources. By understanding the reference modes of the resources that affect scientific vocation formation, it is possible to create targeted and effective strategies to reduce gaps and promote equity in scientific education (Fig. 3.9).

In the final stage of the participatory workshop, the teachers were asked about the strategies they could implement to address the issue of inequality in the development of scientific vocations. The teachers' responses highlighted their intention to seek new ideas, generate creative solutions, improve feedback, and enhance the quality of participants through implementation of improvement plans. They also expressed their willingness to be more open to receiving ideas and to incorporate practice and

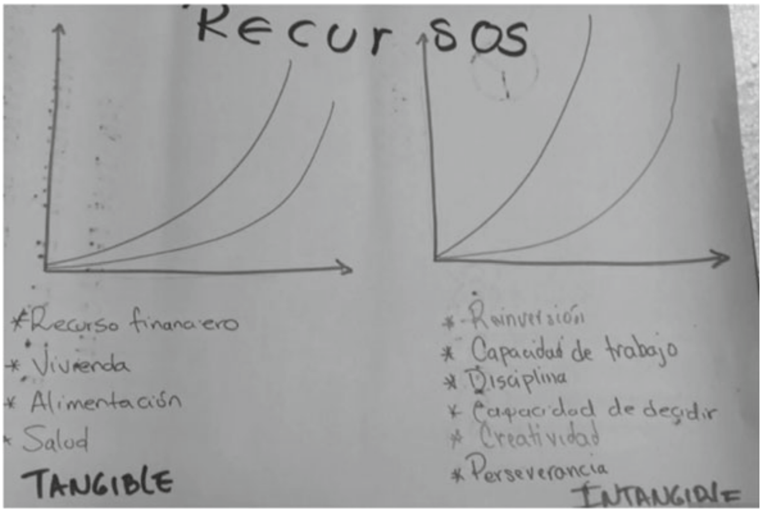


Fig. 3.8 Teachers' answers about the reference mode of tangible and intangible resources that affects scientific vocations

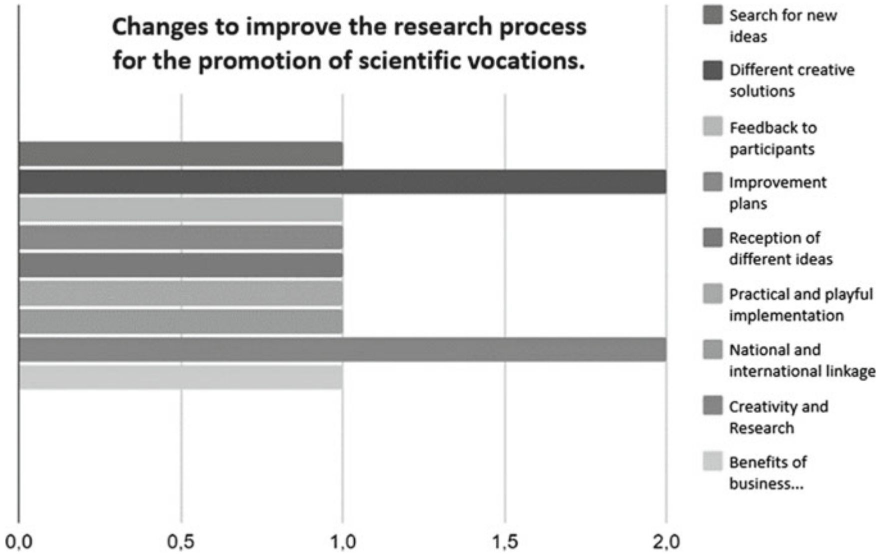


Fig. 3.9 The teachers' strategies were applied after the workshop

playful activities into their teaching methods. In addition, the teachers emphasized the importance of establishing connections with other seedbeds or research groups nationally and internationally to promote collaboration and exchange of ideas. They

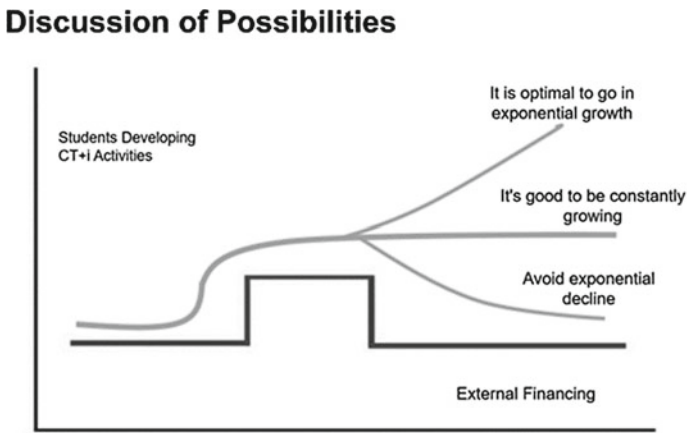


Fig. 3.10 A reference mode with possible behavior about students' science and technology activities over time was used as an interactive object to promote debate about the sustainability of scientific vocations

also identified the need to foster creativity in research to enhance the quality and effectiveness of their work.

During the second participatory workshop, the teachers were presented with a graph to discuss the sustainability of scientific vocations. This graph outlined students' activities in science, technology, and innovation, and prompted the teachers to consider possible trajectories over time, ranging from maintaining growth to experiencing a reduction or deterioration in these activities. As shown in Fig. 3.10, the graph served as an interactive object to stimulate debate about the sustainability of scientific vocations.

Upon analyzing the data in the graph, the teachers identified several issues that hinder the promotion of scientific vocations. These issues present significant barriers to promoting the uptake of scientific vocations and must be addressed to ensure the sustainability of scientific activities in the future. We will presented them later in detail.

As one teacher noted, "In order to encourage and promote the uptake of scientific vocations, we must address the underlying systemic issues that prevent students from pursuing scientific careers. This includes ensuring that students have access to the resources and support they need to succeed, and creating a culture of scientific curiosity and interest among students, teachers, and parents alike." By addressing these issues, we can work towards a future where scientific vocations are sustainable and accessible to all who are interested.

The findings presented in Fig. 3.11 provide insight into the factors that affect the sustainability of scientific vocations, as identified by the participating teachers. The graph shows that the number of scientific vocations, resources applied, support, problems, development, sustainability, institutionalization, learning, and education are the most important variables that have a significant impact on the sustainability of scientific vocations. These variables highlight the need for adequate resources, support, and institutional structures to sustain scientific vocations. Additionally, the findings suggest that problems and challenges must be identified and addressed in order to promote sustainability. The results of this study underscore the importance of addressing these variables to promote the sustainability of scientific vocations and ensure a thriving scientific community.

The teachers' responses to a set of questions about the sustainability of scientific vocations were summarized in two figures, as shown in Figs. 3.11 and 3.12. The teachers identified a number of problems and issues that affect the sustainability of scientific vocations, such as limited time, inadequate institutional structures, poor data management, lack of resources and support for leaders in the community, inadequate learning spaces, inadequate preparation of teachers, lack of incentives, excessive theoretical load in classes, little to no interest from teachers, students, and parents, and a decrease in scientific vocation and interest in acquiring scientific knowledge.

To further explore the availability of strategic resources related to scientific vocation sustainability, the teachers were asked to classify the variables as either high-

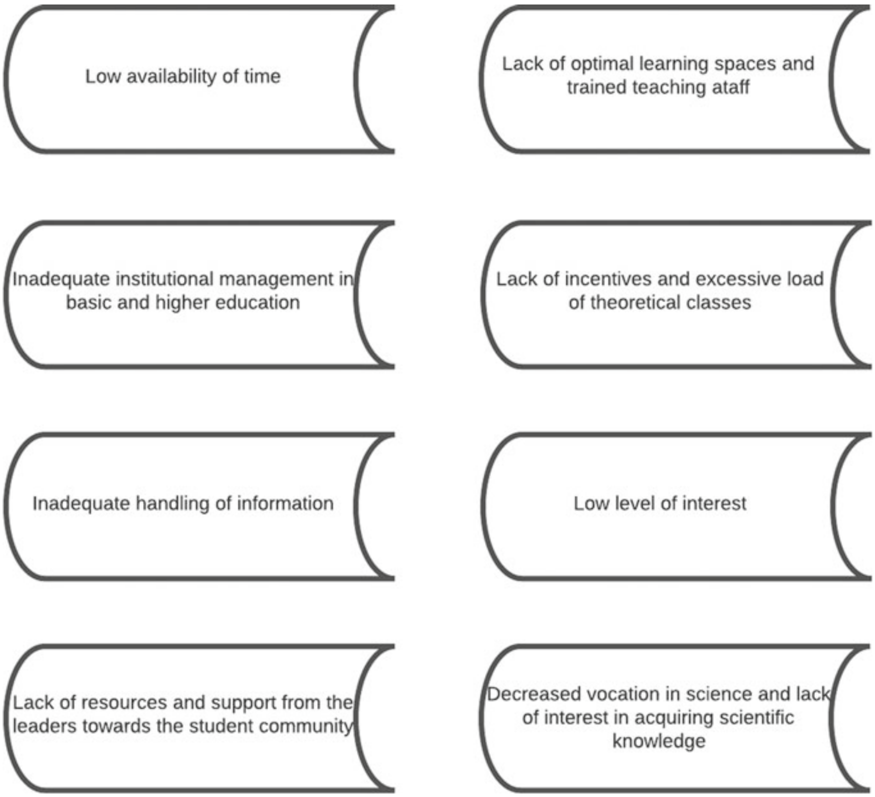


Fig. 3.11 Summary of teachers' answers regarding problems and issues related to the sustainability of scientific vocations

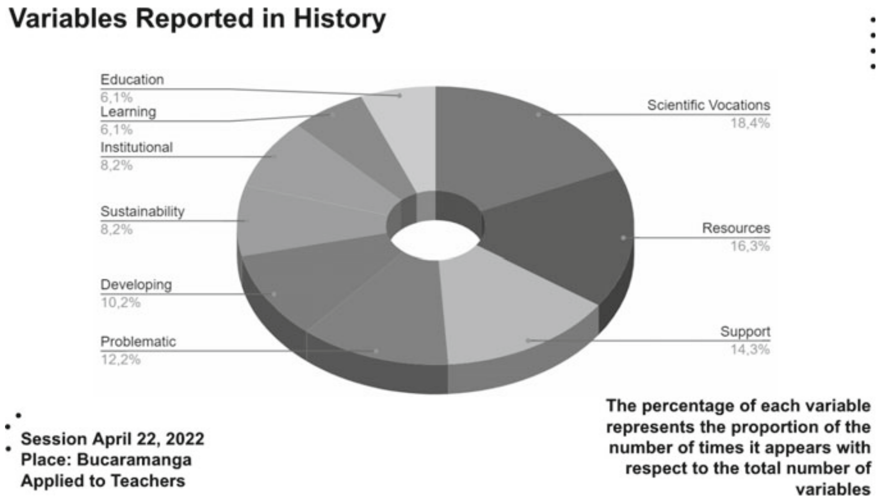


Fig. 3.12 Variables and percentages reported by teachers related to scientific vocations

or low-availability. As illustrated in Fig. 3.13, the teachers identified the available time, inadequate institutional order, inadequate information handling, lack of resources, and absence or lack of support for leaders in student communities as low-availability variables. Conversely, the motivation of students and the intention to promote changes from institutional educational projects that promote the adoption of scientific vocation training were identified as high-availability skills.

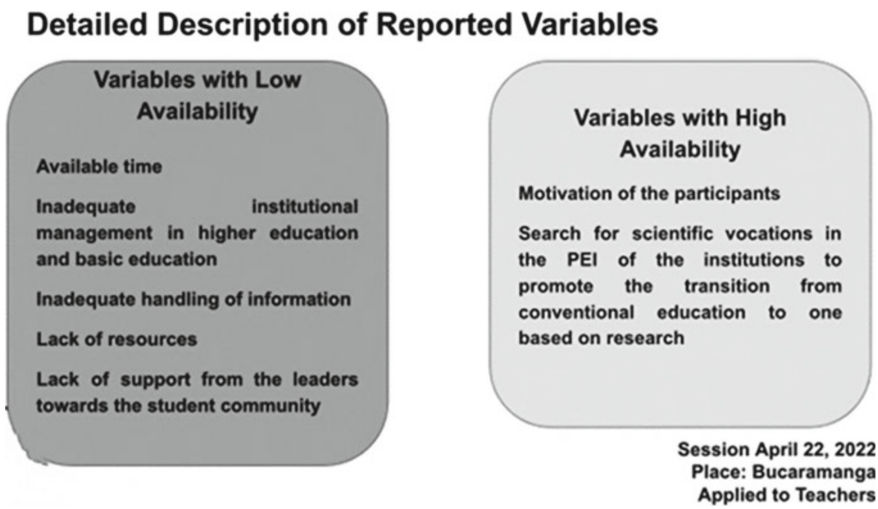


Fig. 3.13 Classification by teachers about the availability (low or high) of variables related to scientific vocation sustainability

These findings highlight the need for attention and support to be directed towards the identified low-availability variables in order to address the problems and issues that hinder the promotion of scientific vocations. Additionally, the emphasis on high-availability skills such as student motivation and institutional educational projects should be utilized to promote and sustain scientific vocations.

This study aimed to assess the sustainable contribution of science to the workforce by analyzing the behaviors and perceptions of teachers from three different regions of Colombia. A compilation of data from all the workshops was presented in Fig. 3.14, which reported the variables identified by the teachers. These variables included participation, interest, knowledge, climate, support resources, and training and research initiatives. The figure highlights the importance of each variable and its contribution to the sustainable development of scientific vocations.

Furthermore, Fig. 3.15 presents the change in behaviors of the participating teachers from Bucaramanga, Sangil, and Barrancabermeja over time. The data shows an improvement in their understanding and perception of scientific vocations, indicating the effectiveness of the participatory workshop in raising awareness and promoting sustainable practices. It is clear that these workshops have the potential to enhance the quality of scientific education and inspire future generations to pursue scientific vocations.

The teachers who participated in the workshops in Bucaramanga, San Gil, and Barrancabermeja were asked to identify the most critical feedback cycles based on the variables identified in the previous sessions. These feedback cycles are essential to improve the sustainability of scientific vocations. Figure 3.15 shows selected photos with the actual reference modes of variables that the teachers used during

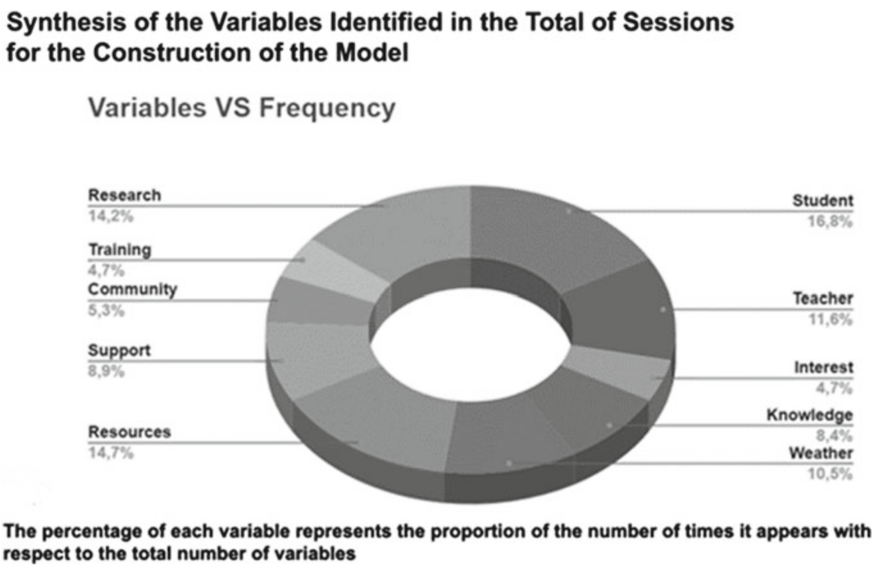


Fig. 3.14 Report of variables identified by teachers in all sessions

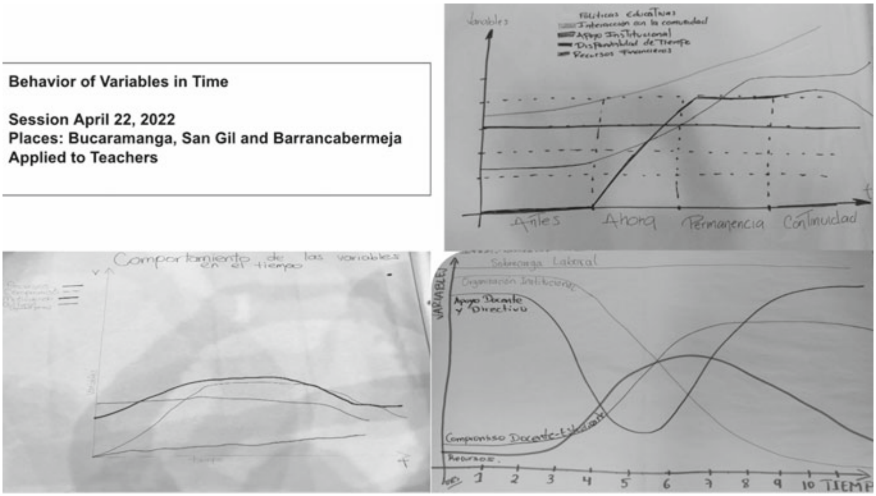


Fig. 3.15 Selected photos with the actual reference modes of variables by teachers regarding scientific vocation sustainability

the workshop. The identified feedback cycles include student participation, interest, and motivation, which lead to the development of skills and knowledge, and subsequently to improved teacher training and support from educational institutions. In turn, these institutions can provide more resources and incentives to promote scientific vocations. The feedback cycles identified by the teachers in these workshops provide valuable insight into the sustainable development of scientific vocations and can help shape policies and initiatives aimed at promoting science and innovation in the workforce.

It is important to note that these findings align with previous research on the benefits of participatory workshops in promoting sustainable practices in education (Hassan & Haque, 2019). The results of this study provide valuable insights into the challenges faced by teachers and the strategies that can be implemented to encourage the uptake of scientific vocations.

The teachers' responses during the workshops helped identify several feedback cycles that impact the sustainability of scientific vocations. Figure 3.16 presents a summary of the most commonly identified feedback loops by teachers in the workshops held in Bucaramanga, San Gil, and Barrancabermeja. These feedback cycles include reinforcing and balancing feedback loops related to teaching resources, institutionalization, and community support, as well as balancing feedback loops related to students' interest and motivation, teacher preparation, and the use of innovative teaching methods. These feedback loops demonstrate the complex and dynamic nature of the factors affecting scientific vocation sustainability and highlight the need for a multifaceted approach to address them. By identifying these feedback cycles, the workshops provided a valuable opportunity for teachers to collaboratively develop strategies to promote and sustain scientific vocations in their communities.

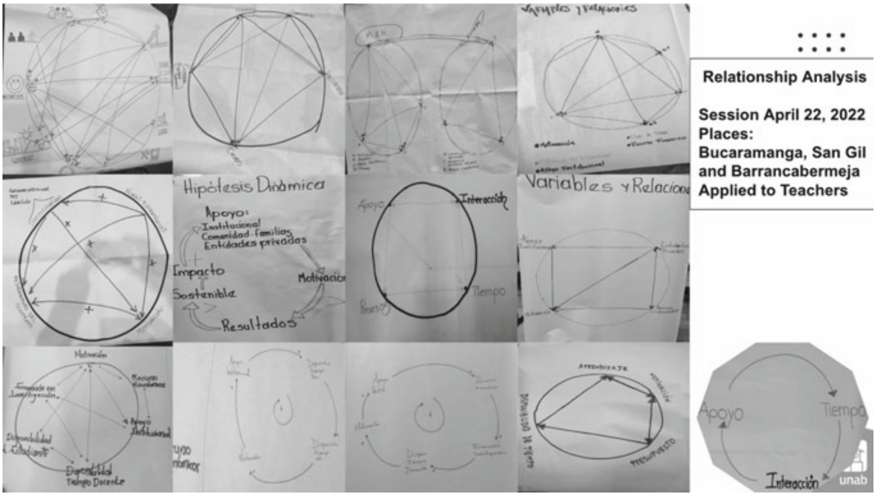
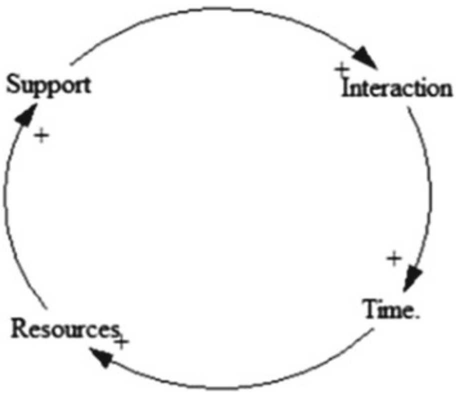


Fig. 3.16 The selected feedback loops proposed by teachers liked variables affecting scientific vocation

Figure 3.17 illustrates the interdependent relationship between resources, support, interaction, and time in the context of scientific vocation training. The feedback loop suggests that increased support for research projects from teachers and other stakeholders results in greater interaction between students and their peers, leading to more time dedicated to training and the use of more resources. In turn, this requires continued support to maintain a virtuous cycle.

This finding highlights the importance of providing students with the necessary resources and support to foster their scientific vocations. By creating a positive feedback loop between resources, support, interaction, and time, we can help ensure that scientific vocations are sustained and nurtured.

Fig. 3.17 Feedback loop integrating resources, support, interaction, time



This feedback loop was one of several identified by teachers during participatory workshops conducted in Bucaramanga, San Gil, and Barrancabermeja, demonstrating the value of incorporating teacher input into discussions of scientific vocation training.

In Fig. 3.18, we present a feedback loop that demonstrates the interdependence of various factors in the context of scientific vocation training. The loop includes motivation, institutional support, economic resources, training research, and teacher availability of time. The teachers' responses in the workshops suggest that institutional support plays a crucial role in providing economic resources and increasing research training, which in turn increases the availability of time for research. As a result, this leads to an increase in motivation among students, which reinforces the need for institutional support and boosts economic resources. Thus, the feedback loop highlights the importance of a continuous cycle of institutional support and resources to sustain scientific vocation training.

Figure 3.19 presents a feedback loop that integrates the variables of impact, institutional support, motivation, results, and sustainability. The cycle starts with family and community institutional support, which then increases motivation, leading to positive results. These results then increase sustainability, which ultimately leads to a greater impact. This increased impact feeds back into the cycle, resulting in increased family and community institutional support. This cycle is essential for promoting sustainable scientific vocation training and ensuring long-term success in the workforce.

This cycle is consistent with research that emphasizes the importance of family and community support for promoting science education and career development (Schultz et al., 2011). It also highlights the need for institutional support, as it plays a critical role in promoting motivation and providing the resources necessary for training and research initiatives.

Overall, this feedback loop provides a valuable framework for understanding the complex interplay between various factors that contribute to sustainable scientific

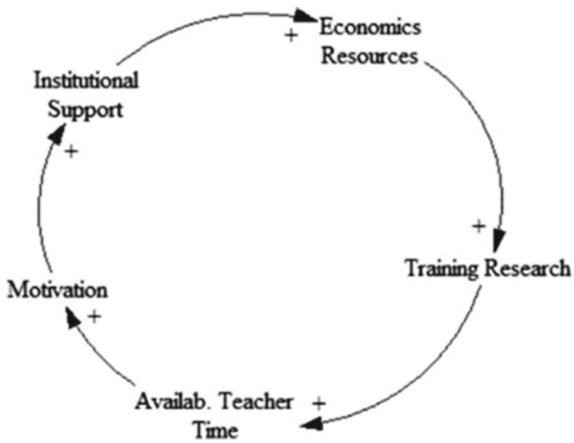


Fig. 3.18 A feedback loop that integrates motivation, institutional support, economic resources, training research, and teacher availability of time

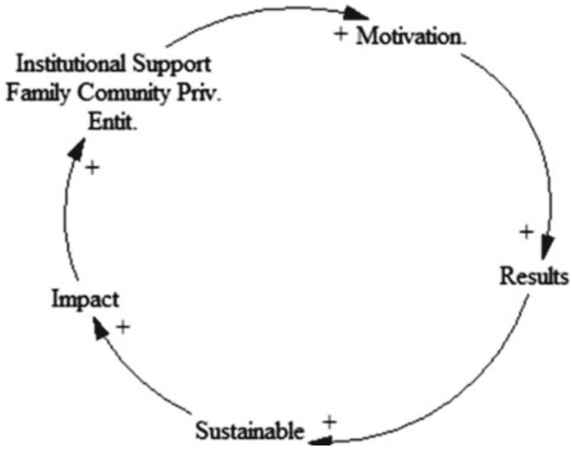


Fig. 3.19 This feedback loop integrates impact, institutional support, motivation, results, and sustainability

vocation training. By identifying and addressing these factors, we can ensure that science education and career development are accessible to all and contribute to a sustainable future.

The strategies proposed by the teachers to increase the sustainability of scientific vocations are summarized in Fig. 3.19. These strategies were identified during the participatory workshops and include:

- Strengthening and creating new relationships to support educational institutions.
- Increasing or strengthening the availability of resources for the development of scientific projects.
- Managing different financial resource forces.
- Designing an innovative methodology to promote research.
- Increasing students' motivation.
- Carrying out adequate project planning.
- Prioritizing the availability of spaces for scientific vocations in educational institutions.

These strategies are essential for promoting the sustainability of scientific vocations. They were proposed by teachers who participated in the workshops in Bucaramanga, San Gil, and Barrancabermeja. The strategies were identified based on the teachers' experience and knowledge of the challenges facing scientific vocation sustainability in their respective communities. Implementing these strategies could lead to a more sustainable and successful scientific vocation culture in the future.

In order to guide the construction of a model process and facilitate discussions with various stakeholders, including teachers, students, and professional advisors, the researchers employed the archetype of overshoot and collapse. This archetype suggests that the availability of a central resource, in this case scientific vocations, is dependent on other renewable and non-renewable resources that must be maintained in order to achieve sustainability (Meadows et al., 1972).

Using the archetype of overshoot and collapse, the researchers aimed to understand how the availability of scientific vocations is dependent on a range of other strategic resources, including high school and university students, as well as teachers. Through the use of dynamic hypotheses, the researchers were able to identify two balance cycles and three reinforcement cycles that demonstrate how these resources are interconnected and essential for maintaining scientific vocation training.

One of the key insights offered by this modeling process is the understanding that the availability of scientific vocations is dependent on a complex network of factors, including the availability of interested students and teachers to form research projects, as well as the availability of financial and institutional support for these projects. The archetype of overshoot and collapse has proved to be a valuable tool for understanding these complex relationships and developing strategies to promote the sustainability of scientific vocation training programs.

We present a dynamic hypothesis about the scientific vocation process, which was developed using participatory modeling. Figure 3.20 illustrates the behavioral dynamics between students and the variables fed into science programs, which were class science projects, science seedlings, science researchers, and science teachers.

The model features a feedback loop, R1, which shows how promoting science initiatives increases the number of elementary students' research projects. Another reinforcement cycle, R2, demonstrates how science projects increase school permanence and interest in science, leading to an increase in the number of students involved in science projects. Additionally, cycle R3 highlights the connection between science initiatives and research groups as promoters of programs linked to science research and development.

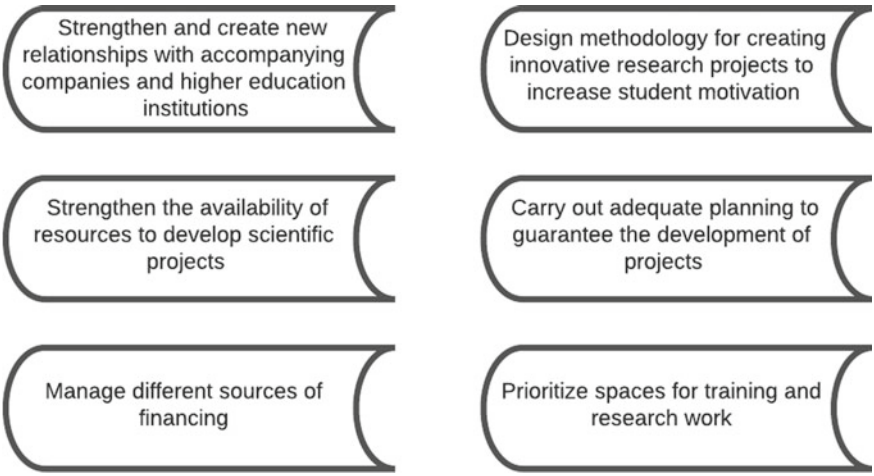


Fig. 3.20 Summary of strategies provided by teachers to increase the sustainability of scientific vocations

The authors also present two balancing loops, B1 and B2, which demonstrate how the number of research groups correlates with the interest and permanence of high school and elementary school students, respectively.

The model's purpose is to highlight the importance of research projects, qualified high school and university students, and adequate teachers to sustain scientific vocations. Scientific vocations are considered central resources for powering sustainable development through interconnected strategic resources. However, it is essential to understand how resources that support improved sustainability are managed to take advantage of their potential fully.

The dynamic hypothesis developed using participatory modeling represents a valuable tool for understanding the interdependence of key resources and the sustainability of scientific vocations. By identifying the feedback loops, the authors show how promoting science initiatives and research groups can increase the number of students involved in science projects and enhance their interest and permanence in science.

In the pursuit of sustainable development through scientific vocation, it is crucial to understand the resources that support it and how to manage them effectively. Research programs, for instance, are heavily reliant on other strategic resources, such as finances, for their creation and completion, and their sustainability can be improved through good management practices.

The educational pathway in Colombia from primary to university levels plays a significant role in nurturing scientific vocations. Figure 3.21 depicts the different pathways that students can take and the potential points of dropout. It highlights the various factors that can affect their educational trajectories, and the possible pathways that they can take after leaving school.

The diagram also illustrates the central structure that is common to those who enter university and those who finish their university career but choose to work

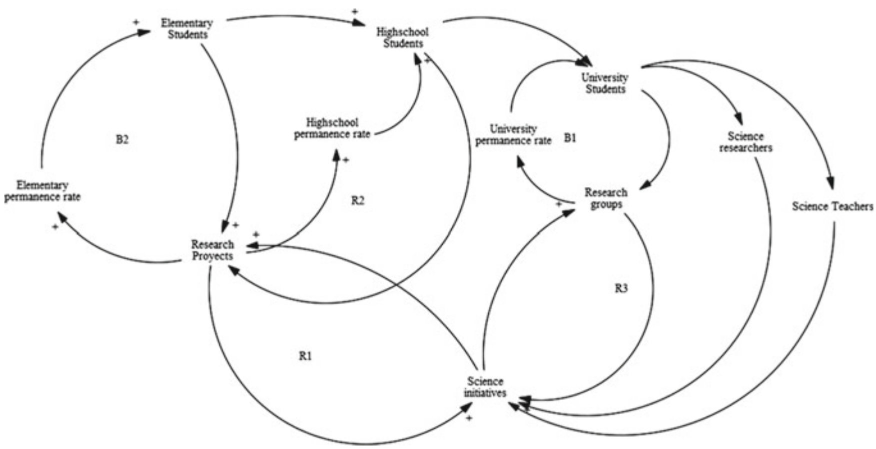


Fig. 3.21 Dynamic hypothesis about the scientific vocation process

as scientists or science teachers. The figure underscores the importance of science teachers as strategic resources that are crucial for the maintenance of the availability of scientific vocations.

Therefore, through participatory modeling, it is possible to understand the behavioral dynamics between students and the variables that feed into science programs, such as science projects, science seedlings, science researchers, and science teachers. By identifying the different feedback loops and balancing and reinforcing cycles that exist, we can gain insight into how scientific vocations depend on key resources for sustainability.

Understanding and effectively managing the resources that support scientific vocation are critical for powering sustainable development. The educational pathway in Colombia plays a crucial role in nurturing scientific vocations, and science teachers are important strategic resources that must be cared for to maintain their availability. Through participatory modeling, we can gain a better understanding of the behavioral dynamics between students and science programs, which can lead to the development of effective management practices and policies for promoting scientific vocations.

Science teachers play a crucial role in nurturing scientific vocations among young students, connecting the various stages of the scientific process and promoting interest in science-related careers. This is especially important as it can help reduce school dropout rates and increase student engagement in scientific fields.

As depicted in Fig. 3.21, strategic resources such as science workers, science teachers, and primary and secondary education students are interconnected and depend on one another in a complex system. Simulation models can help us understand the dynamics of this system and identify key factors that can impact the sustainability of scientific vocations. By analyzing the interactions and feedback loops between these resources, we can develop strategies to strengthen the system and promote sustainable development.

Through participatory modeling, we can engage stakeholders from different sectors and disciplines in the process of identifying challenges and opportunities in the field of science education. This can help us develop more comprehensive and effective solutions that address the complex challenges facing scientific vocations in today's world.

In conclusion, science teachers are an essential group in nurturing and sustaining scientific vocations among young students. By recognizing their pivotal role and promoting effective management of strategic resources, we can help build a brighter future for science education and scientific progress.

Figure 3.22 provides an Overshoot and Collapse Archetype simulation of the sustainability of scientific vocations with a specific focus on science projects as a key resource. The diagram shows how science projects are a resource that can suffer from overuse and eventual collapse within a complex system that is dependent on multiple interconnected resources, including financial, tangible, and intangible resources, as well as teachers and students.

The Overshoot and Collapse Archetype is a well-known system dynamics archetype that describes how a resource can be overused beyond its carrying capacity, leading to a collapse in the resource and the entire system. In the case of scientific

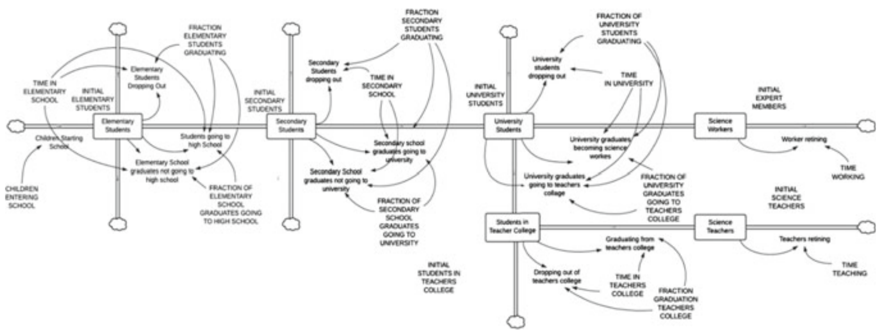


Fig. 3.22 Stocks and flows about scientific vocations as the central resource powering sustainable development through the availability of interconnected strategic resources

vocations, overreliance on science projects can lead to burnout and disengagement among students, teachers, and researchers, ultimately resulting in a decline in the availability of strategic resources and sustainability of scientific vocations.

Thus, it is important to balance the use of science projects with other resources, such as financial support, qualified teachers, and relevant learning materials, to ensure the sustainable development of scientific vocations. This figure underscores the need to maintain a holistic view of the system when managing scientific vocations, and highlights the role of participatory modeling in identifying and addressing the interconnections between different resources.

Overall, the use of system dynamics modeling and participatory modeling techniques can help policymakers, educators, and researchers to better understand and manage the complex and interconnected resources that are critical to the sustainability of scientific vocations.

In Fig. 3.23, we can see how financial resources play a critical role in sustaining scientific vocations. The figure presents a stocks and flows sector diagram that illustrates the interconnectedness of financial resources with other critical resources, including human resources, technology, and infrastructure. The figure also shows how financial resources can experience overflow and collapse in a system that includes multiple nested resources, all of which are necessary to maintain the sustainability of scientific vocations.

The collapse of financial resources can result in a cascade of consequences that affect the sustainability of scientific vocations, including the reduction in the availability of resources such as education, research opportunities, and equipment. Therefore, it is crucial to understand the interdependencies of resources within the system and develop strategies to prevent overspending and collapse of financial resources to maintain the sustainability of scientific vocations.

This understanding of financial resources as a critical resource for the sustainability of scientific vocations can aid policymakers in developing funding strategies that ensure the continuous availability of resources for scientific research and education. Additionally, this figure highlights the need for collaborative efforts among

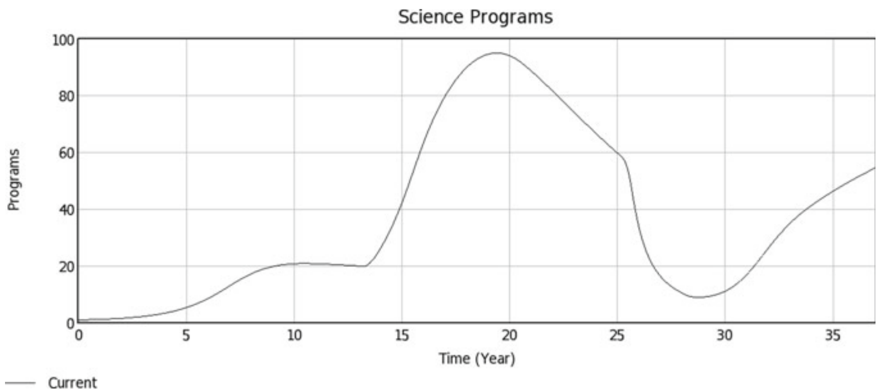


Fig. 3.23 Simulation of science projects as key resource applying overshoot and collapse archetype for understanding the sustainability of scientific vocations

different sectors and stakeholders to ensure that the financial resources necessary for scientific vocations are sustained over time.

In Fig. 3.24, we see a sector diagram that represents the tangible and intangible general resources that make up the system. As seen in Fig. 3.25, this system contains various nested resources that are connected to science projects, including financial, human, and infrastructure resources. This interconnectedness generates a complex behavior, resulting in a structure of overflow and collapse. By applying the Overshoot and Collapse Archetype, we can gain a better understanding of the sustainability of scientific vocations and the importance of managing these resources effectively to maintain their availability for future generations (Fig. 3.26).

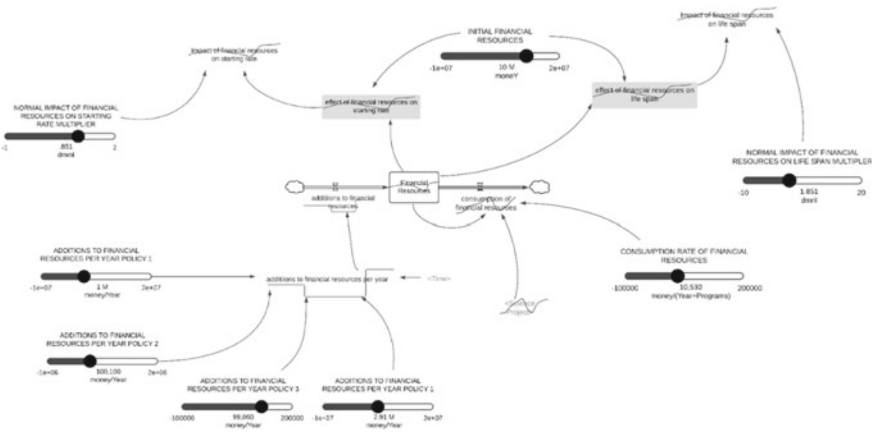


Fig. 3.24 Stocks and flows sector diagram of financial resources as related resources applying overshoot and collapse archetype for understanding the sustainability of scientific vocations

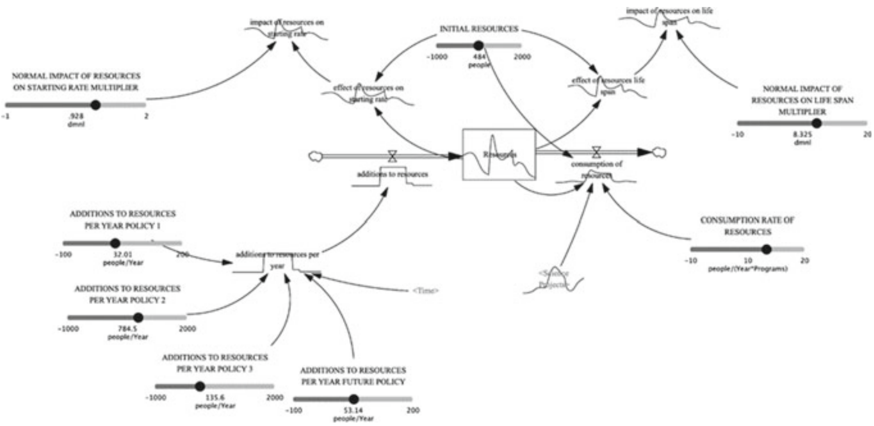


Fig. 3.25 Stocks and flow sector diagram of general resources as related resources applying overshoot and collapse archetype for understanding of the Sustainability of scientific vocations

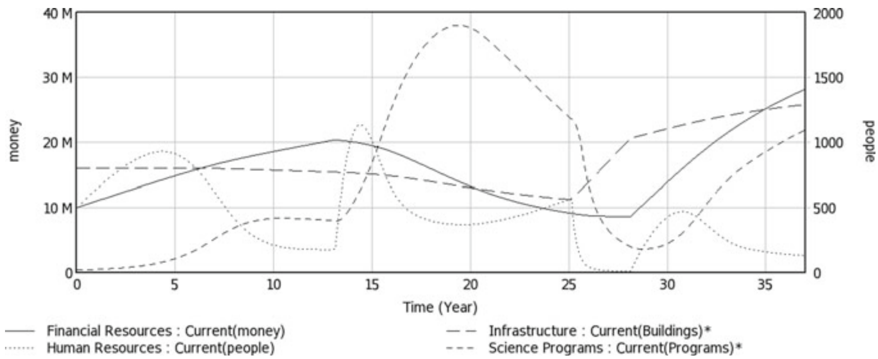


Fig. 3.26 Simulations of coupled resources supporting scientific vocations showing coupled overshoot and collapse behavior

Figure 3.25 presents the simulations of coupled resources supporting scientific vocations, demonstrating the coupled overshoot and collapse behavior. Through two workshops conducted with science teachers in the Department of Santander, Colombia, it was discovered that these teachers tend to have an individualistic mindset that emphasizes individual decisions rather than considering the impact on their environment. However, by applying archetypes such as inequity, overshoot, and collapse, the teachers were able to identify tangible and intangible resources that could contribute to sustainability issues. Simulation models were then created to integrate the essential elements of the system. The results showed that the sustainability of scientific vocations relies on several nested resources, including teachers, financial resources, tangible and intangible resources. The participatory modeling process provided insights into the interconnectedness of the resources and the importance of considering their interactions for sustainability. By applying this approach, science educators can better understand the complexity of the system and make informed decisions to support the sustainability of scientific vocations.

3.6 Conceptual Model Validation

This section of the research chapter on scientific vocations summarizes the validation process performed on the dynamic hypotheses and causal diagrams presented in the chapter. We used the guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010) to assess the structural validity of the system dynamics-type simulation model, including its feedback structure, time delays, and parameter values.

To ensure the behavioral validity of the simulation model and the accuracy of the causal diagrams, we evaluated their ability to reproduce the behavior of the system under study and assessed their structural characteristics, such as feedback loops and time delays. Through this validation process, we established the validity and reliability of causal diagrams for this study.

In this study, the endogenous variables were directly affected by other variables within the same system. By contrast, exogenous variables are influenced by factors outside the system. For example, scientific vocation and education are endogenous variables, as some exogenous variables depend on these factors.

Figure 3.27 includes several variables that are relevant to the analysis of scientific vocations, including endogenous variables like "Scientific Education," "Scientific Vocation," "Occupational Status," "Achievement Motivation," and "Expectancy-Value Beliefs." Notably, some endogenous variables can also act as exogenous variables for other variables within the system. For instance, "Achievement Motivation" and "Expectancy-Value Beliefs" may influence other endogenous variables, highlighting the interconnected nature of the system under study.

Our aim in this study is to develop a qualitative model that can assist decision-makers in making informed decisions regarding scientific vocations. We have defined endogenous and exogenous variables that determine the boundaries of the model, following the guidelines proposed by Qudrat-Ullah and BaekSeo (2010), to ensure its validity and reliability.

By focusing on relevant variables and excluding irrelevant ones, our model can effectively identify the fundamental elements that determine the dynamics in the production of talent in scientific vocations. Our model serves as a tool to provide decision-makers with the necessary insights to make informed decisions regarding the development and promotion of scientific vocations.

In line with Forrester (1961) concept of structural validation, our model is constructed with the sole purpose of fulfilling the decision-making needs of those involved in scientific vocations. The structure of our model generates its behavior, allowing us to provide guidelines that are tailored to the specific context of scientific vocations. By following established guidelines for structural validation, we have ensured that our model is valid and reliable for the purpose of this study.

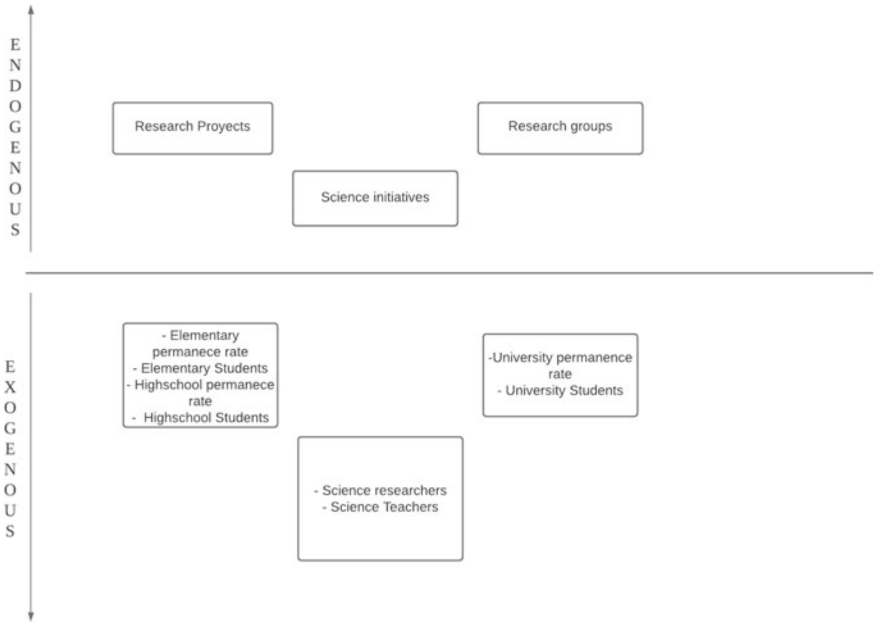


Fig. 3.27 Endogenous and exogenous variables relevant to the analysis of scientific vocations

Table 3.1 structures and concepts adopted from the existing work in CLDs and Dynamic Hypothesis used in the chapter.

This chapter presents dynamic hypotheses and causal loops related to systems thinking and system dynamics. Validation is crucial in simulation modeling to ensure

Table 3.1 Empirical validations of causal loops and dynamic hypotheses in existing literature

Structures/concepts	Remarks
Qudrat-Ullah (2008). 'Behavior validity of a simulation model for sustainable development'. International Journal of Management and Decision Making, 9(2): 129–139	Structural validity of the models
Qudrat-Ullah and BaekSeo (2010). 'How to do structural validity of a system dynamics type simulation model: The case of an energy policy model'. Energy Policy, 38(5): 2216–2224	Structural validity of the models
Hackett (1990). Science as a vocation: Gender and the pre-academic socialization of scientists. Sociology of Education, 63(4), 210–220	The structural formulation was adopted
Stets (2017). Science identity salience: Extending identity theory to understand the effects of science fairs on students' science career intentions." Social Psychology Quarterly 80(2): 126–147	The structural formulation was adopted

the structural and behavioral validity of our conceptual frameworks. Qudrat-Ullah (2008) and Qudrat-Ullah and BaekSeo (2010) emphasize the importance of validating simulation models through expert opinion, empirical data, and sensitivity analysis to assess the structural validity of the model. We refer to the existing literature to validate our conceptual frameworks and identify Besley et al. (2013) study on predicting scientists' participation in public life, Hackett (1990) study on science as a vocation, and Stets (2017) study on science identity salience. These studies support our dynamic hypotheses and provide additional evidence of the validity of our conceptual framework. Table 3.1 summarizes the relevant literature and highlights its relevance to our dynamic hypotheses. Referencing these studies, we provide empirical validation for our conceptual frameworks and support using systems thinking and system dynamics to address complex problems.

Besley, Oh, and Nisbet's (2013) study titled "Predicting Scientists' Participation in Public Life" adopted a relevant causal structure for their study, which aligns with our dynamic hypotheses. Similarly, Hackett (1990) work titled "Science as a Vocation in the 1990s: The Changing Organizational Culture of Academic Science" adopted a structural formulation that supports our dynamic hypotheses.Further empirical validation is provided by Stets' (2017) study, "Science Identity Salience: Extending Identity Theory to Understand the Effects of Science Fairs on Students' Science Career Intentions." The author adopted a relevant structural formulation for their study that bolsters the validity of our conceptual framework.

Referencing these studies in Table 3.1, we provide empirical validation for our dynamic hypotheses and support the use of systems thinking and system dynamics to understand complex problems.

3.7 Discussion

The participatory modeling mechanism with system dynamics used in this study proved highly effective in identifying the causes of inequity and unsustainability in scientific vocations and the fundamental resources needed to sustain them (Sterman, 2022). Specifically, the model features several feedback loops, including R1, which demonstrates how promoting science initiatives increases the number of elementary students' research projects; R2, which shows how science projects increase school permanence and interest in science; and R3, which highlights the connection between science initiatives and research groups as promoters of programs linked to science R&D. The two balancing loops, B1 and B2, demonstrate how the number of research groups correlates with the interest and permanence of high and elementary school students, respectively.

The study also found that the individualistic tendencies of some teachers can impede their ability to identify inequities or unsustainable practices within their environment (Sterman, 2022). However, this study suggests that collaborative teaching practices and fostering a sense of community among teachers can promote a more collective mindset that values inclusivity and sustainability. Providing training and resources on these topics can equip teachers with the necessary knowledge and tools to identify and address issues of inequality and unsustainability in their surroundings. This approach aligns with previous research findings on promoting collective action for sustainable development (Wang, 2019; Borgström-Hansson, 2017).

Teachers' involvement in decision-making is critical for achieving sustainability in scientific vocations. The ability of teachers to identify various resources and their potential impact on the overall system is essential. Therefore, providing teachers with access to necessary resources and adequate support is crucial to identify and develop sustainable practices. Equipping teachers with skills and knowledge to promote sustainability and equity will enhance their abilities and foster the growth and progress of scientific vocations. By doing so, we can ensure that the education system in Santander, Colombia becomes more equitable and sustainable.

Expanding on this idea, providing teachers with tools to better understand the issues associated with inequity and to analyze the structural factors that influence sustainability is essential for ensuring the continuous progress of scientific vocations. This approach aligns with previous findings that emphasized equipping teachers with the skills and knowledge necessary to promote sustainability and equity (Borgström-Hansson, 2017; Wang, 2019). Ultimately, empowering teachers to identify and address issues of inequity and unsustainability in their environment will enable scientific vocations in Santander, Colombia to progress sustainably over time, benefitting both the individuals involved and broader society.

This study shows that system dynamics can be a powerful tool for understanding and addressing the causes of inequity and unsustainability in scientific vocations. This provides a clearer picture of the resources needed to avoid it. However, further research should be conducted on the effects of modeling processes on student engagement and participation, as well as their cognitive understanding of scientific and social systems (Dopico, 2012).

3.8 Conclusion

The potential of Systems Thinking and Participatory Modeling to enhance decision-making in complex systems has been highlighted as a powerful tool for achieving sustainability and promoting equitable futures. This study has demonstrated the effectiveness of these approaches in identifying and addressing the causes of inequity and unsustainability in scientific vocations. This study specifically emphasizes the importance of engaging teachers in simulations and the application of archetypes to equip them with valuable skills and knowledge to promote sustainable practices in scientific vocations. The findings suggest that, by empowering teachers with the resources and support they need, we can drive sustainable solutions and promote a more equitable future.

This study also highlights the significance of System Dynamics as a tool for understanding and addressing inequity in scientific vocations. Through the use of archetypes and simulations, teachers have identified deeper signs of inequity and the resources required to sustain scientific vocations. Future research should further explore the effects of System Dynamics on teachers' and students' engagement and participation, as well as their cognitive understanding of the behavior of scientific and social systems.

In conclusion, this research demonstrates the immense potential of Systems Thinking and Participatory Modeling to improve decision making in complex systems, particularly in scientific vocations. By empowering teachers with the knowledge and skills obtained from this research, we can promote sustainability and equity in scientific vocations, leading to more equitable outcomes for all, including educational administrators and government entities involved in promoting scientific vocations.

3.9 Insights and Implications for Practice

This chapter has shed light on the potential of using archetypes as mediating objects to promote learning in participatory modeling contexts. Specifically, the archetypes of overshoot and collapse, and the archetype of inequity have been identified as valuable tools for understanding the complexity involved in managing the provision of scientific vocations in a sustainable manner.

The contributions of teachers to participatory modeling are crucial for promoting the adoption of the citizen science approach in schools and their communities (Beierle & Cayford, 2002). Furthermore, systemic analysis of the challenges associated with scientific vocations serves as an effective teacher training strategy that can enhance decision-making in science education (Banchi & Bell, 2008). This approach benefits not only teachers but also educational leadership and governance within communities that promote the development of scientific vocations for rural development (Debroux & Stotesbury, 2019). By leveraging the insights and expertise of teachers and engaging in collaborative efforts to address these challenges, we can build a more inclusive, equitable, and sustainable education system that promotes scientific vocations in Santander, Colombia. These findings also support the existing literature on the role of teachers in promoting participatory and inclusive approaches to education (Menezes et al., 2021; Doyle et al., 2019), emphasizing the need to prioritize teacher training and collaboration to achieve these goals.

Key resources of various types that teachers identify as crucial to justify the difficulty of developing CTIE activities that lead to the generation of scientific vocations in children. According to the findings of the study, teachers in Santander, Colombia identified several resources that were essential for promoting scientific vocations among children. These resources include access to laboratory equipment and materials, professional development opportunities, funding for research projects, and support from educational leaders and policymakers (Benitez et al. 2020; López et al. 2018).

Moreover, teachers have emphasized the importance of promoting collaborative learning environments that foster curiosity, critical thinking, and problem-solving skills (Chen et al., 2018; Kahveci & Aydin, 2021). Additionally, they highlight the need for inclusive and culturally responsive teaching practices that value and respect the diverse perspectives and experiences of all students (Llewellyn, 2018; Osborne et al., 2019).

By providing teachers with these resources, schools and educational institutions can create an environment that promotes scientific inquiry and fosters a love for learning. Furthermore, these resources can help address the systemic inequalities and structural barriers that exist in rural and underserved communities, where access to resources and opportunities for scientific exploration may be limited (Astalini, 2020; Kryst, 2015; Alasia, 2005).

By identifying and providing necessary resources, we can support teachers in promoting scientific vocations among children and fostering a more equitable and sustainable future.

By using these archetypes, it is possible to gain a deeper understanding of the potential consequences of unsustainable practices in scientific vocations, such as overshooting the carrying capacity of resources or perpetuating systemic inequities. This knowledge can then be used to inform decision-making processes and to develop more effective strategies for promoting sustainability in scientific vocations.

For practitioners, the insights gained from this research suggest that incorporating archetypes into participatory modeling processes can be an effective way to engage stakeholders and promote learning. By using archetypes to represent complex systems and processes, practitioners can help stakeholders to better understand the dynamics at play and to identify potential points of intervention.

Furthermore, the use of archetypes can also help to promote more equitable decision-making processes, by highlighting the potential consequences of decisions and actions on different stakeholders and communities. This is particularly relevant in the context of scientific vocations, where issues of gender and other forms of systemic inequity continue to persist.

In future work, it will be important to focus on the analysis of the structural causes that limit sustainability and equity in the promotion of scientific vocations. From the perspective of the education system, public policies and science governance would aid in understanding the complex issues that affect science teaching practices in schools.

Overall, this research has important implications for practitioners seeking to promote sustainability in scientific vocations. By using archetypes as mediating objects, practitioners can foster a more nuanced understanding of the complexity involved in managing these systems sustainably, and develop more effective strategies for promoting sustainability and equity in the scientific workforce.

Finally, this exercise of identifying key resources for promoting scientific vocations has significant implications for all the actors involved in science education. Teachers can guide them towards more effective teaching strategies and activities. Educational institution administrators can inform decisions regarding resource allocation and curriculum development. Finally, the government can provide insights into systemic issues that hinder the sustainability and equity of science education.

By recognizing and addressing these challenges, we can work towards a future in which scientific vocations are promoted and supported for all.

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Chapter 4
Bringing Behavioral Economics into System Dynamics: Some Challenges, Solutions, and a Path Forward

Souleymane Bah, Michael J. Radzicki, and Alexander D. K. Smith

Abstract System dynamics models are used to understand how complex system structures cause problematice system behaviors. An important aspect of understanding the relationship between system structure and system behavior involves capturing the ways in which human decision makingcan influence a system's time path. Although system dynamicists use rigorous techniques to represent human decision makingin their models, these techniques are almost never tied directly to behavioral economics. As such, an opportunity exists for creating a method for bringing structures from behavioral economics directly into system dynamics modeling, in a manner that is deemed acceptable to both groups of scholars. A crucial issue related to merging behavioral economics and system dynamics involves the representation of time. This is because system dynamicists work in continuous time and behavioral economists typically work in discrete time. This issue is also confusing as discrete time formulations are routinely used in system dynamics models, and behavioral economists acknowledge that continuous time structures can be used to address some deficiencies in their discrete time models. Moreover, since system dynamics models are simulated on digital computers, their continuous time differential equation solutions are approximated with algorithms that are based on discrete time difference equations. This chapter attempts to clear-up the confusion over discrete and continuous time modeling and demonstrate how either can be used in a system dynamics environment. Moreover, since both discrete and continuous representation are possible, the direct relationship between the two is explored to determine the degree to which a particular representation of time matters. Samuelson's multiplier-accelerator model, Allen's cobweb model, and three methods for discounting streams of benefits stemming from future consumption spending (exponential discounting, quasi-hyperbolic discounting, and hyperbolic discounting) are used as examples. The results show that the continuous versions of both Samuelson's and Allen's models are broadly similar, but different in important detail, and are less transparent relative

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to their original, discrete, counterparts. On the other hand, the discrete and continuous versions of all three discounting structures yield very similar dynamics and can, in principle, be used interchangeably. That said, there are certain circumstances under which a continuous representation is preferable and others under which a discrete representation is preferable. The chapter concludes with some discussion about turning insightful system dynamics models into games for use in experimental economics, and on assembling a catalog of faithfully replicated molecules from behavioral economics so that the system dynamics community can use them to create richer, and more insightful, models.

Keywords System dynamics · Behavioral economics · Differential equations · Difference equations · Exponential discounting · Quasi-hyperbolic discounting · Hyperbolic discounting

4.1 Introduction

For decades economists have constructed theories based on the assumption of "homo economicus" or rational economic man. Under this assumption robot-like representative agents make optimal economic decisions by solving constrained optimization problems using all available (perfect and symmetric) information in a completely unbiased and unemotional manner.[1] Of course, psychologists and behavioral scientists have repeatedly pointed out that actual human beings cannot, and do not, make these types of decisions. Rather, their decision makingis fraught with cognitive limitations, information asymmetries, and irrational biases that are driven by environmental factors, habits, emotions, and various aspects of their mental status.[2] The traditional retort by economists is that models and theories are not real but rather egregious (but useful) simplifications of reality and, as such, cannot be legitimately criticized by pointing to their unrealistic assumptions. Moreover, they argue that their models and theories embodying the homo economicus assumption are related to individual *households* and *firms*, not individual household *members* or individual firm *managers*, and hence should *not* be judged by how accurately they capture individual decision makingrules but rather by how well they can predict household-level and firm-level data.[3]

Although critiques of the homo economicus assumption, and hence of the theories associated with it, dogged modern economics throughout the twentieth century,[4] an alternative approach, termed behavioral economics by Becker (1976), began to

[1] See Becker (1976) for an overview of the application of homo economicus to a broad collection of socioeconomic problems.

[2] See Samson (2020) for a summary.

[3] Friedman (1953) is the classic example of the defense of homo economicus. Dean et al. (2023) present a summary of how well the neoclassical theory of the firm explains firm-level data.

[4] See for example Galbraith (1967) and Simon (1982).

gain acceptance within the economics profession in the 1970s with the work of Kahneman and Tversky (1974) on decision makingin the face of uncertainty.[5] This foundational academic work was greatly expanded over the next thirty years by a core group of leading economists,[6] and diffused into the business community and public-at-large via the publication of general interest books, and articles appearing in the popular press.[7] Today behavioral economics, and its empirical counterpart experimental economics,[8] are part of the mainstream of modern economic science, and their core insights are routinely used to address a wide variety of socioeconomic problems.[9]

In a somewhat parallel fashion, system dynamics computer simulation modeling was developed by MIT electrical engineer Jay W. Forrester, beginning in the mid-1950s, as a tool for helping managers solve corporate problems and improve firm behavior. At its core, system dynamics is a combination of the things Forrester knew best: servomechanisms (i.e., feedback systems), digital computing, and management. His experience as a manager on large-scale engineering projects led him to conclude that corporate systems could be modeled by mapping-out a firm's overall physical and financial structure, much of which could be readily identified (e.g., an accounting subsystem, a manufacturing subsystem), and then enriching it by talking to employees and/or observing their behavior, and then writing equations that capture the decision rules they use to influence the firm's dynamics. A common result was that the interaction of the seemingly reasonable, albeit bounded rational, employee decision rules would cause the overall corporate system dynamics model to behave poorly and mimic the actual firm's problematic dynamics.[10] The model was then used as a laboratory for running "what-if" experiments aimed at identifying policies (i.e., system redesigns) that could improve the firm's behavior.[11]

Forrester argued that the decision rules used by actors in a system describe how available information is used to determine action. These rules are composed of both a structure (i.e., the information sources selected and the manner with which they are used) and parameters (i.e., the determinants of the amount of influence the information has, and how much action it generates).[12] The most widely used decision rule or "molecule" in system dynamics modeling is, by far, a first order negative feedback loop.[13] This structure is used by itself, or in concert, to represent any process within

[5] Thaler (2015) and Witynski (2023) present nice overviews.

[6] For example Thayler (1990), Laibson (1997), Shiller (2005), and Camerer et al.(2011).

[7] See for example Levitt and Dubner (2005), Thaler and Sunstein (2008), Kahneman (2011), Shiller (2015), and Gal (2018).

[8] See Smith (1989).

[9] See Thaler and Sunstein (2008) and Mohsenin (2017).

[10] See Morecroft (1983, 1985) and Sterman (2000, Chap. 15—Modeling Human Behavior: Bounded Rationality or Rational Expectations).

[11] For a sweeping overview of Forrester's career see Sterman (2018).

[12] Forrester (1971).

[13] Paich (1985) discusses the use of reusable generic structures and "molecules" in system dynamics modeling. In the STELLA software package molecules are called "assemblies.".

which a person seeks a goal such as inventory control actions, capital acquisition decisions, and pricing strategies aimed at capturing a target market share. The signature technique in system dynamics for integrating parameters into decision rules involves estimating their "normal" values and then allowing these values to be modified by nonlinear "table functions" in response to pressures emanating from other parts of the system.[14]

It is important to note that the proper use of table functions in system dynamics modeling is typically not well understood and/or valued by economists.[15] Moreover, although rigorous techniques for specifying table functions, both logically and empirically, have been developed,[16] they have no *direct* connection to psychology or behavioral economics. As a consequence, an opportunity exists for creating methods for formally bringing decision making structures from behavioral economics directly into system dynamics modeling, in a manner that would be deemed acceptable to both system dynamicists and economists. Indeed, this is the focus of this chapter.[17]

4.2 The Primary Challenge

Perhaps the most significant challenge to developing a teachable and repeatable method for merging system dynamics modeling with behavioral economics involves addressing the apparent conflict between the representation of time typically utilized by behavioral economists (i.e., discrete time) and the representation of time utilized by system dynamicists (i.e., continuous time).[18] Although models built via these competing representations of time have many similarities, they also have significant

[14] Other techniques for representing decision rules in system dynamics models have been developed as well. For example, it is common to integrate a weighted average of a desired and a traditional value of a variable, with the weights changing in response to pressures from other parts of the system, into a decision structure. For example, in Forrester's (1968a, 1968b) market growth model the operating goal for a firm's product delivery delay time is a weighted average of management's goal for the delivery delay time and the firm's traditional delivery delay time. The latter is formed by averaging the delivery delay time recognized by the firm, which in turn is formed by smoothing the firm's actual product delivery delay time.

[15] For example see the discussion of, and confusion over, table functions in the debate between Nordhaus (1973) and Forrester et al. (1974).

[16] See Sterman (2000; Chap. 14—Formulating Nonlinear Relationships) and Naill (1969).

[17] This is not to say that there has been no effort to blend elements of behavioral and experimental economics with system dynamics modeling. Sterman (1987) Sterman (1989). Diehl and Sterman (1995), Kleinmuntz (1993), Kampmann and Sterman (2014), Bahaddin et al. (2019), Lane and Rouwette (2023) are examples of scholars who have addressed this challenge. Although these efforts are noteworthy none of them has yielded a consensus framework for merging behavioral economics and system dynamics.

[18] Romanchuk (2017) argues that the use of discrete time in economic modeling has the advantages of being simple, of matching the availability of economic data, of making time delays easy to model, and of being able to represent accounting relationships in the usual manner. He also argues that the only drawback to discrete time analysis is that some easily understood stability results are lost.

differences.[19] Getting practitioners from both fields to fully understand the formal relationship between the two representations of time, as well as any differences that may arise, particularly with respect to policy recommendations, is crucial for moving a merger forward. That said, one of the ironic aspects of this challenge is that the use of discrete time formulations is wholly consistent with the system dynamics paradigm and continuous time formulations appear to be entirely acceptable within the field of behavioral economics. According to Forrester (1961, Chap. 5):

> In formulating a model of an industrial operation, we suggest that the system be treated, at least initially, on the basis of continuous flows and interactions of the variables. Discreteness of events is entirely compatible with the concept of information-feedback systems, but we must be on guard against unnecessarily cluttering our formulation with the detail of discrete events that only obscure the momentum and continuity exhibited by our industrial systems.
>
> These comments should never be construed as suggesting that the model builder should lack interest in the microscopic separate events that occur in a continuous-flow channel … By studying individual events we get a picture of how decisions are made and how the flows are delayed. The study of individual events is one of our richest sources of information about the way the flow channels of the model should be constructed.
>
> The preceding comments do not imply that discreteness is difficult to represent, nor that it should forever be excluded from a model … When a model has progressed to the point where such refinements are justified, and there is reason to believe that discreteness has a significant influence on system behavior, discontinuous variables should then be explored to determine their effect on the model.

Similarly, well-known behavioral economist Laibson (1997, p. 468) suggests that a continuous time analog of his golden eggs model could solve a liquidity problem that arises in its discrete representation:

> A second problem associated with the model is the anomalous prediction that consumers will always face a binding self-imposed liquidity constraint. For example, the golden eggs model predicts that after making their consumption choice, consumers should have no liquid funds left in their bank accounts. This prediction contradicts many consumers' experiences. However, this problem can be readily addressed by introducing a precautionary savings motive for holding liquidity. For example, consider a continuous-time analog of the golden eggs model, and assume that instantaneous liquidity needs arrive with some hazard rate. Then in equilibrium the consumer will only rarely completely exhaust her liquidity.

Of course, although the general sentiments about the usefulness of discrete and continuous time are positive, the "devil is always in the details."

4.3 A Common Area of Confusion

A question that is often asked by newcomers to the field is whether or not system dynamics is truly a continuous time simulation modeling technique. This is because they quickly notice that system dynamics models are solved numerically by using

[19] See Tobin's (1982, p. 189) discussion of the advantages and disadvantages of both discrete and continuous time modeling in his Nobel Prize winning lecture.

discrete time difference equations to approximate the underlying continuous time differential equation system.

From a system dynamics point of view, "solving" a dynamic system means determining how much "stuff" has accumulated in each of a system's stocks at every point in time.[20] To solve a dynamic system a digital computer must take a small discrete step forward in simulated time, calculate how much "stuff" has flowed into and out of each of the system's stocks, and then add or subtract this amount from the amount of stuff already in the stocks. This process repeats until the end of the simulation has been reached.

If a system dynamics modeler asks the computer to take discrete time steps that are too large relative to the time constants of the real world processes being modeled, the approximation of the underlying continuous time dynamics will be very inaccurate.[21] This is called integration error or "truncation error" and is directly related to the particular numerical integration technique used to do the approximation. To increase accuracy, the time step can be made smaller but the gain in accuracy comes at the price of a slower simulation speed, since the computer will have to make more calculations.[22] Alternatively, a more sophisticated numerical integration technique can be used with the same, or smaller, step size.

Simulation speed aside, at some point it is not possible to reduce step size below a defined minimum value because the amount of round-off error[23] becomes too large.[24] Round-off error involves the limitation on the number of significant digits to the right of the decimal point a computer can store. In other words, step size can be reduced and integration error made smaller up until the point at which round-off error becomes significant.[25] Thus, the size of the discrete step in simulated time is bounded by integration error on the high side and round-off error on the low side.

[20] The stocks represent the state of the system.

[21] See Sterman (2007).

[22] For most models run on a modern digital computer, simulation speed is not an issue. Indeed, some modern system dynamics software packages have an option that *slows down* a simulation so that the unfolding dynamics can be observed. The issue with simulation speed arises when a larger model must be run thousands of times, such as during optimization runs, calibration runs, and Monte Carlo experiments. In these sorts of situations the selection of step size, and the trade-off between accuracy and simulation speed, matters.

[23] The field of numerical analysis has identified lots of other accuracy problems that can arise when digital computers are asked to do sophisticated mathematical calculations. A complete discussion of this topic is beyond the scope of this chapter.

[24] Stated differently, a digital computer cannot take infinitesimally small steps forward in simulated time.

[25] Naill (1975, p. 6).

To select the "correct" solution interval Forrester (1968a, 1968b, p. 6–3) recommends a time step of "half or less of the shortest first-order delay in the system."[26,27] The salient point, however, is that the time step is rarely, if ever, chosen to be "1" because the numerical integration recipes embedded in system dynamics modeling environments are not intended to solve difference equation systems, but rather to approximate continuous time processes. Thus newcomers to the field are often confused as to how time is actually being represented, and how the solution interval should be interpreted, in a system dynamics model.

4.4 Replication of Results

An additional challenge for developing a teachable and repeatable method for merging system dynamics modeling with behavioral economics involves the creation of a process for exactly replicating discrete time results from behavioral economics in a continuous time system dynamics environment. Replicability is a hallmark of science[28] and system dynamicists take great pride in presenting models that are

[26] Naill (1975, p. 7) presents a rigorous case for a step size of "less than one-tenth the smallest adjustment time of the system" in order to achieve 1% accuracy over the simulated time period." He also notes that "the most common rule used by system dynamicists in choosing [a time step] is also prevalent in the numerical analysis literature," i.e., using "a constant step size h to obtain a solution, and then… another…using a smaller step size, say h/2. If the 2 solutions yield results which are in good agreement…it is fairly safe to assume that both are reasonably accurate…" [Naill quote of James et al. (1967)].

[27] There is an additional complication in the selection of step size, however. Naill (1975, p. 2) notes that since the"per step roundoff error associated with any numerical integration scheme is essentially independent of the step size being used, and therefore the total roundoff error normally increases with the number of steps,…the total roundoff error is also dependent on the *stability* of the integration routine used." An integration routine is said to be stable if the total error between the actual and simulated solution decreases as the simulation proceeds. Naill (1975, p. 11) points out that: "After one chooses an integration step size (one-tenth the smallest delay) the length of the run relative to [the step size] must not be excessive, or the total number of calculations n = (length/ [step size]) will be excessive. System dynamics models have another rule of thumb that helps to avoid this difficulty: in modeling a dynamic phenomenon, no delays are included that are less than approximately one-tenth of the time horizon for [the] phenomenon. This rule is based on the fact that phenomena of much shorter time constants normally cannot explain the behavior of interest.".

[28] Unfortunately, the economics profession has had a somewhat poor record in this area. For example, Chang and Li (2017) looked at sixty-seven papers published in thirteen economics journals and found they could only replicate thirty-three percent of the results independently, and only forty-nine percent with the help of the authors. Similarly, McCullough et al. (2006) found that they could only fully replicate the results presented in fourteen of sixty-two articles submitted to the *Journal of Money, Credit and Banking*. Further, in 2008 they found that they could only replicate the results presented in twenty-nine of one hundred thirty-three articles submitted to the *Federal Reserve Bank of St. Louis Review*. Results like these contribute to a loss of confidence in economic research.

extensively documented so that other scholars can exactly reproduce their results.[29] Replicable results help to create clarity, boost confidence, generate credibility within a scientific community, and make the extension of a research thread more straightforward and valuable. Both system dynamicists and behavioral economists can thus benefit from the development of a method for faithfully replicating discrete time results from behavioral economics in a system dynamics environment.

4.5 Questions

The preceding list of challenges lead directly to several important questions:

1. Is it possible to faithfully replicate a discrete time difference equation model in a system dynamics modeling environment? Can a discrete step size of less than one be used?
2. Is it possible to faithfully convert a discrete time difference equation model into its equivalent continuous time differential equation representation and run it in a system dynamics modeling environment?
3. Is it possible to faithfully replicate a discrete time structure or molecule from behavioral economics and then integrate it into an otherwise continuous time system dynamics model, which almost always must be simulated with a step size of less than one?
4. Is it possible to faithfully convert a discrete time structure from behavioral economics into its equivalent continuous time representation and then integrate it into a system dynamics model?
5. Is it better to bring a discrete time version of a structure from behavioral economics into an otherwise continuous time system dynamics model? Or is it better to convert the discrete time version of a structure from behavioral economics into its equivalent continuous time formulation before embedding it into a system dynamics model?
6. Is there value in turning a system dynamics model embodying structures (molecules) from behavioral economics into a system dynamics flight simulator (i.e., a game) for use in an experimental economics context?
7. What might a catalog of behavioral economics/system dynamics "molecules" look like?

This chapter will present answers to all of these questions and in so doing define a path forward for the merging of behavioral economics with system dynamics.

[29] Rahmandad and Sterman (2012) present a detailed method for properly documenting a system dynamics model so that its results can be replicated.

4.6 Replicating Difference Equation Models

Although system dynamics models are solved in (approximated) continuous time, it is possible to simulate a pure difference equation model in a system dynamics modeling environment. The most common reason for doing this is to replicate a discrete time model created by someone else. Indeed, many well-known models in economics have been created with difference equations.

In order to illustrate a method for faithfully replicating a traditional difference equation model in a system dynamics environment two examples will be presented: one from macroeconomics (Samuelson's multiplier-accelerator model) and one from microeconomics (the cobweb model).

There are three basic ways to replicate a pure difference equation model in a system dynamics modeling environment. The first is to make any lagged value of a model variable a stock that is part of first order negative feedback loop structure with a *time constant* of one. This technique also requires the modeler to specify a *time step* of one, which is consistent with the time step of a pure difference equation, and to use Euler's numerical integration method. The drawback of this technique is that the time shape that is generated in a typical system dynamics modeling environment looks continuous, as the native plotting routines directly connect each ordered pair. This is, of course, misleading as the state of a difference equation system does not change between time steps, but is logical within a system dynamics modeling environment as the plotting routines have been designed to consider the distance between ordered pairs as continuously changing.

A second technique presented by Radzicki (2019) utilizes infinite order delays, does *not* require a step size of one, and can accurately mimic a difference equation's time shape. The main advantages of this technique are that it is fairly simple to execute and any numerical integration method can be used to run the simulations. The main drawback is that it uses canned infinite order delay functions to represent lagged variables and hence the model contains no *explicit*, traditional, stock-flow structure, which can be confusing to those who are familiar with the basics of system dynamics modeling.[30]

A third technique that can also accurately mimic a difference equation model's time shapes and does not require a time step of one involves discretizing the values of any variables that are to be lagged, as continuous time unfolds during a simulation. This discretizing process is in addition to, and separate from, the discretization of time that is occurring as the computer solves the model.[31] The advantage of this

[30] This technique was originally suggested by Sterman (2007), who notes that it is possible to reformulate a discrete-time map in continuous time: "The difference equation formulation implies that there is a time delay of 1 'period' in [a] feedback loop from x to its rate of change. Further, that delay is a 'pipeline' delay: output(t)—input(t-L), where L is the length of the delay, in this case, one 'period.' The pipeline delay is the limit of the Erlang delay family as the order of the Erland delay goes to infinity (it is thus also called an infinite-order delay). Consequently, the continuous time equivalent of [a] discrete time mapping … is actually an infinite-order system."

[31] The process of discretizing a continuous wave or time shape is well known in engineering and the hard sciences, particularly in the area of signal processing. Modern radios for example are "software

technique is that it reveals the stock-flow structure inherent in the model, which makes the model clearer to those who are familiar with the basics of system dynamics. The disadvantages of the technique are that it requires more steps to code and is limited to Euler's method of numerical integration.[32] Two examples should make this technique more understandable.

4.6.1 Samuelson's Multiplier-accelerator Model

Samuelson (1939) well-known discrete time multiplier-accelerator model lays out the interaction of two macroeconomic feedback processes: the multiplier, which involves the consumption spending of the household sector of the economy and the accelerator process, which involves the investment spending of the business sector of the economy.

Following Samuelson:

$$Y_t = g_t + C_t + I_t \tag{4.1}$$

$$C_t = \boldsymbol{\alpha} * Y_{t-1} \tag{4.2}$$

$$I_t = \boldsymbol{\beta}^*(C_t - C_{t-1}) \tag{4.3}$$

$$g_t = 1 \tag{4.4}$$

Substituting (4.2) into (4.3) yields:

$$I_t = \boldsymbol{\alpha} * \boldsymbol{\beta} * \left(y_{t-1} - y_{t-2}\right) \tag{4.5}$$

Substituting (4.2), (4.4), and (4.5) into (4.1) yields:

$$Y_t = 1 + \left[\boldsymbol{\alpha} * Y_{t-1}\right] + \left[\boldsymbol{\alpha} * \boldsymbol{\beta} * (Y_{t-1} - Y_{t-2})\right] \tag{4.6}$$

which is a second order difference equation that can be replicated with the third technique in a system dynamics environment.

Figure 4.1 presents the replication of Samuelson's multiplier-accelerator model in a system dynamics environment. Although the complete code for the model can be examined in the appendix, the logic behind the discretization process appears in the flow equations associated with the model's two stocks (i.e., with the two lagged

defined," which means they receive continuous radio waves from an antenna, discretize them via a sampling method, process them via an internal digital computer to improve clarity, and then convert them back to continuous (sound) waves so that the information they contain can be heard.

[32] It also requires the use of canned infinite order delay functions as in technique number two.

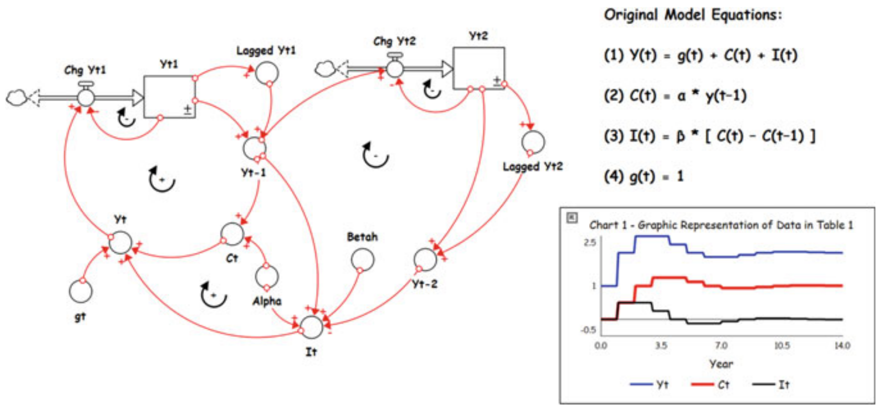

Fig. 4.1 Replication of Samuelson's multiplier-accelerator model

variables) and in the calculations of the current values of the model's endogenous variables.

In general, the discretization process relies on the following logic[33]:

(a) Variable(t1) = ∫ Variable(t1)$_{\text{t-DT}}$ + [Change Variable(t1)] * DT
(b) Change in Variable(t1) = If Time = Int(Time) Then [Variable to be Lagged - Variable(t1)]/DT Else 0[34]
(c) Lagged Variable(t1) = Delay[Variable(t1), 1, Variable(t1)]
(d) Variable(t-1) = IF Time = Int(Time) Then Variable(t1) Else Lagged Variable(t1)

4.6.2 Cobweb Model

The cobweb model is a dynamic microeconomic model that describes the behavior of prices and quantities in a market in which there is a time delay in the adjustment of supply to demand. Over the years, various versions of the cobweb model have appeared in the economics literature.[35] In this chapter Allen (1956, pp. 15–17) discrete time Model II is used as an example. This version of the cobweb model assumes that the suppliers hold a stock of inventory and adjust their product's price based on the actual amount of inventory they hold relative to the amount they desire.

Following Allen:

The quantity demanded is a linear function of the current price:

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[33] As was previously mentioned, this technique requires the use of Euler's method of numerical integration to get the proper results.

[34] This sort of discretization process has been used in the past in system dynamics modeling, most commonly when historical data are matched to synthetic data that is "picked" at integer intervals. Sterman (1984) uses this technique to calculate Theil's inequality statistics in order to evaluate the fit of a system dynamics model to historical data.

[35] Meadows (1970, Chap. 3) presents a comprehensive summary of the history of the cobweb model.

$$D_t = \boldsymbol{\alpha} - a * P_t \tag{4.7}$$

The quantity supplied is a linear function of the current price:

$$S_t = \boldsymbol{\beta} + b * P_t \tag{4.8}$$

Suppliers adjust the product's price in proportion to the gap between last period's actual inventory and desired inventory:

$$P_t = P_{t-1} - \boldsymbol{\lambda}^* \left(Q_{t-1} - Q^{Desired}\right) \tag{4.9}$$

Equation (4.9) implies:

$$P_{t-1} = P_{t-2} - \boldsymbol{\lambda}^* \left(Q_{t-2} - Q^{Desired}\right) \tag{4.10}$$

Subtracting (4.10) from (4.9) yields:

$$(P_t - P_{t-1}) = (P_t - P_{t-2}) - \boldsymbol{\lambda}^* \left(Q_{t-1} - Q_{t-2}\right) \tag{4.11}$$

Or:

$$P_t = (P_t - P_{t-2}) - \boldsymbol{\lambda}^* \left(Q_{t-1} - Q_{t-2}\right) + P_{t-1} \tag{4.12}$$

Recognizing that $Q_{t-1} - Q_{t-2}$ is the change in the *stock* of product inventory and that (4.7) and (4.8) represent the *flows* of supply and demand (and hence $S_{t-1} - D_{t-1}$ is the *net flow* that changes the stock of inventory), (4.12) can be re-written as:

$$P_t = 2 * (P_{t-1} - P_{t-2}) - \boldsymbol{\lambda} * (S_{t-1} - D_{t-1}) \tag{4.13}$$

Substituting (4.7) and (4.8) into (4.13) yields:

$$P_t = 2 * (P_{t-1} - P_{t-2}) - \boldsymbol{\lambda} * (\boldsymbol{\beta} + b * P_{t-1}) + \boldsymbol{\lambda} * (\boldsymbol{\alpha} - a * P_{t-1}) \tag{4.14}$$

Or:

$$P_t = [\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})] + [2 - \boldsymbol{\lambda} * (a + b)] * P_{t-1} - P_{t-2} \tag{4.15}$$

which is a second order difference equation that can be replicated with the third technique in a system dynamics environment.

Of note is that, in equilibrium: $P_{equilibrium} = P_t = P_{t\text{-}1} = P_{t\text{-}2}$ and $Q_{equilibrium} = D_t = S_t$. Thus (4.15) becomes:

$$P_{equilibrium} = [\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})] + [2 - \boldsymbol{\lambda} * (a + b)] * P_{equilibrium} - P_{equilibrium} \tag{4.16}$$

And thus:

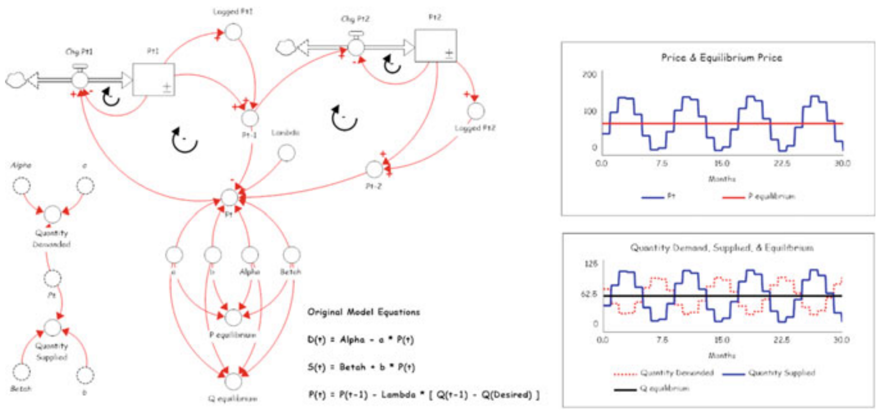

Fig. 4.2 Replication of Allen's cobweb model

$$P_{\text{equilibrium}} = (\boldsymbol{\alpha} - \boldsymbol{\beta})\,/(a + b) \tag{4.17}$$

$$Q_{\text{equilibrium}} = [(b * \boldsymbol{\alpha}) + (a * \boldsymbol{\beta})]/[a + b] \tag{4.18}$$

Although the level of inventory desired by the supplier can take on any value, in the present case it will be designated as (4.18).

Figure 4.2 presents the replication of the cobweb model in a system dynamics environment. Again, although the complete code for the model can be examined in the appendix, of note is that the model consists entirely of negative feedback loops. This is in contrast to Samuelson's multiplier-accelerator model, which contains two positive feedback loop processes (the multiplier and the accelerator) and a negative feedback loop that also influences the accelerator process.[36] One of the advantages of replicating these discrete time models in a system dynamics environment is the ability to analyze them via a feedback perspective. Although economists are certainly aware of feedback processes they rarely analyze their models and theories from this vantage point.[37]

4.7 Converting Difference Equation Models into Their Equivalent Continuous Time Counterpart

In light of the fact that it is possible to faithfully replicate a pure difference equation model in a continuous time system dynamics modeling environment, a somewhat natural question to ask is whether or not it is possible to convert a difference equation

[36] Not counting the two minor negative loops that update the model's stocks.

[37] See the discussion in Radzicki (2021a).

model into its equivalent continuous time representation with minimal-to-no loss of fidelity and, if so, identify the relative similarities and differences, and advantages and disadvantages, of each depiction. This is the sort of question that is implicitly asked, for example, when customers inquire about the different rates of return that are generated when bank interest is compounded (say) annually versus quarterly, monthly, weekly, daily, hourly, minute-by-minute, second-by-second, and in the limit, continuously. Indeed, this is a common intellectual journey taken to derive Euler's number "e."[38]

Within economics the question of analyzing the same dynamic phenomenon with both difference and differential equations has its roots in the work of Baumol (1951) and Allen (1956). Both of these authors demonstrate how to convert basic difference equation models into their continuous time counterparts and note that they generate mostly similar, but sometimes significantly different, results. In more recent times Tarasova and Tarasov (2017) have produced a rigorous approach for exactly discretizing continuous time macroeconomic models with power law memory so that they have the same solutions, and predict the same behavior, for a model economy.

In the system dynamics literature, Low (1980) analyzes Hicks' (1950) discrete time multiplier-accelerator model and recasts it from a system dynamics perspective.[39] He represents the two lagged values of national income as traditional system dynamics information smoothing delays but notes that the discrete time version does not differentiate between the model's time step and the adjustment times (i.e., time constants) for the smoothing delays. As such, they do "not really represent the continuous accumulation of information that characterizes most decision processes."[40] Low goes on to build a broadly similar, but significantly different, continuous time system dynamics version of Hicks' model.

Taking a different approach from Low, Goodman (1974, p. 21) illustrates how the system dynamics equations that underlie a first order positive feedback loop process can be conceptually manipulated to derive the exact continuous time solution they are approximating. He does this by replacing the model's finite time step DT, with an infinitesimally small time step dt, and then analytically solving the corresponding integral. Although clever, this approach is not generalizable and is difficult to apply to higher order systems.

The solution offered in this chapter is inspired by Goodman's approach. It is based on the discrete time mean value theorem, which extends the mean value theorem for continuous functions to the discrete case, in which functions are defined only at discrete points in time.

The discrete-time mean value theorem states that for any function f(t) that is defined and continuous over the interval $[t - \Delta t, t]$, and differentiable over the open interval $(t - \Delta t, t)$, there exists a point c within $(t - \Delta t, t)$ such that:

[38] See Azad (2023).

[39] Low first replicates Hick's discrete time model in a system dynamics modeling environment utilizing a step size of one.

[40] Low (1980, p. 111).

$$f(t) - f(t - \Delta t) = f'(c) * \Delta t \tag{4.19}$$

where f′c is the average rate of change of the function over the interval $[t - \Delta t, t]$.

Rearranging (4.19) yields:

$$f'(c) = [f(t) - f(t - \Delta t)]/(\Delta t) \tag{4.20}$$

Taking the limit as $\Delta t \rightarrow 0$ of both sides of (4.20) and keeping in mind that $c \in [t - \Delta t, t]$ yields:

$$\lim_{\Delta t \to 0} f'(c) = \lim_{\Delta t \to 0} \boxed{f_0} [f(t) - f(t - \Delta t)]/\Delta t = \lim_{\Delta t \to 0} f'(c)$$
$$= f'(t) = \lim_{\Delta t \to 0} f'(c) = df(t)/dt \tag{4.21}$$

In the discrete to continuous conversion process, $\lim_{\Delta t \to 0} \boxed{f_0} [f(t) - f(t) - \Delta t]/\Delta t$ is replaced by df(t)/dt to create the continuous version of a model. For example, when $\Delta t = 1$, the expression $f(t) - f(t - 1) = f'(t)$ is replaced by df(t)/dt in the continuous time version of a model. Similarly, the expression $[f(t) - f(t - 1)] - [f(t - 1) - f(t - 2)] = f'(t) - f'(t - 1) = f''(t)$ is replaced by $d^2f(t)/dt^2$ in the continuous time version of a model.

To convert Samuelson's multiplier-accelerator model into its equivalent continuous time representation rewrite Eq. (4.6):

$$Y_t = 1 + \left[\alpha * (1 + \beta) * Y_{t-1}\right] - \left[\alpha * \beta * Y_{t-2}\right] \tag{4.22}$$

Or:

$$Y_t = 1 + \alpha * \left[Y_{t-1} + *\beta(Y_{t-1} - Y_{t-2})\right] \tag{4.23}$$

Inserting the positive and negative versions of: $\beta * (Y_t - Y_{t-1})$ into (4.23) yields:

$$Y_t = 1 + \alpha * \left[Y_{t-1} + \beta * (Y_t - Y_{t-1}) - \beta * (Y_t - Y_{t-1}) + \beta * (Y_{t-1} - Y_{t-2})\right] \tag{4.24}$$

Or:

$$Y_t = 1 + \alpha * \left[Y_{t-1} + \beta^*(Y_t - Y_{t-1}) - \beta^*\left[(Y_t - Y_{t-1}) - (Y_{t-1} - Y_{t-2})\right]\right] \tag{4.25}$$

Since $Y'_t = Y_t - Y_{t-1}$ (4.25) can be rewritten as:

$$Y_t = 1 + \alpha * \left[Y_{t-1} + \beta * Y'_t - \beta * \left[\left(Y'_t - Y'_{t-1}\right)\right]\right. \tag{4.26}$$

Distributing α and inserting the positive and negative version of $\alpha * Y_t$ into (4.26) yields:

$$Y_t = 1 + \alpha * Y_t - \alpha * Y_t + \alpha * Y_{t-1} + \alpha * \beta * Y'_t - \alpha * \beta * \left[\left(Y'_t - Y'_{t-1}\right)\right] \tag{4.27}$$

Since $Y''_t = Y'_t - Y'_{t-1}$ (4.27) can be rewritten as:

$$Y_t = 1 + \alpha * Y_t - \alpha * (Y_t - Y_{t-1}) + \alpha * \beta * Y'_t - \alpha * \beta * Y''_t \tag{4.28}$$

Solving (4.28) for Y'_t yields:

$$Y''_t = [1/(\alpha * \beta)] + [(\alpha - 1)/(\alpha * \beta)] * Y_t + [(\beta - 1)/\beta] * Y'_t \tag{4.29}$$

Utilizing the results from (4.21), (4.29) can be rewritten as:

$$d^2Y(t)/dt^2 = [1/(\alpha * \beta)] + [(\alpha - 1)/(\alpha * \beta)] * Y_t + [(\beta - 1)/\beta] * dY(t)/dt \tag{4.30}$$

In order to unpack (4.30) and represent it as two, coupled, first order ordinary differential equations, which is necessary to simulate the model in a system dynamics environment, define a new auxiliary variable X(t) as:

$$X(t) = dY(t)/dt \tag{4.31}$$

Therefore:

$$d^2Y(t)/dt^2 = dX(t)/dt \tag{4.32}$$

Recalling (4.2) from Samuelson's original model: $C_t = \alpha * Y_{t-1}$.
Inserting $Y_t - Y_t$ into (4.2) yields:

$$\begin{aligned} C_t &= \alpha * (Y_t - Y_t + Y_{t-1}) = \alpha * \left[Y_t - (Y_t - Y_{t-1})\right] \\ &= \alpha * \left[Y_t - Y'_t\right] = \alpha * [Y(t) - dY(t)/dt] = \alpha * [Y(t) - X(t)] \end{aligned} \tag{4.33}$$

Recalling (4.5) from Samuelson's original model: $I_t = \alpha * \beta * (Y_{t-1} - Y_{t-2})$.
Inserting $(Y_t - Y_{t-1}) - (Y_t - Y_{t-1})$ into (4.5) yields:

$$\begin{aligned} I_t &= \alpha * \beta * \left\{(Y_t - Y_{t-1}) - \left[(Y_t - Y_{t-1}) - (Y_{t-1} - Y_{t-2})\right]\right\} \\ &= \alpha * \beta * \left[Y'_t - \left(Y'_t - Y''_t\right)\right] \end{aligned} \tag{4.34}$$

Taking the limit as the time step approaches zero yields:

$$I_t = \alpha * \beta * \left(dY(t)/dt - d^2Y(t)/dt^2\right) = \alpha * \beta * (X(t) - dX(t)/dt) \tag{4.35}$$

Equations (4.33) and (4.35) can now be represented in a system dynamics environment.

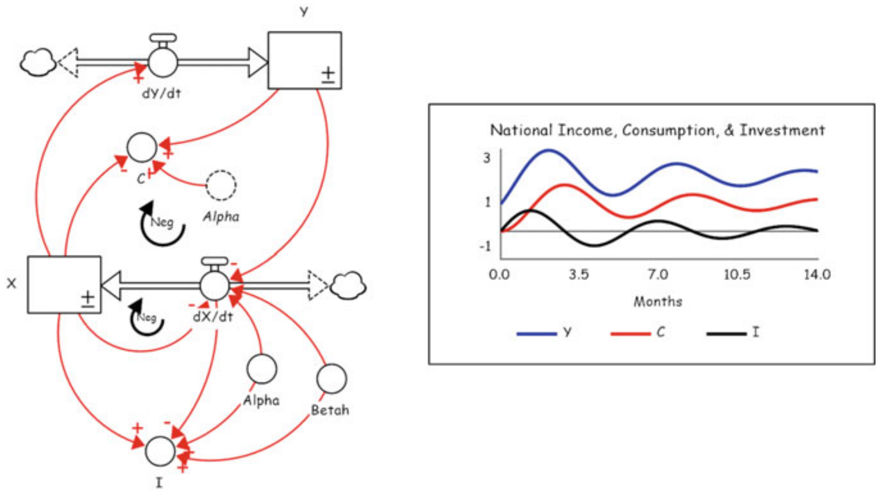

Fig. 4.3 Continuous time version of Samuelson's multiplier-accelerator model

Figure 4.3 presents the continuous time version of Samuelson's multiplier-accelerator model and can be directly compared to Fig. 4.1. Although the complete code can be examined in the appendix, several aspects of the model are worth noting. First the parameter values chosen for Alpha and Beta are 0.5 and 0.8 respectively. Although the value for Alpha is the same in both versions of the model, the values for Beta are different. Second, although both models exhibit an oscillatory time shape, the character of the time shapes is a bit different. More specifically, the phase relationships are the same in both models but the amplitude and timing of the peaks and troughs differ. Third, the need to recast the second order differential equation in terms of two first order ordinary differential equations requires the creation of an auxiliary variable X for which there is no precise economic interpretation. Thus, the continuous case is less transparent than the original.

To convert Allen's Cobweb model into its equivalent continuous time representation rewrite Eq. (4.15):

$$P_t = [\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})] + \left[2 * P_{t-1} - \boldsymbol{\lambda} * (a + b) * P_{t-1}\right] - P_{t-2} \tag{4.36}$$

Disaggregating P_{t-1} and rearranging yields:

$$P_t = \left[\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})\right] + P_{t-1} + (P_{t-1} - P_{t-2}) - \left[\boldsymbol{\lambda} * (a + b) * P_{t-1}\right] \tag{4.37}$$

Adding in the positive and negative versions of P_t, subtracting P_t from both sides, and rearranging yields:

$$\begin{aligned} 0 = [\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})] - \left[(P_t - P_{t-1}) + (P_{t-1} - P_{t-2})\right] \\ - \left[\boldsymbol{\lambda} * (a + b) * P_{t-1}\right] \end{aligned} \tag{4.38}$$

Recognizing that $\left[(P_t - P_{t-1}) + (P_{t-1} - P_{t-2})\right] = \left[P'_t - P'_{t-1}\right] = P''_t$ yields:

$$0 = [\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})] - P''_t - \left[\boldsymbol{\lambda} * (a + b) * P_{t-1}\right] \tag{4.39}$$

Solving for Pt”

$$P''_t = d^2P/dt^2 = [\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})] - \left[\boldsymbol{\lambda} * (a + b) * P_{t-1}\right] \tag{4.40}$$

Define the auxiliary variable:

$$X = dP/dt \tag{4.41}$$

which means that $d^2P/dt^2 = dX/dt$ and (4.40) can be rewritten as:

$$dX/dt = [\boldsymbol{\lambda} * (\boldsymbol{\alpha} - \boldsymbol{\beta})] - [\boldsymbol{\lambda} * (a + b) * P] \tag{4.42}$$

Equations (4.41) and (4.42) can now be simulated in a system dynamics modeling environment.

Figure 4.4 presents the continuous time version of Allen’s cobweb model and can be directly compared to Fig. 4.2. Although the complete code can be examined in the appendix, several aspects of the model are worth noting. First, for the same parameter values the models generate similar, but slightly different behavior. More specifically, the phase relationships and periodicity are very similar in both models, but the amplitude of the peaks and troughs differ somewhat. Second, as with the Samuelson model, the need to recast the second order differential equation in terms of two first order ordinary differential equations requires the creation of an auxiliary variable X for which there is no precise economic interpretation. Thus, the continuous case is again less transparent than the original.

4.8 Replicating Discrete Time Molecules from Behavioral Economics

In system dynamics modeling it is quite common to add a discrete time structure or molecule to an otherwise continuous model. For example, minimum and maximum functions, pipeline delays, ovens, conveyors, queues, and first order control flow structures that include the model’s time step in order to prevent the last entity leaving a stock from pushing the stock into negative territory, are routinely added to system dynamics models. In light of the openness in the modern system dynamics paradigm to adding discrete structures to otherwise continuous time models, a natural question to ask is whether or not it is possible and profitable to replicate discrete time structures from behavioral economics and integrate them into a system dynamics model. The answer is “yes” and three methods for discounting a future stream of benefits will

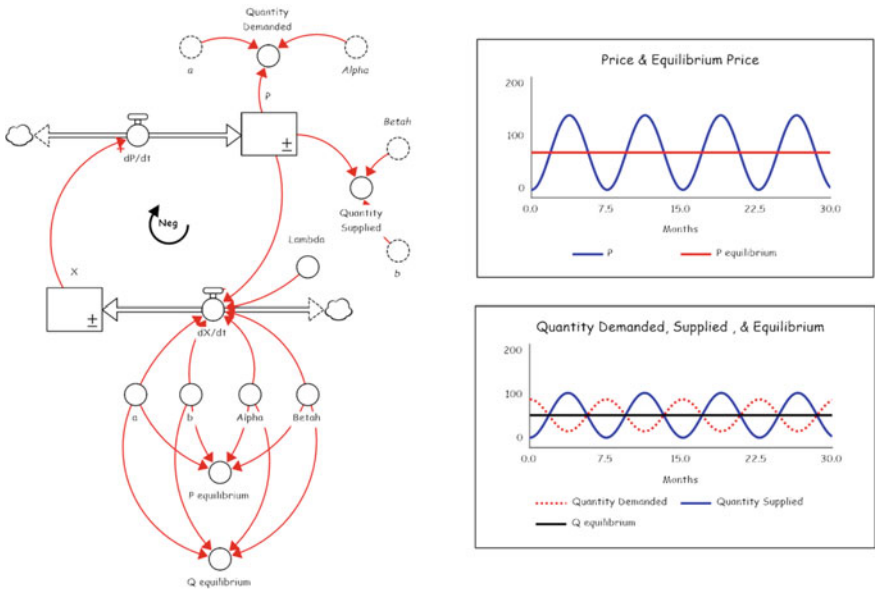

Fig. 4.4 Continuous time version of Allen's cobweb model

be used as examples: exponential discounting, quasi-hyperbolic discounting, and hyperbolic discounting.[41]

Discounting is a widely used technique in economics that is used to convert the value of something in the future to its value in the present. To discount a stream of benefits over time, a discount rate is applied to the value of each future benefit. Typically this means that the future value of something is deemed to be worth less than its present value due to factors such as the time value of money or human biases toward more immediate satisfaction.

A common use of discounting in economics is to apply a discount rate to a utility function so that a person derives less satisfaction from future consumption spending than s/he derives from consumption spending undertaken earlier. Following Rasmusen (2008):

$$U(t) = C(t) + f(t+1) * C(t+1) + f(t+2) * C(t+2) + f(t+3) * C(t+3) + \cdots \quad (4.43)$$

where the discount function is $f(t) < 1$ and f is declining over time.

One of the main issues when using discounting to model human decision makingis the form of the discounting function. Different functional forms imply different

[41] Angeletos et al. (2001) and Frederick et al. (2002) provide detailed overviews of the three discounting methods presented here.

human decision makingprocesses and laboratory experimentsare often used to shed light on the most realistic and useful structures.

The first and most traditional method for modeling discounting is exponential discounting, which assumes that people are rational and hence discount future rewards at a constant rate Unfortunately, laboratory experimentswith human subjects show that people do not generally employ this method of discounting in real life situations.

From (4.43), the general form for exponential discounting is:

$$U_0 = C_0 + (\boldsymbol{\delta} * C_1) + (\boldsymbol{\delta}^2 * C_2) + \left(\boldsymbol{\delta}^3 * C_3\right) + \cdots \tag{4.44}$$

The parameter $\boldsymbol{\delta}$ $\{\boldsymbol{\delta} <= 1\}$ is called the standard discount factor and represents long-run and time-consistent discounting.

A second method for modeling discounting is quasi-hyperbolic discounting, which assumes that people use two different discounting rates: a "present biased" rate for short-term rewards and a "future biased" rate for long-term rewards. The present biased rate reflects the higher value people place on instant gratification, while the future biased rate reflects a greater willingness of people to delay their gratification in order to receive larger rewards later. Laboratory experimentshave shown that, generally speaking, people tend to prefer smaller rewards that are available immediately over larger rewards that are available at some point in the future. However, as the delay between the decision and the reward increases, people tend to become more patient and shift their discounting to the future biased rate. Quasi-hyperbolic discountinghas been used to explain a wide range of phenomena such as procrastination, addiction, and saving behavior.

From (4.43), the general form for quasi-hyperbolic discountingis:

$$U_0 = C_0 + (\boldsymbol{\beta} * \boldsymbol{\delta} * C_1) + \left(\boldsymbol{\beta} * \boldsymbol{\delta}^2 * C_2\right) + \left(\boldsymbol{\beta} * \boldsymbol{\delta}^3 * C_3\right) + \cdots \tag{4.45}$$

As before, the parameter δ is called the standard discount factor representing long-run and time-consistent discounting, whereas the parameter β is called the present bias factor and represents short-term impatience and time inconsistency discounting. When the beta factor is equal to 1, quasi-hyperbolic discountingdefaults to exponential discounting.

A third method for modeling discounting is hyperbolic discounting which, according to Rasmusen (2008, p. 3), has the unique property of using "relativistic time" (i.e., "the distance in time from the present"), rather than "absolute time" (i.e., " the date"). Again, according to Rasmusen (2008, p. 4):

> Hyperbolic discounting is a useful idea for two reasons. First, it can explain revealed preferences that are inconsistent with exponential discounting. Second … it can explain certain observed behaviors such as people's commitments to future actions when other explanations such as strategic positioning fail to apply, e. g., a person's joining a bank's saving plan which penalizes him for failing to persist in his saving.

From (4.43), the general form for hyperbolic discounting is:

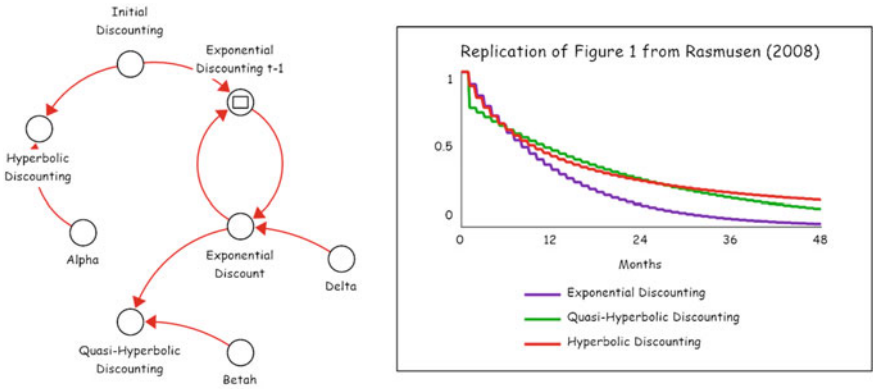

Fig. 4.5 Replication of exponential, quasi-hyperbolic, and hyperbolic discounting from Rasmusen

$$
\begin{aligned}
U_0 = C_0 &+ \{[1/(1+\alpha)] * C_1\} + \{[1/(1+2*\alpha)] * C_2\} \\
&+ \{[1/(1+3*\alpha)] * C_3\} + \cdots
\end{aligned}
\tag{4.46}
$$

where α is a parameter governing the degree of discounting such as a relevant rate of interest.[42]

Figure 4.5 reproduces (4.43), (4.45), and (4.46) in a system dynamics modeling environment. The figure was created using the second discretization technique described above and all of the equations used to produce the figure are contained in the appendix. The graph in the figure reproduces a time series plot from Rasmusen (2008, p. 7).

4.9 Converting Discrete Time Molecules into Their Continuous Time Counterparts

Analogous to converting complete difference equation models into their equivalent differential equation representations, it is possible to convert discrete time decision makingstructures or molecules into their equivalent continuous time representations with a minimal loss of fidelity.

Figure 4.6 presents the equivalent continuous time representation of the three discounting methods from Fig. 4.5. As before, the complete set of equations is contained in the appendix. Of note is that the three discounting methods are quite

[42] As noted by Rasmusen (2008, p. 8), Harvey (1986) and Loewenstein and Prelec (1992) propose a more general form for hyperbolic discounting.

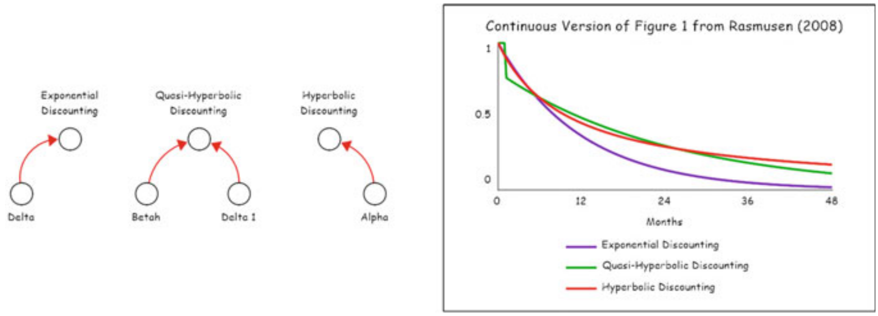

Fig. 4.6 Continuous time version of exponential, quasi-hyperbolic, and hyperbolic discounting from Rasmusen

simple and easy to replicate in a system dynamics modeling environment.[43] Moreover, the continuous time versions of the discounting methods are strikingly similar to their discrete time counterparts.

4.10 Summary and a Path Forward

The preceding discussion can be summarized in the following way. Bringing laboratory tested structures from behavioral and experimental economics into continuous time modeling is an important way to advance the field of system dynamics. In order to do this properly, however, candidate structures must first be faithfully replicated before they are introduced into models, and this typically requires the simulation of discrete time structures in a continuous time system dynamics modeling environment.

Although techniques for simulating discrete time models in system dynamics environments have been developed over the years, their use has been somewhat limited and can be confusing to newcomers to the field. This is due to the fact that the algorithms that are used to solve system dynamics models involve various forms of discrete time difference equations. This muddies the waters as to the fundamental nature of system dynamics modeling, and raises the question as to how it might be possible to model purely discrete time models in a system dynamics environment. This chapter has attempted to shed light on this area by laying out the details of continuous time simulation on a digital computer and presenting techniques for replicating both complete discrete time difference equation models, as well as limited discrete time modeling molecules, in a continuous time system dynamics environment.

This chapter also addressed a natural question that arises when simulating discrete time structures in a continuous time modeling environment: Is it possible to do everything in a continuous time framework? The answer is "yes," and a technique

[43] Bah (2023), however, shows how it is possible to convert the discrete time version of quasi-hyperbolic discounting from (4.45) into its equivalent continuous time representation using the technique presented earlier in this chapter.

for converting from the discrete world to the continuous world was presented. The results of the conversions, however, were a bit disappointing as the continuous time versions of the difference equation models were similar but different, and less than completely transparent. Of note is that this result is consistent with the classic findings of both Allen (1956) and Baumol (1951). The good news is that the discrete time versions of the three discounting methods from behavioral economics were both completely replicable and strikingly similar to their continuous time counterparts.

The answers to questions 5–7 above in some sense define a path forward for integrating behavioral economics into system dynamics. Although converting a pure difference equation model into its equivalent differential equation format is probably not a good use of a modeler's time, the results are different in the case of discrete time *molecules* from behavioral economics. Both the discrete and continuous cases can be represented in a system dynamics modeling environment in a straightforward manner and yield the same results. The question then becomes, when does it make sense to utilize each representation of humandecision making? The answer is that, generally speaking, it probably doesn't matter very much and that if the rest of a model is represented in continuous time a behavioral molecule should probably be represented in the same manner. The exception to this claim was originally suggested by Laibson (1997, p. 468) who noted that a continuous time representation of consumer spending in his golden eggs model would stop the complete exhaustion of liquidity at each time step, which is more in line with reality. Details matter, and in these sorts of situations the ability to represent behavioral formulations in either discrete or continuous time is clearly an advantage.

More broadly, the general debate over when to use discrete versus continuous time modeling has existed since at least the early 1960s. Lane and Routwette (2023) argue that discrete time modeling is more appropriate for examining problems at the operational and tactical levels, whereas continuous time modeling is best used to investigate strategic, "big picture," issues. Beyond this very general statement, however, is a specific situation in which it may well be preferable to represent an entire system dynamics model, behavioral formulations and all, in a discrete manner: gaming. Indeed, in system dynamics it is very common to take an insightful model and turn it into an engaging and user-friendly game that can be played by those who did not build the model but stand to benefit from the insights it can generate. In cases such as this an entirely discrete version of a system dynamics model may very well be the preferred format for a game. Moreover, this possibility leads directly to the area of experimental economics, as human subjects can be asked to play a system dynamics game, within which their decisions can be recorded and analyzed so that behavioral formulations can be validated and additional insight into human decision makingcan be generated.

Finally, system dynamics modelers do not operate in a vacuum. Rather they use principles of systems, as well as generic structures, to guide them when confronted with a new modeling problem.[44] To the extent that a catalog of faithfully replicated molecules from behavioral economics can be assembled and made available to

[44] See the discussion in Radzicki (2021b).

the system dynamics community, a richer and more insightful collection of system dynamics models can be built to address the seemingly endless array of modern socioeconomic problems.

Appendix

System Dynamics Equations for Samuelson's Multiplier-Accelerator Model

```
Yt1(t) = Yt1(t - dt) + (Chg_Yt1) * dt, ~ Dollar/Year INIT Yt1 = 0, ~
Dollar / Year
Yt2(t) = Yt2(t - dt) + (Chg_Yt2) * dt, ~ Dollar/Year INIT Yt2 = Yt1,
~ Dollar/Year
Chg_Yt1 = IF TIME = INT( TIME ) THEN ( Yt - Yt1 ) / DT ELSE 0, ~ Dollar/
(Year*Year) Chg_Yt2 = IF TIME = INT( TIME ) THEN ( "Yt-1" - Yt2 ) / DT
ELSE 0, ~ Dollar/(Year*Year)
Alpha = .5, ~ Dimensionless
Betah = 1, ~ Dimensionless
Ct = Alpha * "Yt-1" gt = 1, ~ Dollar/Year
It = Alpha * Betah * ( "Yt-1" - "Yt-2" ), ~ Dollar/Year
Lagged_Yt1 = DELAY( Yt1 , 1 , Yt1 ), ~ Dollar/Year
Lagged_Yt2 = DELAY( Yt2 , 1 , Yt2 ), ~ Dollar/Year
Yt = Ct + It + gt, ~ Dollar/Year
"Yt-1" = IF TIME = INT( TIME ) THEN Yt1 ELSE Lagged_Yt1, ~ Dollar/Year
"Yt-2" = IF TIME = INT( TIME ) THEN Yt2 ELSE Lagged_Yt2, ~ Dollar/Year
Time Step = .1 ~ Year
```

System Dynamics Equations for Allen's Cobweb Model

```
Pt1(t) = Pt1(t - dt) + (Chg_Pt1) * dt, ~ Dollar INIT Pt1 = 15, ~
Dollars
Pt2(t) = Pt2(t - dt) + (Chg_Pt2) * dt, ~ Dollar INIT Pt2 = Pt1, ~
Dollars
Chg_Pt1 = IF TIME = INT( TIME ) THEN ( Pt - Pt1 ) / DT ELSE 0, ~ Dollars/
Year
Chg_Pt2 = IF TIME = INT( TIME ) THEN ( "Pt-1" -Pt2 ) / DT ELSE 0 a =
.5, ~ Dollars/Year
Alpha = 100, ~ Widgets
b = .7, ~ Dimensionless
Betah = 10, ~ Dollar
Lagged_Pt1 = DELAY( Pt1 , 1 , Pt1 ), ~ Dollars
Lagged_Pt2 = DELAY( Pt2 , 1 , Pt2 ), ~ Dollars
Lambda = .5, ~ Dimensionless
P_equilibrium = ( Alpha - Betah ) / ( a + b ), ~ Dollars
Pt = ( Lambda * ( Alpha - Betah ) ) + ( ( 2 - ( Lambda * ( a + b ) ) ) *
"Pt-1" ) - "Pt-2", ~ Dollars
"Pt-1" = IF TIME = INT( TIME ) THEN Pt1 ELSE Lagged_Pt1, ~ Dollars
"Pt-2" = IF TIME = INT( TIME ) THEN Pt2 ELSE Lagged_Pt2, ~ Dollars
Q_equilibrium = ( ( b * Alpha ) + ( a * Betah ) ) / ( a + b ), ~ Widgets
Quantity_Demanded = Alpha - a * Pt, ~ Widgets
```

```
Quantity_Supplied = Betah + b * Pt, ~ Widgets
Time Step = .1, ~ Years
```

System Dynamics Equations for the Continuous Time Version of Samuelson's Multiplier-Accelerator Model

```
X(t) = X(t - dt) + ("dX/dt") * dt, ~ Dollar/Year INIT X = 1, ~ Dollars/
Year
Y(t) = Y(t - dt) + ("dY/dt") * dt, ~ Dollar/Year INIT Y = 1, ~ Dollars/
Year
"dX/dt" = ( 1 / ( Alpha * Betah ) ) + ( (Alpha - 1 ) / (Alpha * Betah )
) * Y + ( 1 - ( 1 / Betah ) ) * X, ~ Dollars/(Year*Year)
"dY/dt" = X, ~ Dollar/(Year*Year) Alpha = .5, ~ Dimensionless
Betah = .8, ~ Dimensionless
C = Alpha * ( Y - X ), ~ Dollars/Year
I = Alpha * Betah * ( X - "dX/dt" ), ~ Dollars/Year
Time Step = .1, ~ Years
```

System Dynamics Equations for the Continuous Time Version of Allen's Cobweb Model

```
P(t) = P(t - dt) + ("dP/dt") * dt, ~ Dollar/Year INIT P = 13.2, ~
Dollars/Year
X(t) = X(t - dt) + ("dX/dt") * dt , ~ Dollar/Year INIT X = 0
"dP/dt" = X
"dX/dt" = Lambda * ( Alpha - Betah ) - ( Lambda * ( a + b ) * P ) a = .5,
~ Dimensionless
Alpha = 100, ~ Dollars
b = .7, ~ Dimensionless
Betah = 10, ~ Dollars
Lambda = .57, ~ Dollars
P_equilibrium = ( Alpha - Betah ) / ( a + b ), ~ Dollars
Q_equilibrium = ( ( b * Alpha ) + ( a * Betah ) ) / ( a + b ), ~ Widgets
Quantity_Demanded = Alpha - a * P, ~ Widgets
Quantity_Supplied = Betah + b * P, ~ Widgets
Time Step = .1, ~ Years
```

System Dynamics Equations for the Discrete Versions of Exponential, Quasi-Hyperbolic, and Hyperbolic Discounting

```
Alpha = .1, ~ Dimensionless
Betah = .8, ~ Dimensionless
Delta = .96, ~ Dimensionless
Delta_1 = .92, ~ Dimensionless
Exponential_Discount = IF TIME <= STARTTIME + 1 THEN 1 ELSE Delta *
"Exponential_Discounting_t-1", ~ Dimensionless
"Exponential_Discount_t-1_1" = DELAY( Exponential_Discounting , 1
, Initial_Discounting ), ~ Dimensionless
Exponential_Discounting = IF TIME <= STARTTIME + 1 THEN 1 ELSE
Delta_1 * "Exponential_Discount_t-1_1", ~ Dimensionless
"Exponential_Discounting_t-1" = DELAY( Exponential_Discount , 1 ,
Initial_Discounting ) ~ Dimensionless
```

```
Hyperbolic_Discounting = IF TIME <= STARTTIME + 1 THEN 1 ELSE
Initial_Discounting * ( 1 / ( 1 + Alpha * INT( TIME ) ) ) ~ Dimen-
sionless
Initial_Discounting = 1
"Quasi-Hyperbolic_Discounting" = IF TIME <= STARTTIME + 1 THEN 1
ELSE Betah * Exponential_Discount ~ Dimensionless
Time Step = .1 ~ Months
```

System Dynamics Equations for the Continuous Versions of Exponential, Quasi-Hyperbolic, and Hyperbolic Discounting

```
Alpha = .1 ~ Dimensionless
Betah = .8 ~ Dimensionless
Delta = .92 ~ Dimensionless
Delta_1 = .96 ~ Dimensionless
Exponential_Discounting = Delta ^ TIME
Hyperbolic_Discounting = 1 / ( 1 + Alpha * TIME ) ~ Dimensionless
"Quasi-Hyperbolic_Discounting" = IF TIME <= STARTTIME + 1 THEN 1
ELSE Betah * Delta_1 ^ TIME ~ Dimensionless
Time Step = .1 ~ Months
```

References

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Chapter 5
From Value Networks to Causal Loop Diagrams: Strategic Preparation for Designing Systemic Interventions in Organizations

Fabian H. Szulanski and Hassan Qudrat-Ullah

Abstract The subject matter of this chapter introduces a novel way to navigate between two different conceptual worlds: that of value networks and that of causal loop diagrams. It answers the question of how to connect the world of interdependent value flows to the world of interdependent causal relationships between variables. A pragmatic methodology is presented to the strategic management community for the first time. Some examples will be shared. This is an advancement compared to what was common practice: additive analyses of value networks and causal loop diagrams, with separate sensemaking efforts, without an integrative stance. This methodology will offer strategic management practitioners and researchers a way of setting the stage for designing a systemic intervention through modification of system structure's causal loop diagrams, when the only available information is a diagnostic of a value network, and derived from it, thus offering an opportunity for an increase in strategic management academic and professional writings.

Keywords Methodology · Methodological innovation · Concept blending · Mapping · Value networks · Resource flows · Value generation · System dynamics · Information feedback · Causal feedback loops · Reference mode · Dynamic hypothesis · Sensemaking · Problem identification · Decision making

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5.1 Introduction

"A value network can be defined as "any purposeful group of people or organizations creating social and economic good through complex dynamic exchanges of tangible and intangible value"" (Allee, 2009).

A minimal expression of a value network can be seen in Fig. 5.1.

We prefer offering this alternative definition: A value network is a system in which two or more actors, playing different roles, create emergent value through mutually exchanged resource flows. In a certain way, there is a great similarity between the definition of a value network and the definition of a system. A value network is a system whose purpose is value generation. Mapping and analyzing a value network is a way of making sense about value generation in any given socio-technical system. A value network can also serve as a diagnostic, a transformation tool; and as a social object, the latter meaning that it can trigger generative conversations.

5.1.1 Some Characteristics of a Value Network

The resources that flow between roles can be tangible or intangible. Note: formal information flows are considered tangible. Examples of tangible flows that could be given are: products, services, resources, written documents, audios and videos. Examples of intangible flows that could be given are: trust, influence, pressure and care. The value network maps all resource flows- formal and informal- that are exchanged between the most relevant actors in a system, which collectively contribute to emergent value generation. When trying to analyze a value network, a resource

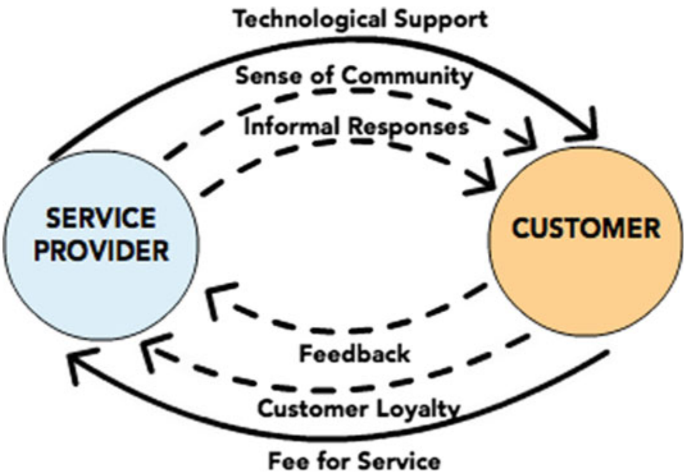

Fig. 5.1 Adapted from (Allee, 2002a)

flow cannot be assimilated to a variable. Each resource flow can be assimilated as a container of attributes and values. An attribute is a tangible dimension of a resource flow, while a value is an intangible one.

5.1.2 Some Examples of Resource Flow Attributes and Values

Resource: Product (tangible): Attributes: Quantity. Manufacturing errors per million units. Delivery delay. Values: Perceived quality. Perceived delivery delay. Perceived manufacturing accountability.

Resource: Support (intangible). Attributes: Quantity of positive mentions in internal communication platforms. Frequency of positive mentions. Values: Perceived Authenticity, Perceived Political Power.

Paraphrasing (Allee, 2009), a value network without enough informal flows is very rigid, reflecting an organization that may not be resilient when facing a complex challenges. it is important for a value network to include a balanced quantity of formal and informal flows. It is well known that informal networks are the ones that actually move organizations forward and help fulfill their purpose. As a value network includes mapping informal resource flows, then it reflects reality more faithfully than just mapping formal roles and resource flows.

5.1.3 Value Generation in a Value Network

Value creation indicators show the capacity for each role to generate both tangible and intangible value. Perceived value (brand) assesses the level of value roles feel they receive from individual deliverables, from other roles, and from the network as a whole. Asset impact indicators are used to consider which assets are most affected by the network behavior as a whole and by the actions of specific roles. Reciprocity indicators, such as mutual support, can point to a more hierarchical structure or show instability.

Structural dependency: role centrality. In Value Network Analysis, high centrality for a role may actually be a risk factor for the network. Certain role clustering may offer similar risks, configurating internal self-interested alliances Agility depends on how quickly information can move around the network and how easy it is for any individual to reach the person who might be able to solve a specific problem. Stability is revealed by measures of network density, the overall connectedness of the network.

5.2 Value Network Analysis

In (Allee, 2002b), it is said that there are three dimensions of value network analysis:

"Exchange Analysis-What is the overall pattern of exchanges in the system?

Impact Analysis-What impact does each value transaction have on the Participants involved?

Value Creation Analysis-What is the best way to create, extend, and leverage value, either through adding value, extending value to other Participants, or converting one type of value to another?".

Value creation indicators show the capacity for each role to generate tangible and intangible value.

Note from authors: Offered value is not the same as Perceived value. Perceived value assesses the level of value that the different roles feel they receive from individual deliverables, from other roles, and from the network as a whole. Asset impact indicators are used to consider which assets are most affected by the network behavior as a whole and by the actions of specific roles. Reciprocity indicators can point to a hierarchical structure or show instability.

5.2.1 Value Network Structural Characteristics

Structural dependency and risk indicators include role centrality. In Value Network Analysis, high centrality for any one role may actually be a risk factor for the network—or certain patterns of clustering may serve the overall value creation dynamics in unique ways.

Structure and value relationships are revealed by incoming and outgoing deliverables for each role. Note from authors: An analyst may map an exposure-influence matrix for identifying the most affected or influential roles in a value network. How agile a value network is depends on how fast information can move around the network and how easy it is for any individual to reach the person who might be able to solve a specific problem.

Note from authors: Thus the importance of mapping informal roles and resource flows. How stable a value network can be is revealed by measuring its resource flow density. The more dense the resource flow network is in its informal flow quantity, the more stable the value network could be.

5.3 Problem Definition in a Value Network

In a value network, for identifying a challenge, analysts may:

Identify what the most critical roles are, for example, by observing what are the roles that receive the higher quantity of tangible and intangible resources, making them potentially unstable. Identify which are the crucial resource flows, those that necessarily have to be preserved and help them delivering value in optimal conditions. Identify which are potentially the most problematic flows when performing the analysis. Analysts may elaborate a short report where they share the narrative that develops on the context, situations and reasons for them having chosen those sets of roles and flows as challenging or problematic. After this analysis phase, the analysts may design a network level intervention.

5.4 Network Level Interventions

In a value network, there are few ways of intervening in order to increase value generation or decrease value destruction. Specifically, adding or removing a role, or adding or removing resource flows. Those interventions are generally designed as a team effort, with diverse enough members to guarantee diversity in perspectives.

As per the above, interventions in a value network are qualitative, and the expected attribute or value behavior are collectively defined but in a qualitative way, as a value network doesn't include attribute and value mapping, but just roles and resource flows. In (Allee, 2009) an example of a value network intervention at The Boeing Company is shown in detail, as part of their initiative of becoming a complex adaptive system organization. Note from authors: We couldn't find a photography in which Boeing engineers are looking at two diagrams, one of them showing a value network and the other showing a stock and flow diagram, reflecting they were analyzing a certain value creation system from two separate perspectives, built in separate efforts. It was this photography that triggered the curiosity in us and the inquiry about the possibility of connecting value networks to system dynamics modeling.

5.5 Revealing the Magician Trick

How to connect the worlds of value flows to causal relationships? That seems to be a very difficult challenge. However, like in a magician kit, there exists a way of navigating from the former to the latter. What's the trick?

We have already developed, in this chapter, on problem definitions within the value network world. A problem, in the value network world, is a set of crucial or problematic resource flows. However, how can that problem be operationalized?

We have also developed about the notion of resource flow attributes and values, which translate into tangible and intangible variables. If the inquiry lead to asking how is the historic or desired behavior over time of the attributes and values of the problematic or crucial resource flows, what could be derived is a set of behavior over time graphs that collectively constitute the challenge. Here follows a crucial question that will lead towards reveling the magician trick: *Where else does this same set of behavior over time graphs reflect a challenge?*

It is in the world of causal relationships, stocks, flows and delays. It is in the system dynamics world. How is this set of behavior over time graphs that constitute a problem called in the system dynamics world? It is called reference mode, term coined by Professor Dr. Jorgen Randers (Randers, 1973), and notably mentioned by Prof Dr. Khalid Saeed (Saeed, 1992).

What can the analyst do with a validated reference mode when operating inside the system dynamics world? Among other actions, she can derive a speculative minimum set of causal feedback loop diagrams with the capacity of generating the reference mode behavior. That is called Dynamic Hypothesis, a term that has been also coined by Prof Dr. Jorgen Randers (Randers, 1973).

Why speculative? Because the derivation isn't univocal, ambiguity is always present (Mashayekhi & Ghili, 2010), implying there might exist many different sets of causal feedback loop diagrams with the aforementioned capacity. And the magic trick has been revealed. From a value network, to a reference mode, to a dynamic hypothesis. From the world of roles and resource flows to the world of causal feedback loops, stocks, flows and delays. From arrows meaning resource flows, to arrows meaning feedback relationships.

5.6 A Small Illustrative Example

5.6.1 The Network Itself

The value network that has been chosen is a Business to Business to Consumer value generation network for a physical product company, and it's mapped in Fig. 5.2.

The chosen roles are the minimum possible, for depicting the main resource flows. Economic resource manager hasn't been included for simplification of the resulting diagram. The critical flows have been identified and signaled by thicker arrows.

5.6.2 The Map's Narrative

The three crucial and potentially critical resource flows that have been identified are:

Raw materials that the Supplier to Manufacturer provides to the Product Manufacturer.

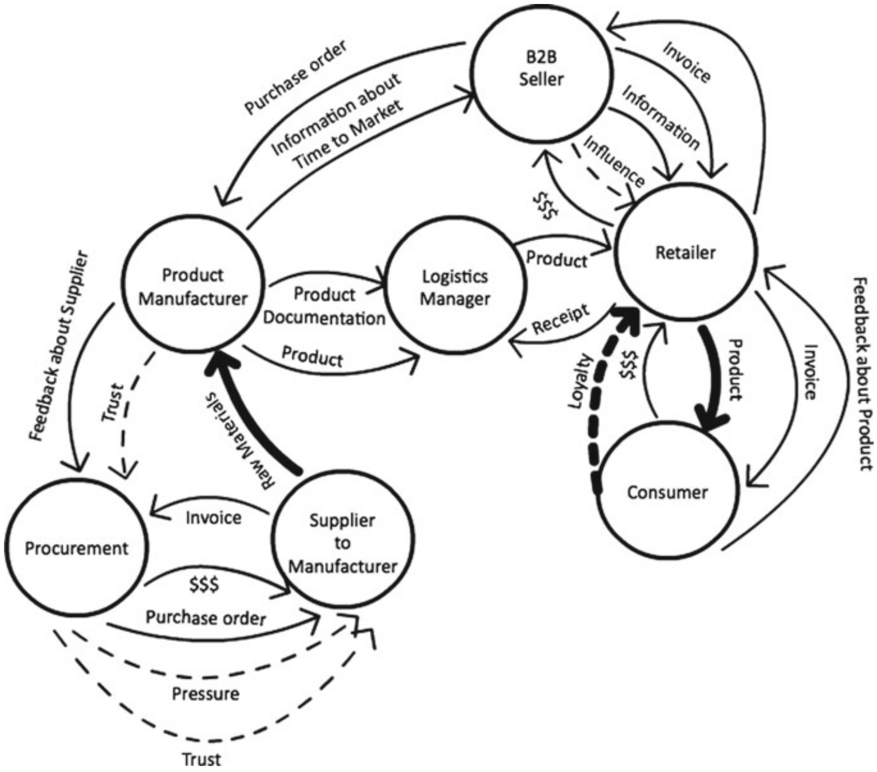

Fig. 5.2 A value network of a manufacturing company B2B2C business

Consumer Loyalty towards the product brand, whose experiential touchpoint is the Retailer.

The product that the Consumer buys from the Retailer.

A small narrative that could relate the three resource flows, zooming into them for identifying attributes and values that could be working non satisfactorily might be:

Supplier to Manufacturer has been economically impacted during the pandemics, which decreased their possibility of timely delivery of the raw materials to the Product Manufacturer. Therefore, after navigating through the supply network, the company's product has been arriving lately with an increasing delivery delay to the Retailer, resenting repeating Consumer loyalty over time.

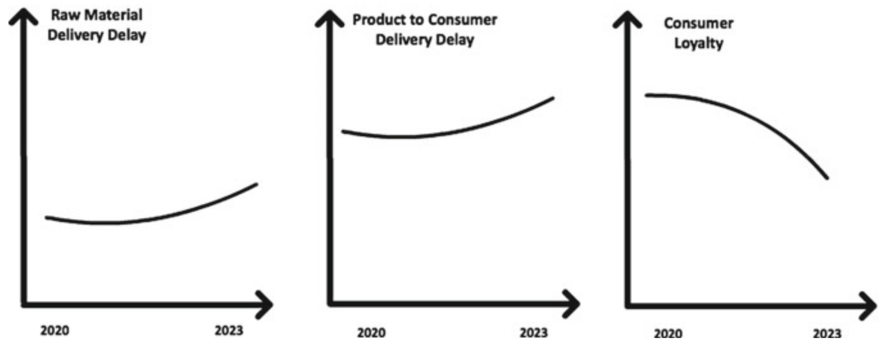

Fig. 5.3 Reference mode

5.6.3 How to Visually Translate This Small Narrative?

Starting from left to right, the first two diagrams of the reference mode show variables that are exponentially increasing their magnitude, while the third one shows an exponentially decreasing magnitude of the related variable. Structure drives behavior, that is one of the principles of system dynamics. (Forrester, 1961), (Richardson, 1991). A simple causal feedback loop structure consisting in a single reinforcing casual feedback loop is capable of generating exponential behavior of the related variable. It can have two types of exponential behavior: Exponential increase, or exponential decrease. Having said this, in all cases of this story, each of those variables should be part of reinforcing causal feedback loops.

5.6.4 Dynamic Hypothesis of the Narrative

What follows is an attempt of mapping a set of three causal loops, the dynamic hypothesis of this story, which adds Product demand as an intermediate variable that helps telling the story.

5.6.4.1 Structural Validation of the Causal Model

Before describing how this Dynamic Hypothesis has the capacity of driving the Reference Mode, the Dynamic Hypothesis' causal model will be structurally validated.

As this book chapter didn't include mapping nor specification of a stock and flow system dynamics model; and neither did it include any data set, we will apply just the Boundary Adequacy structural validation test from the five available structural validation tests mentioned in (Qudrat-Ullah & BaekSeo, 2010).

5.6.4.2 Boundary Adequacy Structural Validation Test

Consistent with the purpose of this book chapter Dynamic Hypothesis section, which is illustrating a possible Dynamic Hypothesis helping to make the point of the whole Book Chapter, with it being traveling the journey from value networks to causal feedback loop diagrams, and assuming that ambiguity in causal relationships in complex contexts allow for more than one dynamic hypothesis to be chosen as capable of driving the given reference mode behavior, all major aggregate variables, raw material production, logistics, commerce, customer satisfaction, and demand have been included, therefore the Dynamic Hypothesis, passing the Boundary Adequacy structural validation test. The only exogenous variable (Level of macroeconomic prosperity), whose decrease triggers all the endogenous causal feedback structure driving a vicious behavior, wasn't included for simplicity purposes, and made implicit.

5.6.4.3 Explanation of Dynamic Hypothesis Causal Feedback Loops

Loop R1 shows the profitability erosion of Raw Material Supplier, which decreases Production Capacity, Resulting in an increase in their throughput, feeding back in their profitability again.

Loop R2 shows an additional impact of Raw Material Supplier profitability erosion, carrying the delivery delay towards the end of product manufacturing, increasing Retailer's product delivery delay to the customer. This feeds back into supplier's profitability, as raw material orders start to decrease their frequency over time, extending their time to profit.

Loop R3 reflects the impact of Product delivery delay to the customer, on her loyalty to the product's brand, eroding Product demand and feeding back into Raw material supplier profitability.

For the sake of simplicity, with the purpose of not adding more variables nor additional causal feedback loops to the Dynamic Hypothesis, some explanatory variables such as Raw Material Demand, Retailer's profitability, and their interdependent relationships with the existing variables have not been included.

5.7 Discussion

5.7.1 Relationship Between the Example's Dynamic Hypothesis and Reference Mode

All three loops, R1, R2 and R3 are reinforcing causal feedback loops. All of them drive a vicious reference mode, meaning that the depicted situation that evolves in such a way that becomes worse for the three dependent variables that were chosen to be included.

In the case of loops R1 and R2, that decay looks like an exponential increase, while in loop R2 the worsening situation looks like an exponential decrease.

5.7.2 Sensemaking, Problem Definition, Decision Making and Systemic Interventions

Some professionals confuse their selves with the tools they use. This is true in the case of network analysis in general (which includes social and organizational networks, and value networks), and in other domains as well. Systems thinkers usually prefer using tools from the systems thinking toolkit. But up till now, it has not been identified a methodological bridge between this two worlds.

Stepping on the two worlds, not in a decoupled way but in an interrelated way, allows the analyst to gain insights from both worlds, with increased methodological rigor.

5.8 Conclusion

We have shared a methodological innovation that blends the worlds of value networks and system dynamics, with the purpose of leveraging sensemaking, decision making and systemic intervention design in organizational settings when facing complex challenges.

Through a short example, it was shown how the journey from one world to the other is possible. As our dynamic hypothesis (Fig. 5.4) depicts, and after our explanation, it was made evident that it is capable of driving the Reference Mode behavior. As the Dynamic Hypothesis is solely composed by vicious reinforcing causal feedback loops, it is important to add one or more balancing causal feedback loops to reverse the erosive situation, and restore profitability of both raw material supplier and retailer; while increasing customer loyalty.

We have chosen stopping the description of their methodological innovation at this point of the article, as they consider having shared enough essence and substance of an elegant way of connecting the worlds of different arrows: those depicting resource flows to those depicting causal feedback relationships.

They expect the managerial community to take note and apply this novel connection to high meaning and value complex challenges, enriching and leveraging the sensemaking effort in a more rigorous way.

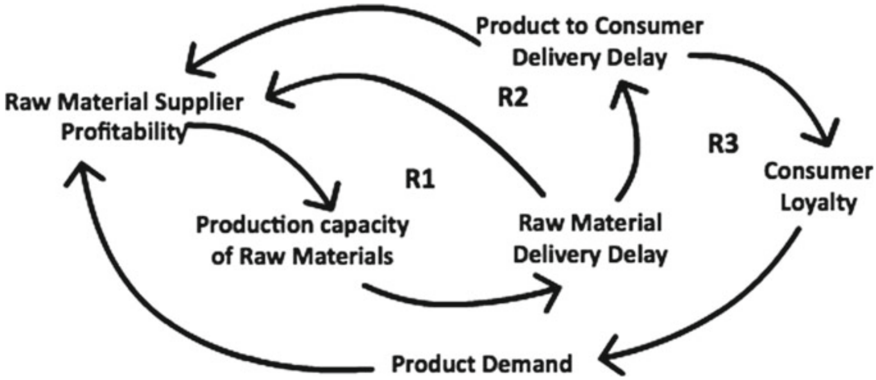

Fig. 5.4 Dynamic hypothesis of the simple example

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Part III
Applications of Systems Thinking in Education

Chapter 6
Learning Analytics and Interactive Multimedia Experience in Enhancing Student Learning Experience: A Systemic Approach

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Abstract Learning Analytics (LA) is a feedback loop process that generates data based on learning activities defined by teachers. These data are then stored, adapted, reviewed, and cleaned to derive recommendations to improve the learning experience in an endless cycle. LA has been integrated into user-experience-oriented multimedia systems, and the design of Interactive Multimedia Experiences (IME) can include LA to enhance the learning experience and collect data. However, the efficacy of LA in improving students' learning experiences remains uncertain with mixed findings from various studies. Therefore, further research is required to evaluate the effects of LA tools on student retention. It is also crucial to consider the correlation between multimedia elements and performance, including the quantity and quality of multimedia features and how they interact with learners' needs and abilities. It is essential to investigate the effectiveness of multimedia elements in engaging users and their impact on learning outcomes. This chapter proposes the identification of critical feedback loops that connect the LA process with IME in multimedia projects. The goal was to develop a dynamic hypothesis explaining how the learning experience relates to user experience and teacher enthusiasm. Researchers and teachers will collaborate to identify reference modes, variables, and feedback loops that connect the Learning Experience with the User Experience. By doing so, we can better understand and improve students' learning experiences by effectively using LA tools and multimedia elements in IME.

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6.1 Introduction

6.1.1 What Do Learning Analytics (LA) and Interactive Multimedia Experience (IME) Mean?

Learning Analytics (LA) offers a promising approach to enhancing the learning experience by providing insights into learning activities and learner progress. However, their effectiveness may be limited when used alone. Decision-making and feedback approaches can complement learning analytics to improve the learning process. In this chapter, we explore the potential impact of dynamic complexity on decision-making and how it can be leveraged to enhance the learning experience by integrating learning analytics and feedback approaches. By reviewing the literature on learning analytics, decision-making, and feedback, we provide insights into the benefits of combining these elements and how they can effectively enhance the learning experience using participatory systems modeling.

LA is a data-generative approach to improving educational outcomes through informed decision-making (Yanyan, 2021). LA has been used to monitor teacher behaviors and support teacher professional development, and it has also been integrated into educational platforms to create adaptive and personalized learning experiences (Vesin et al., 2018). However, privacy concerns have been identified as a significant obstacle to adopting LA (Mutimukwe et al., 2022).

LA tools can address practical classroom orchestration challenges such as managing, adapting, scaffolding, and assessing learning activities (Mavrikis et al., 2019). In addition, these tools can also enhance teaching and learning environments by offering real-time opinions and recommendations through LA panels and visualization systems (Silva et al., 2021). Nonetheless, it is essential to use LA in a user-centered and ethical manner and to address privacy concerns (Yanyan, 2021; Mutimukwe et al., 2022; Ramaswami et al., 2022).

A multimedia system allows for value creation for interested parties by deploying an Interactive Multimedia Experience (IME) using an ethical and responsible design approach. Besides, a multimedia system addresses the users' needs, interests, and expectations by influencing their human senses via storytelling using digital media resources (Peláez et al., 2021). Therefore, the IME is considered a key element in designing a multimedia system through which value is delivered to its stakeholders (Peláez et al., 2021).

IME has positively affected student learning outcomes and motivation (Budiarto & Jazuli, 2021). IME can facilitate students' understanding of concepts and learning materials, and LA can provide insights into student performance and engagement, enabling personalized and targeted interventions (Martinez-Maldonado et al., 2016). Using multimedia components in eConsent can create an interactive experience for participants aligned with their preferences, needs, and learning styles, improving their understanding and empowering them to make informed decisions (Vanaken & Masand, 2019). Nevertheless, it is crucial to note that using these technologies does not replace the site-participant relationship in the consenting process (Vanaken & Masand, 2019). Overall, LA and IME can potentially enhance student learning experiences and outcomes. The Lee and Owens (2004) model has developed interactive multimedia learning materials (Nur'Azizah et al., 2018).

6.1.2 How Are LA and IME Related?

In recent years, integrating technology into education has increased the use of LA and IME to improve student learning outcomes and motivation. LA utilizes data to gain insights into student performance and engagement, while IME uses interactive multimedia to simplify complex concepts and materials. Integrating these two technologies has shown promising results in improving student learning experiences and outcomes. Hani Nur'Azizah et al. researched the development of interactive multimedia to improve the analytical thinking ability of elementary school students. The study utilized Lee and Owens' model for research and development, and the results revealed that students in a limited group trial positively reviewed interactive multimedia learning. Using LA and IME in education can potentially enhance student learning outcomes and motivation, and future research in this area can help overcome challenges and limitations.

Integrating LA and IME can positively impact student motivation and learning outcomes and provide educators with valuable insights into student performance and engagement. LA can track student progress, identify areas where students struggle, and provide targeted interventions to enhance learning outcomes. IME can identify the types of multimedia components most effectively strengthen student understanding and motivation, informing the design and implementation of future educational materials and activities.

However, challenges associated with using LA and IME in education include the need for educators to be trained in using these technologies and the potential for bias in the data processed by LA. Furthermore, the cost of implementing these technologies can be a barrier for some educational institutions.

Research by Budiarto and Jazuli in 2021 showed that interactive multimedia benefits students' happiness and motivation, resulting in better learning outcomes. Other studies have also reported that interactive multimedia helps increase motivation, interest, and enthusiasm for learning and aids students' understanding of concepts and learning materials. Therefore, using interactive learning multimedia can significantly improve student learning outcomes (Budiarto & Jazuli, 2021).

Integrating LA and IME can improve student learning outcomes and educational motivation. LA can help track student progress and identify areas where students struggle, while IME can enhance student understanding and engagement. However, implementing these technologies presents challenges and limitations, including the need for educator training, cost, and potential bias in data. Vanaken and Masand (2019) discuss the effectiveness of eConsent technology, which incorporates multimedia components to improve research participants' comprehension. Martinez-Maldonado et al. (2016) provide a framework for analyzing the implementation of learning analytics and interactive surfaces in education, highlighting the challenges and opportunities associated with their use. The effectiveness of technology in enhancing learning outcomes requires careful analysis and evaluation. The literature emphasizes the benefits of using interactive multimedia to improve motivation, interest, and understanding. However, further research is needed to understand the potential of dynamic complexity and its role in enhancing the multimedia experience.

To fully understand LA and its significance in optimizing learning outcomes, it is essential to recognize the importance of feedback loops. LA collects, analyzes, and interprets data to gain insights into learners and their environments. Using multimedia, a crucial aspect of LA can enhance students' UX and decision-making capabilities. Feedback loops play a critical role in facilitating the continuous improvement of the learning experience based on user feedback. Data analysis has led to the development of user-experience models that determine learner satisfaction, which is essential for enhancing institutional performance and developing plans to improve teaching and learning experiences.

Additionally, the integration of LA and IME has shown promising results in improving students' learning experiences and outcomes. While challenges and limitations exist, further research is necessary to understand these technologies' potential in education fully. For example, Hani Nur'Azizah et al. showed that interactive multimedia learning effectively improved the analytical thinking ability of elementary school students, emphasizing the potential of IME in enhancing student learning outcomes. Therefore, integrating LA and IME can provide educators with valuable insights into student performance and engagement, ultimately improving the educational experience.

LA is a field that uses various methodologies and data to provide insights for supporting learning, teaching, organizational efficiency, and decision-making (Ifenthaler & Yau, 2021). It employs static and dynamic information about learners and learning environments, assessing, eliciting, and analyzing it for real-time modeling, predicting, and supporting learning processes, learning environments, and educational decision-making (Ifenthaler et al., 2023). The field is gaining attention for its ability to provide lead indicators related to learning processes and outcomes (Ifenthaler & Yau, 2021). Personalized recommendations, visualization of learning data, and personalized reports on progress or performance are among the approaches used to achieve these goals. These approaches can improve student retention, support informed decision-making, increase cost-effectiveness, help understand learning behavior, provide personalized assistance, and deliver feedback and interventions (Ifenthaler & Yau, 2020). However, it is essential to consider the absence of a student's voice in decision-making regarding learning analytics (Roberts et al., 2016).

Shen et al. (2020) highlights the importance of combining learning design and LA to empower teachers to make decisions regarding interventions. LA has many applications in tertiary education, including enhancing learning, evaluating efficiency, improving feedback, and supporting decision-making (Yahya et al., 2021).

LA involves collecting, analyzing, and using data to improve learning outcomes, which can inform instructional designs and personalize learning experiences for individual students. Additionally, multimedia user experience can impact student engagement and motivation, encompassing various factors such as content clarity and ease of navigation. Finally, the learning experience, which includes the quality of instruction, level of attention, and content relevance, can be enhanced through gamification, personalized learning, and social learning. Multimedia user experience refers to the quality of the UX when interacting with multimedia content, while the learning experience encompasses aspects such as the quality of instruction and student engagement (Chan et al., 2021).

Therefore, educators can improve learning outcomes by utilizing LA, providing high-quality multimedia content, and creating engaging and personalized learning experiences for their students.

LA involves measuring, collecting, analyzing, and reporting data on the progress of learners and the context of learning (Wilkinson et al., 2019). The primary objective of LA is to enhance learning outcomes and improve students' learning experiences (Abdelnour-Nocera et al., 2015). This process should focus on providing personalized learning experiences, timely feedback on learners' progress, and furnishing educators with detailed information about learners' contexts (McCoy & Shih, 2016).

Learners interact with digital tools in digitally-based learning environments, creating a unique learning experience that generates a large volume of digital data (Melnikova et al., 2022). LA can improve learning outcomes and student experience in university settings (Wilkinson et al., 2019). Learning analytics can enhance teaching and learning by enabling customized learning experiences that cater to individual student preferences, approaches, and needs (Chan et al., 2021).

LA is a field that focuses on analyzing data to support learning and decision-making processes (Ifenthaler & Yau, 2021). The domain uses various methodologies to assess and analyze information about learners and learning environments, providing real-time support and predicting learning processes and outcomes (Ifenthaler et al., 2023). LA can offer lead indicators related to learning processes and products and provide personalized assistance, feedback, and interventions to improve student retention, support informed decision-making, and increase cost-effectiveness (Ifenthaler & Yau, 2021). LA can also utilize group modeling techniques, such as the group investigation-type cooperative learning model, to promote critical thinking and cooperation among students and facilitate decision-making (Ifenthaler & Yau, 2021). By combining LA with group modeling techniques, instructors can better understand student performance and develop more effective strategies to improve their learning experience.

Integrating learning design and LA is a powerful tool for educators to make informed decisions on interventions to improve student learning outcomes (Shen et al., 2020). LA involves measuring, collecting, and analyzing data about learners and their context to enhance their learning experience and outcomes (Wilkinson et al., 2019). It has the potential to offer personalized learning experiences, timely information about learners' progress, and detailed information about the learner's context to educators, thereby improving learning outcomes and student experience (Abdelnour-Nocera et al., 2015; McCoy & Shih, 2016).

To maximize the benefits of LA, including the student's voice in decision-making is essential (Roberts et al., 2016). In addition, the quality of multimedia user experience and learning experience are important factors influencing learning outcomes.

By utilizing data to inform instructional design, providing high-quality multimedia content, and creating engaging and personalized learning experiences, educators can help students achieve their full potential. With these factors, LA can significantly enhance the learning process, evaluate efficiency, improve feedback, enrich the learning experience, and support decision-making (Yahya et al., 2021).

In this chapter, the authors explore the potential of LA and IME to enhance students' learning experiences. They employ a combined methodology of group modeling, participatory modeling, and system dynamics to achieve this. This approach involves engaging diverse stakeholders, including educators, researchers, and students, to develop a conceptual framework applicable across various educational settings and incorporating multiple perspectives. In addition, the participatory modeling process also involves end-users in LA and IME's design and development process to ensure that the resulting products meet their needs and preferences. Finally, the system dynamics model simulates the feedback loops connecting LA and IME to test different scenarios and identify the most effective strategies for enhancing students' learning experiences. By employing this methodology, the authors hope to contribute to the existing knowledge on integrating LA and IME and provide practical insights for improving students' learning experiences.

6.2 Methodology

In this text, the authors discuss their methodology for understanding the feedback loops between LA and IME in multimedia projects. They combine system dynamics and group modeling techniques to involve stakeholders in the modeling process and better understand the system's dynamics. The methodology consists in gathering and classifying relevant data about the system, understanding its structure and dynamics, and developing a causal diagram. The system dynamics approach helps recognize the dynamic behavior that a system experiences and mitigates decision-makers' cognitive limits. The authors realize that the number of steps in the methodology may vary but emphasize the importance of utilizing approaches such as system dynamics modeling to improve decision-making in complex systems. By combining these techniques, the authors hope to gain practical insights into the integration of LA and IME and contribute to the existing knowledge on the subject.

The authors used a combination of system dynamics and group modeling techniques to enhance student's learning experience by identifying the feedback loops between LA and IME. This approach facilitated discussions with experts and stakeholders to understand the LA dynamics better and build a shared understanding of the problem addressed. Group model building, a participatory approach widely used to think systemically, provided a practical means of introducing the core ideas of the systems approach to stakeholders and fostered a shared understanding of the feedback loops in LA and IME. The authors also gathered and classified relevant data on the system to develop an initial qualitative understanding of its structure, dynamics, and system context. Finally, they used system dynamics modeling to recognize the dynamic behavior of the system and mitigate the cognitive limits of decision-makers, ultimately providing a basis for understanding the feedback loops in LA and IME (Berard, 2010; Hovmand & Hovmand, 2014; Rouwette et al., 2002; Sterman, 2002).

To provide practical insights for improving students' learning experience through the integration of LA and IME, we engaged a diverse group of stakeholders, including researchers, educators, and students, in a participatory group-modeling process. This approach allowed us to incorporate multiple perspectives and foster a shared understanding of the feedback loops connecting LA and IME. Group model building was a participatory approach to help practitioners think systemically and build capacity (Delobelle, 2020; Voinov, 2021). By combining system dynamics and group modeling techniques, we aimed to contribute to the existing knowledge on the interconnectedness between LA and IME. The results of our study provide practical insights for educators and practitioners to enhance students' learning experiences by improving the integration of LA and EMI.

6.3 Development of a Dynamic Hypothesis Formed by Feedback Loops that Explains How the Learning Experience Relates to the User Experience and the Teacher's Enthusiasm

The system dynamics analysis conducted in this study revealed the intricate connections among UX, IME, learning experience, teacher enthusiasm, and student engagement and performance. Our dynamic hypothesis aligns with previous research emphasizing the significance of these factors in shaping the overall learning environment (Larusson & Alterman, 2009; Li et al., 2015). Furthermore, the approach employed in this study offers a practical means of identifying potential areas for improvement and prioritizing intervention areas, enabling educators to make informed decisions about enhancing the learning environment for their students.

Our study not only provides a deeper understanding of the interconnectedness between LA and IME but also presents a valuable approach to identifying potential areas of improvement in the learning environment. Educators can use our results to prioritize areas of intervention and make informed decisions about optimizing the learning experience for their students. For example, they can focus on improving the UX with multimedia materials or increasing teacher enthusiasm to enhance student engagement and performance. Our study provides practical insights for educators and practitioners to enhance their student's learning experiences, contributing to the existing knowledge of the complex dynamics of the learning environment.

6.4 Building the Reference Model

In a group modeling session, we explored the feedback relationships between LA, Learning Experience, and Multimedia Systems to understand better how they interact (see Fig. 6.1).

To facilitate this process, a group model workshop was proposed by experts, which focused on the concept of the reference mode. During the workshop, participants collaborated in groups to discuss and evaluate a given learning landscape. By combining structured activities with independent reflection, each group member could bring unique perspectives and insights into their learning process, enabling the group to analyze, question, and assess their own and their peers' learning experiences more deeply. Through this process, participants better understood their individual and collective learning capabilities, allowing them to improve their learning strategies and apply them more effectively to their learning environment (see Fig. 6.2) (Voinov et al., 2021).

Experts emphasized the concept of the reference mode during the group model workshop, where participants worked collaboratively in groups to evaluate a specific learning landscape using structured activities and independent reflection. This approach allowed participants to understand their individual and collective learning capabilities better and apply effective learning strategies to their learning environment. Our approach builds upon system dynamics and group modeling principles, which have been identified as powerful tools for enhancing shared understanding and stakeholder collaboration. This is consistent with previous work by Rouwette

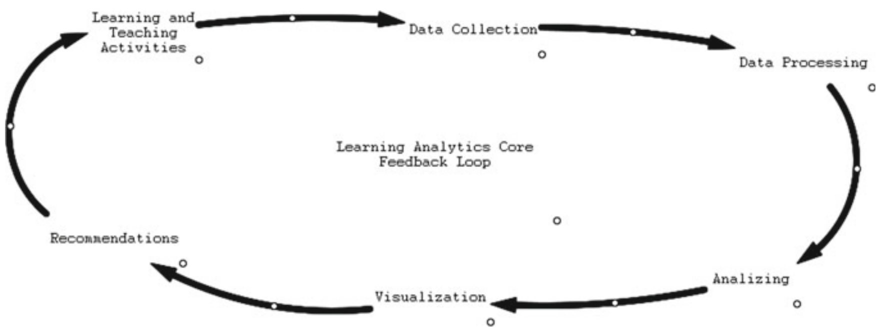

Fig. 6.1 Overview of the learning analytics process as a circular or feedback-loop process

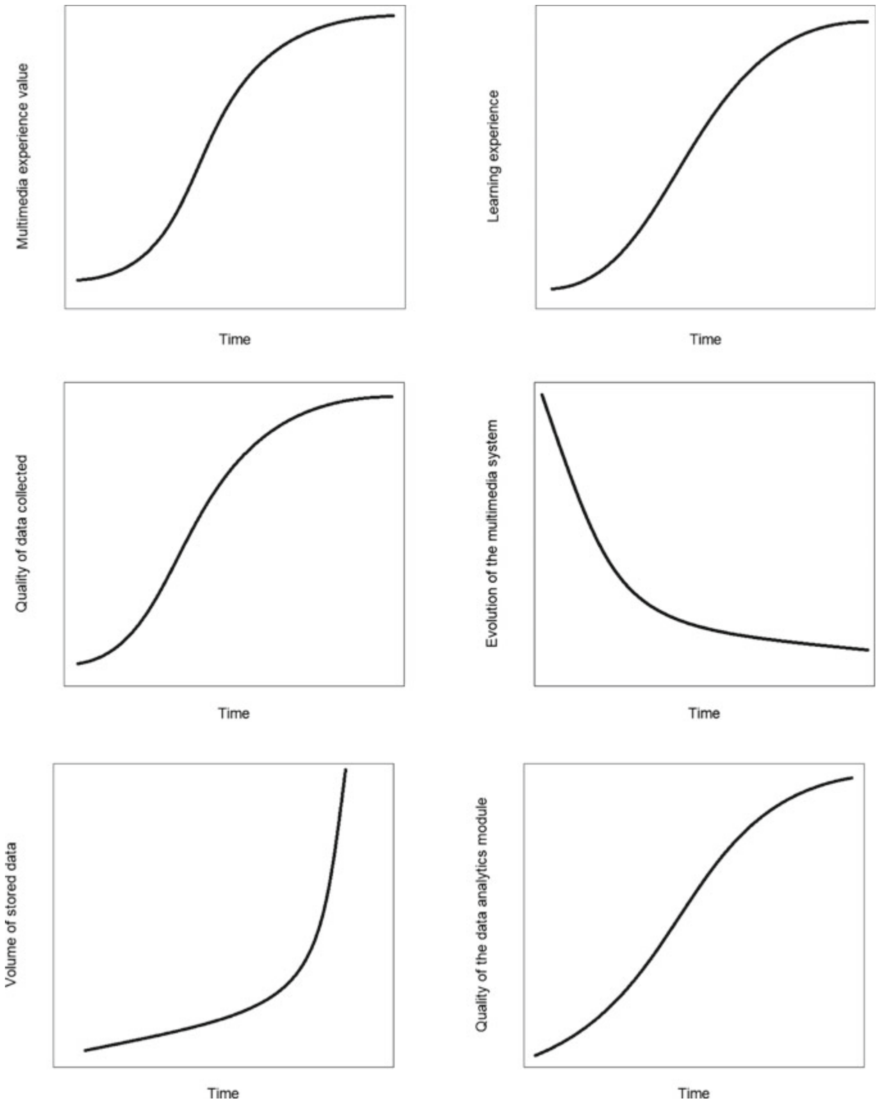

Fig. 6.2 The behavior of variables in time

et al. (2002) and Hovmand and Hovmand (2014). Figure 6.2 depicts the reference mode of action during the group model workshop.

The workshop encouraged collaboration among participants to analyze and evaluate a given problem situation, utilizing structured activities and independent reflections to incorporate various perspectives and perceptions. Individuals can improve their learning strategies and apply them to their educational environments by engaging in this process. Furthermore, the data generated from this mediation object can be analyzed to improve learning and teaching processes and provide recommendations and feedback to optimize the use of multimedia systems. Experts emphasize the importance of selecting data and variables that capture the student's interaction with the mediating objects or multimedia system.

LA is a valuable tool for educators to enhance academic efficiency and provide a personalized learning experience. LA enables the identification of different actors, such as teachers, students, and administrators, and their respective performance levels and learning styles. This information can be used to offer relevant feedback and content tailored to individual interests and needs, improving the learning experience for all parties involved. Multimedia content managers can benefit from LA by adjusting platforms to user preferences. Furthermore, LA data collecting can be customized to meet the information needs of various stakeholders, facilitating improvements to the multimedia system.

The experts in the group modeling workshop provided valuable insights into the importance of data collection, contextual factors, and the active involvement of each actor in the learning analysis process. Their contributions emphasized the need to identify different actors and their performance, classify and order styles to offer relevant feedback, and consider storage time, relevant elements, and educational objectives when collecting data. These insights highlight the importance of user-centered design and the role of interactivity in multimedia systems to provide personalized content and meet a broader range of current needs. Overall, the participants' contributions provide a better understanding of the feedback loops, UX, and learning environment essential to improving the educational experience.

In a participatory modeling workshop, experts emphasized the importance of teachers understanding the meaning of LA data to use it to improve student outcomes effectively. They stressed that LA should not be used as a predictive tool but rather as a means of identifying patterns and trends in the classroom. The team recommended using LA to support teachers in making informed decisions about teaching strategies and catering to each student's needs. The success of LA in educational settings depends on teachers, administrators, and multimedia system designers being committed to obtaining the correct data and recognizing the value of improving recommendations based on those data.

A participatory modeling workshop highlighted the importance of utilizing LA to improve teaching strategies and student outcomes. The process of using LA should focus on the uniqueness of the data and involve a commitment from all parties involved to generate value from the process. Teachers must take the lead in investigating and implementing LA tools that are individually applied to their needs to maximize learners' potential. By utilizing data-driven insights and strategies, educators can better understand and address the individual needs of each student and develop targeted action plans to promote higher achievement, foster engagement, and improve learning outcomes. Modifying LA programs to suit the particular requirements of educational and teaching institutions is essential to obtain better control of the data and achieve expected success. Overall, this approach ensures that teachers can bridge the gap between data-driven decisions and the human element of learning, providing students can reach their full potential.

Having teachers set objectives and identify variables, monitor those variables, and take action to change the state of those variables to reach the goals is essential. To achieve this, teachers should be able to investigate, test, and implement tools that are individually applied to their needs to control the data better and use the knowledge obtained from them. Therefore, the possibility of modifying the LA program according to the needs of educational and teaching institutions is key. Thus, teachers will be able to achieve their expected success.

LA systems need to be flexible to meet the specific needs of educational institutions and provide teachers with the necessary data, strategies, and tools to achieve their goals. Designers should consider the analytics results, ensure the data is helpful to teachers, and create effective improvements. Furthermore, it is crucial to recognize that the process of progress and improvement goals are context-dependent. LA's success relies on its ability to meet the needs of the context. An LA system that does not cater to the context's needs will not lead to improved learning experiences, user experiences, or multimedia systems and will not realize its full potential.

The participatory modeling workshop emphasized the need for teachers to clearly articulate their goals and objectives for analytics learning and continuous improvement. This should be personalized as each institution and individual has different improvement needs. Multimedia designers are crucial in providing technical resources and recommendations to ensure effective multimedia analysis that identifies gaps and defines improvement recommendations. The data should be visualized in a way that considers the personal characteristics, worldview, and sense of the teacher, student, and multimedia designer. The data must be tailored to meet informational needs and motivation to build relevant recommendations that improve the learning process, professor's enthusiasm, UX, and multimedia design.

The participatory modeling workshop discussed the use of multimedia analytics in the education sector. It was emphasized that the design process should start with the need for continuous improvement and personalization of goals. Multimedia designers are vital in providing technical resources to identify process gaps and define improvement recommendations. Data visualization must be personalized according to the individual characteristics of the teacher, student, and designer and must be considered in terms of informational needs and motivation. Using cybernetic principles, the multimedia designer can efficiently inform each user according to their needs and provide effective improvement recommendations, enhancing the learning experience, enthusiasm of the teacher, and commitment of the students. Using LA allows for good decision-making to improve teaching processes and communication of new concepts. Different institutions have varying dynamics and aggregation levels, which must evolve according to the context.

In a participatory modeling workshop, experts highlighted the importance of collaboration between parents and teachers for successful academic development. Teachers should be responsible for monitoring, evaluating, and improving the multimedia system design, taking into account students' situations with empathy. Collaboration between the LA system, interactive user interface, and multimedia system can improve the learning experience and meet the needs of students. To optimize the learning experience, familiar elements can be used to develop an IME, articulating

LA and creating value. This results in a feedback cycle where more learning interactions and data generation occur, providing an embedded learning model and LA that must detect a series of patterns in variables. Additionally, teachers must understand how to interpret LA data to make informed decisions about catering to each student's needs. LA should not be used as a predictive tool.

Experts in the participatory modeling workshop emphasized the importance of not homogenizing data when improving recommendations, as each institution has unique requirements. Teachers, administrators, and multimedia system designers must work together to obtain most of the data, and teachers must test and implement tools tailored to their needs. To achieve this, the LA system must be flexible enough to adapt to an institution's specific needs, providing teachers with the data, strategies, and tools required to achieve their goals. Designers must be aware of the results of LA to improve the process and goal-setting for the context. The data visualization process should follow the personal characteristics, worldview, and particular sense made by the teacher, student, and multimedia designer. Multimedia designers are crucial in identifying process gaps and defining improvement recommendations. Each type of use must be considered in terms of its informational needs and motivation for that information to provide the most relevant data for improvement recommendations that enhance the learning process, enthusiasm of the professor, and UX. Therefore, LA systems must recognize the unique needs of the context to promote improvements in the learning experience, UX, and multimedia systems.

Experts from a participatory modeling workshop discussed the role of LA in improving student outcomes and effective teaching strategies. For LA to be effective, all parties involved, including teachers, administrators, and multimedia designers, must be committed to obtaining the most out of the data. In addition, the LA system must also be flexible enough to adapt to the institution's needs. Multimedia designers must ensure that data is used efficiently to determine the "why" and "what for" of the analysis and determine what improvements can be made concerning the data.

To improve the learning experience, creating a feedback loop that allows for value creation for the user and the learning experience is essential. The IME is connected to an LA system that can help improve the learning experience by adding value to the experience and process of improving the IME for project users. The analytic learning system helps enhance the IME and adds extra value to all those involved by providing useful information about users' interactions with the system. The goal is to improve the learning experience by adding value to the IME and reformulating it to increase the richness of design elements. This process can be beneficial to all those involved in the project.

The analytics learning system enhances the IME by providing valuable information about user interactions with the system. This allows monitoring of user satisfaction levels relative to expectations, improving the experience for all parties involved. The focus on user-centered attention is crucial in providing a relevant and satisfying experience over time. The ultimate goal of LA and integrated multimedia systems is to generate meaningful learning experiences for students, teachers, and stakeholders. By identifying the context and generating value, everyone involved can receive significant learning, grow, and improve.

A group of experts identified the components of modern educational systems and their value to students and teachers. The workshop explored the importance of multimedia systems, interactive technologies, personalized learning paths, and student and teacher feedback. The group also discussed the significance of data collection and the objectives of the information. The workshop highlighted the importance of creating an engaging and effective learning experience that provides the necessary data to track progress, gauge user satisfaction, and meet objectives. The group agreed that IME is essential for providing personalized learning paths and feedback to students and teachers so that each individual can get the most out of their learning environment and gain the most significant value from their experience. The identified variables include multimedia systems, interactive technologies, personalized learning paths, feedback, learning environment, data collection, objectives, and IME.

A group of experts in educational systems convened a workshop to discuss the critical components of modern education systems and their value to students and teachers. The workshop emphasized the significance of multimedia systems, interactive technologies, personalized learning paths, and student and teacher feedback. Additionally, the group highlighted the importance of data collection to track progress, gauge user satisfaction, and meet objectives, as well as the value of IME in providing personalized learning paths and feedback.

By focusing on these variables and implementing LA to monitor and improve the learning experience, we can create an engaging and effective learning environment that provides value to all stakeholders. The experts identified multimedia systems, interactive technologies, personalized learning paths, feedback, learning environment, data collection, objectives, and IME as the critical components of modern educational systems. This approach can help create a meaningful learning experience for students, teachers, and administrators, generating value for everyone involved.

6.5 The Conceptual Model

The participatory modeling workshop led to the development of the dynamic hypothesis, which incorporates several feedback cycles to explain the dynamics of LA and its impact on the learning experience, teacher enthusiasm, and UX. For example, one of the feedback cycles shows that UX increases the learning experience, reinforcing UX and creating a reinforcement-feedback loop (see Fig. 6.3). Another feedback loop indicates that the learning experience increases teacher enthusiasm, increasing students' learning experience (see Fig. 6.4).

The dynamic hypothesis assumes that students generate learning interactions that create data, which is used to improve the learning experience and UX. This creates a reinforcing loop, where the user experience reinforces teacher enthusiasm and learning experience. These feedback loops work together to continuously improve the learning experience and user satisfaction.

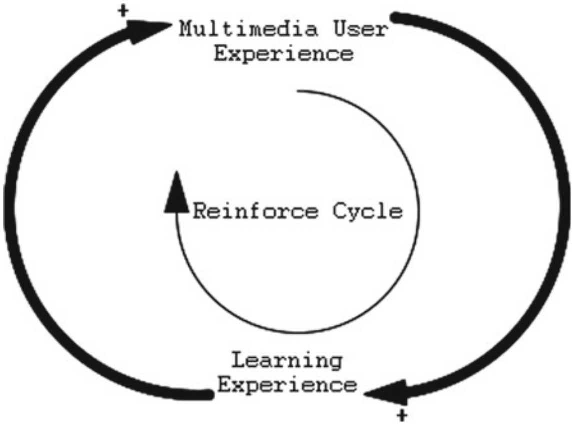

Fig. 6.3 The feedback loop between User Experience and Learning Experience

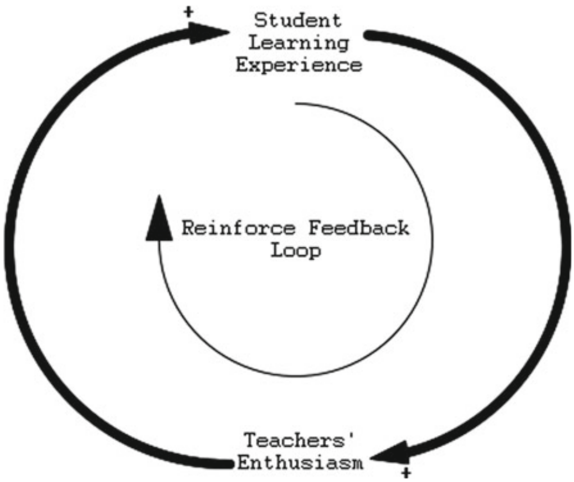

Fig. 6.4 The feedback loop between students' learning effectiveness and teacher enthusiasm

The dynamic hypothesis integrates several feedback cycles, as explained below. It accounts for the dynamics of LA and its improvement and effects on the learning experience, teacher enthusiasm, and user experience.

The feedback cycle illustrated in Fig. 6.4 shows how user experience increases learning experience and how learning experience increases user experience. This is a reinforcement-feedback loop. Learning experience increases teacher enthusiasm, which increases students' learning experience, as illustrated in this reinforcement feedback loop.

The consolidated dynamic hypothesis assumes that students generate learning interactions, which generate data that then create recommendations to improve the learning experience and user experience. This, in turn, reinforces the UX, which increases teacher enthusiasm and, in turn, increases the learning experience. Finally,

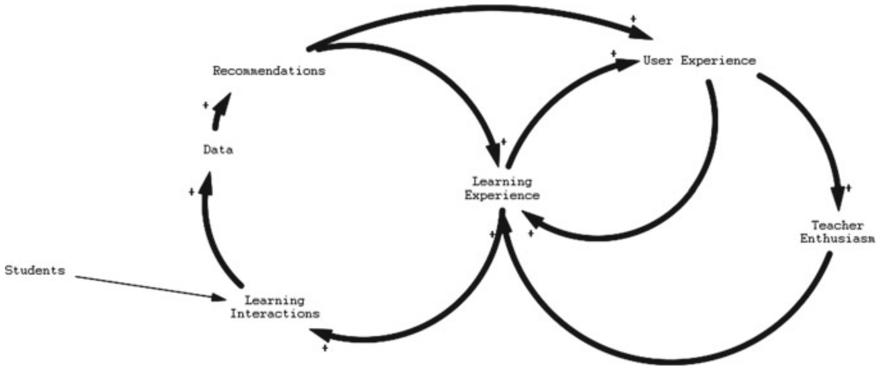

Fig. 6.5 The dynamic hypothesis of the influence of learning analytics and interactive multimedia experiences on student learning experience

the learning experience reinforces the learning interactions; five feedback loops were identified here (see Fig. 6.5).

To validate the dynamic hypothesis developed in the participatory modeling workshop, the experts used an instrument to evaluate the strength of each relationship (see Fig. 6.6). This validation process involved analyzing the variables used in the hypothesis and their connections to ensure accuracy and assessing the impact of multimedia systems, interactive technologies, personalized learning paths, and feedback on learning experiences. The experts used their expertise and knowledge to check the validity of the hypothesis, which was further supported by the data collected from the instrument. The validation process ensured that the dynamic hypothesis accurately reflects the relationships between the variables and provides a solid framework for understanding the dynamics of learning analytics and its effects on the learning experience, teacher enthusiasm, and UX.

The results from the participatory modeling workshop highlighted the significance of several factors for both students and teachers, including multimedia systems, interactive technologies, personalized learning paths, and feedback. The use of multimedia experiences contributed to student learning outcomes, indicating its importance in modern educational systems. The experts also emphasized the importance of collecting data to track progress, gauge user satisfaction, and meet objectives, as well as the value of EMI in providing personalized learning paths and feedback. By focusing on these variables and implementing learning analytics to monitor and improve the learning experience, an engaging and effective learning environment can be created that provides value to all stakeholders. Overall, the dynamic hypothesis presents a comprehensive model for the dynamics of learning analytics in modern educational systems. However, further research and investigation are needed to fully evaluate the strength of the relationships in the dynamic hypothesis and refine the model for future use.

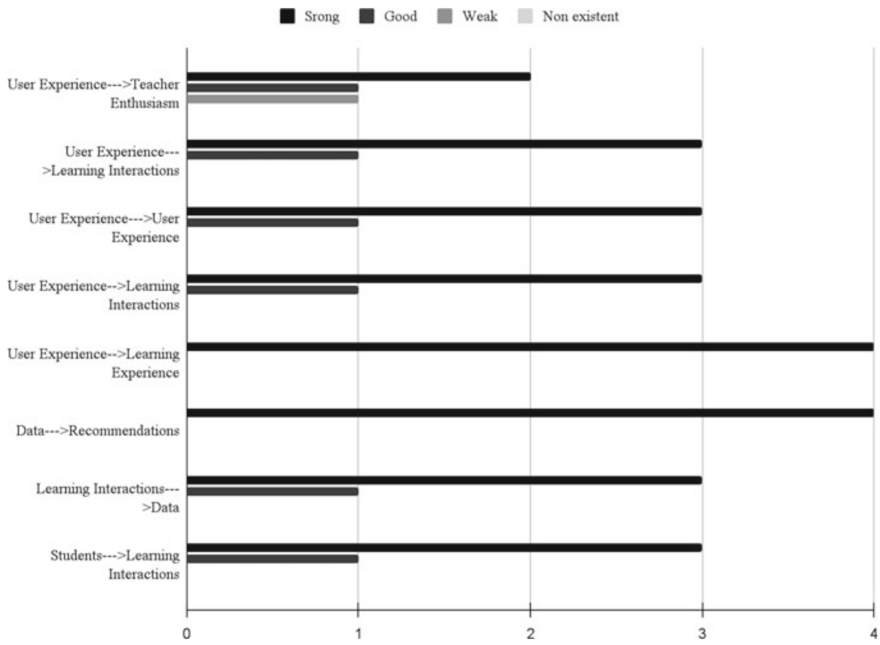

Fig. 6.6 Answers from experts about how strong the relationships could be in the dynamic hypothesis

6.6 Involvement of Researchers and Teachers in Identifying the Reference Modes, Variables, and Feedback Loops that Connect the Learning Experience with the User Experience

During a group modeling session, researchers and teachers collaborated to identify the reference modes, variables, and feedback loops that connect the Learning Experience with the UX and their relationships with LA and IME. The experts emphasized the importance of using LA to support teachers, inform teaching strategies, and improve student outcomes. The study revealed that UX, IME, learning experience, teacher enthusiasm, student engagement, and performance are interconnected and shape the learning environment. The design of multimedia systems should consider contextual factors to meet a broader range of current needs. Results showed that multimedia systems, interactive technologies, personalized learning paths, and feedback influenced student learning experiences. While experts support relationships between UX, IME, and learning experience, they have varying opinions on the exact relationship between user experience and teacher enthusiasm. Further research is needed to fully understand the dynamics of these relationships and refine the model for future use.

In the participatory modeling workshop, experts examined the relationships between Learning Analytics, Learning Experience, and Multimedia Systems to identify how these components connect and interact. They recommended the use of LA to support teachers and improve student outcomes. The experts stressed that UX, IME, learning experience, teacher enthusiasm, and student engagement are interconnected and influenced by contextual factors. The impact of multimedia systems, interactive technologies, personalized learning paths, and feedback on learning experiences was assessed, with results indicating their positive influence. Although experts generally support relationships between UX and learning outcomes, opinions on the relationship between UX and teacher enthusiasm varies.

6.7 Conceptual Model Validation

In this chapter, we present dynamic hypotheses and causal diagrams that have been validated against relevant literature and modeling discussions by the authors. To ensure the reliability and validity of our causal diagrams, we followed the guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010) for assessing the structural validity of simulation models.

According to Qudrat-Ullah (2008), a simulation model's ability to reproduce a system's behavior is crucial for evaluating its behavioral validity. On the other hand, Qudrat-Ullah and Baek Seo (2010) proposed guidelines for determining the structural validity of a system dynamics-type simulation model, including assessing the model's feedback structure, time delays, and parameter values.

By applying these guidelines, we validated the causal diagrams presented in this chapter by evaluating their ability to reproduce the system's behavior under study and assess their structural characteristics, such as feedback loops and time delays. This validation process ensured the reliability and validity of our causal diagrams.

Figure 6.7 represents a subset of the endogenous variables relevant to the study. These variables included learning interactions, data, recommendations, learning experiences, user experience, and teacher enthusiasm. A corresponding set of exogenous variables crucial for the existence and sustainability of these endogenous variables accompany each endogenous variable. The only exogenous variable in this study was student participation.

Table 6.1 presents a comprehensive overview of the structures and concepts adopted from the literature to validate the causal loops and dynamic hypotheses presented in this chapter on learning analytics. The table includes authors' names, publication years, and titles of the works from which these structures and concepts were adopted.

These concepts are crucial in defining the boundaries of our model and identifying the critical variables that determine the dynamics of student learning. They cover a range of topics, such as the impact of learning analytics on student performance, the role of learning analytics in predicting student outcomes, and the effects of personalized learning on student engagement.

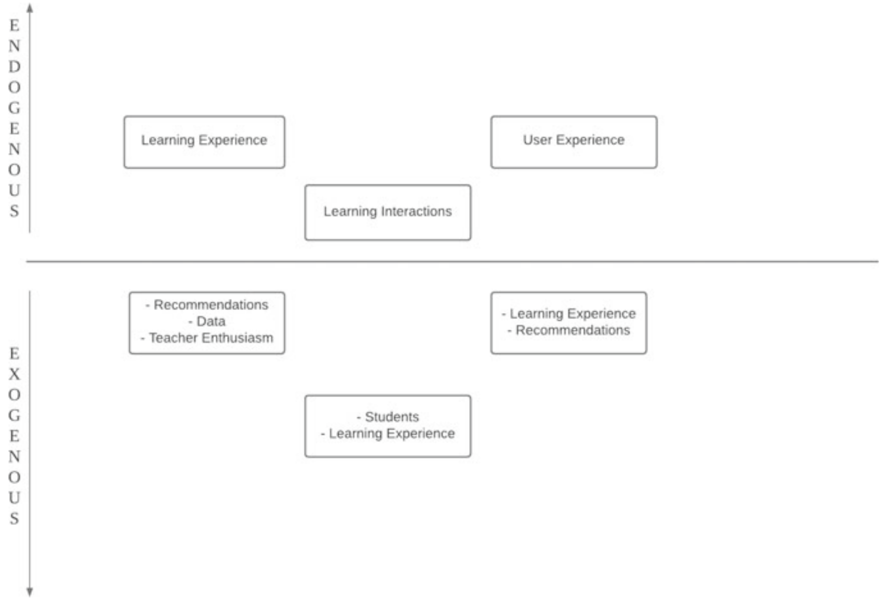

Fig. 6.7 Endogenous and exogenous variables

Table 6.1 Structures and Concepts adopted from the existing work in the causal loops diagrams presented in this chapter

Structures/concepts	Remarks
'Behavior validity of a simulation model for sustainable development' (Qudrat-Ullah, 2008)	Causal structure was adopted
'How to do structural validity of a system dynamics type simulation model: The case of an energy policy model' (Qudrat-Ullah & Baek Seo, 2010)	Structural formulation was adopted

The structures and feedback loops presented in Table 6.1 are essential to our research, as they enable us to develop a comprehensive understanding of the dynamics of learning analytics and their impact on student learning outcomes. Validation is crucial in simulation modeling to ensure the structural and behavioral validity of our conceptual frameworks. We referred to the existing literature to validate our conceptual frameworks, and Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010) emphasized the importance of validating simulation models through expert opinion, empirical data, and sensitivity analysis to assess the structural validity of the model.

Table 6.1 emphasizes the significance of the learning analytics system's structure and feedback loops in driving student data collection, analysis, and utilization. This supports the dynamic hypotheses and causal loops presented in this chapter and highlights the importance of validation in simulation modeling.

This table demonstrates how concepts such as the impact of learning analytics on student performance, the role of learning analytics in predicting student outcomes, and the effects of personalized learning on student engagement were integrated into our causal hypotheses. These concepts were taken from the works of various researchers in the field of learning analytics, and they helped us define the boundaries of our model and identify the critical variables that determine the dynamics of student learning.

Table 6.1 emphasizes the structure of the learning analytics system and the feedback loops that drive the collection, analysis, and utilization of student data. These structures and concepts were essential to our research, as they enabled us to develop a comprehensive understanding of the dynamics of learning analytics and their impact on student learning outcomes.

6.8 Discussion

The dynamic hypothesis presented in this study assumes that students generate learning interactions, which generate data that create recommendations to improve their learning and user experiences. This, in turn, reinforces user experience, which increases teacher enthusiasm and ultimately increases the learning experience. This model identified two feedback loops, as shown in Fig. 6.5.

The results of the participatory modeling workshop highlighted the significance of several factors for both students and teachers, including multimedia systems, interactive technologies, personalized learning paths, and feedback. Multimedia experiences contribute to students' learning outcomes, indicating their importance in modern educational systems. The experts also emphasized the importance of collecting data to track progress, gauge user satisfaction, and meet objectives, as well as the value of EMI in providing personalized learning paths and feedback. By focusing on these variables and implementing learning analytics to monitor and improve the learning experience, an engaging and effective learning environment that provides value to all stakeholders can be created.

The dynamic hypothesis presents a comprehensive model of the dynamics of learning analytics in modern educational systems. However, further research and investigation are needed to fully evaluate the strength of the relationships in the dynamic hypothesis and to refine the model for future use. This study provides a foundation for future research on the use of learning analytics and interactive multimedia to enhance students' learning experiences. This highlights the importance of a systemic approach to address the complexity of modern educational systems.

In conclusion, the findings of this study emphasize the importance of incorporating multimedia systems and interactive technologies into educational systems and the value of personalized learning paths and feedback to enhance the learning experience. Using learning analytics to monitor and improve learning experiences, educational systems can create an engaging and effective learning environment that benefits all stakeholders. The dynamic hypothesis provides a comprehensive model for understanding the relationships between these variables, which can inform the development of effective interventions for improving students' learning outcomes.

6.9 Conclusion

According to this chapter, involving researchers and teachers in identifying reference modes, variables, and feedback loops has led to a better understanding of the interconnectivity of factors that impact student learning outcomes. In addition, the study emphasized the importance of considering contextual factors in designing multimedia systems to meet a broader range of needs.

Group modeling and system dynamics were powerful tools for building expert knowledge and understanding complex interactions between system elements. These methodologies can improve experts' ability to ask questions, analyze data, and develop knowledge proactively and creatively. Furthermore, using these techniques, experts can better understand system structures and their effects on performance, which is essential for creating a better future.

The chapter discussed how system dynamics simulations could help us understand the relationships between different system elements and inform decision-making for optimizing them. The simulations identified potential areas of improvement, and the long-term implications of certain changes were better understood. However, the accuracy of these simulations depends on reliable data, assumptions, and complex interactions. Further data science and artificial intelligence research are necessary to refine the data collection processes and ensure more accurate simulations. The potential of LA and IME in student retention should also be explored further to understand the feedback loop that connects UX, teacher enthusiasm, and learning outcomes. By gaining a deeper understanding of these relationships and how they interact, applying system dynamics simulations can significantly improve our ability to make effective decisions in educational systems.

The investigation of LA is crucial for improving students' learning experiences. LA and IME provide educators with data that can be used to inform decisions about instructional practices, resources, and interventions. By analyzing student data, educators can identify patterns and trends to inform decisions on improving instruction and supporting student learning. Furthermore, data analysis can reveal areas of concern that may hinder student learning, allowing for targeted interventions and support. Investigating the effectiveness of these tools can provide evidence-based insights into teaching strategies and interventions and improve student learning outcomes.

The effectiveness of LA and IME is critical for improving students' learning experiences. Analyzing data generated by students' learning activities using these tools can provide evidence-based insights into the effectiveness of different teaching strategies and interventions, identify areas of concern, and tailor instruction to meet individual learner needs. Evaluating the impact of LA and IME on learning outcomes is also necessary to ensure that these tools are used ethically and responsibly. Educators can use the insights gained from this evaluation to make informed decisions about instructional practices and interventions that align with students' interests and rights.

The study highlights the importance of group modeling and system dynamics in building expert knowledge and understanding complex systems. System dynamics simulations are an effective tool for understanding relationships between system elements and making decisions on optimizing them. However, accurate predictions require reliable data, assumptions, and complex interactions, and further research is needed to refine modeling techniques and improve input quality. In addition, LA and EDM have the potential to improve student's learning experiences, allowing educators to analyze data generated by students' learning activities to inform decisions about instructional practices, resources, and interventions. As a result, evidence-based decisions can be made about instructional practices and interventions, the individual learner needs can be addressed, and ethical and responsible use of these tools can be ensured by analyzing data and evaluating the impact of LA and IME on learning outcomes.

The research book chapter underscores the importance of investigating the relationships between UX, IME, learning experience, teacher enthusiasm, student engagement, and performance to improve educational systems. Using system dynamics simulations and analyzing data generated by LA, educators can make evidence-based decisions that promote student learning and engagement, address areas of concern, and tailor instruction to meet individual learner needs. The study suggests that further research is needed to identify critical feedback loops between LA and IME in multimedia projects. Overall, this study has significant implications for improving educational systems and optimizing them for student success.

This study discusses the limitations and challenges of using system dynamics simulations to understand complex systems and make decisions. While these simulations are practical for optimizing systems, they require access to sufficient data, accurate assumptions, and quality inputs to create realistic models. Additionally, predicting long-term effects accurately can be challenging. To improve the accuracy and effectiveness of system dynamics simulations, further research in data science, artificial intelligence, and machine learning is needed to refine data collection processes, validate inputs, and enhance the accuracy of the simulations. Research on more advanced modeling techniques could also improve the efficacy of system dynamics simulations in understanding and predicting system changes.

The text discusses limitations in identifying critical feedback loops between LA and IME in multimedia projects, such as the complex relationships between LA, EMI, student learning outcomes, and ethical concerns surrounding data privacy and protection. To address these limitations, future research should focus on developing more sophisticated data collection methods and analysis techniques that consider the multifaceted nature of student learning and explore the potential of emerging technologies like blockchain for data security and privacy. Moreover, the text suggests integrating LA and IME with other technologies, such as virtual and augmented reality, to provide more immersive and engaging learning experiences. This would let to a better understanding of the interplay between different factors that affect student learning outcomes and the development of more effective interventions and strategies to support student success.

The research book chapter concludes that further research is needed to refine the use of system dynamics simulations in education. While simulations can help understand relationships within a system, accurate data and assumptions are necessary for effective implementation. Additionally, researchers should focus on the relationships between LA, IME, and student learning outcomes. Limitations, including data privacy and protection, must be addressed to ensure the ethical use of data. Advanced modeling techniques and algorithms should be developed to enhance these tools, and new technologies, such as blockchain and virtual reality, should be explored. Finally, longitudinal studies are necessary to assess the long-term effects of LA and IME on student success. Researchers can develop effective tools to support student learning and success by addressing these limitations.

6.10 Insights and Implications for Practice

Making decisions to improve the learning experience with LA can be challenging due to the volume and interdependence of data and ethical considerations. The vast amounts of data generated by LA tools can be overwhelming, and it can be challenging to interpret them. Additionally, student outcomes are influenced by multiple factors, making it difficult to isolate specific factors. To balance the potential benefits of learning analytics with ethical concerns, ensuring transparency in using these tools and informing students how their data are being used is essential. Nevertheless, effective use of LA can provide valuable insights into student learning and targeted interventions to enhance the learning experience.

Improving the learning experience using LA is complex due to several factors. One of the main challenges is dealing with the vast amount of data generated by LA tools, which can be overwhelming and challenging to interpret. Furthermore, these data are often highly interdependent, making it difficult to isolate specific factors that may contribute to student outcomes. Another complexity is balancing the potential benefits of using LA with ethical considerations such as privacy and data security. Nevertheless, LA can provide valuable insights into student learning and targeted interventions to improve the learning experience. Still, ensuring that these tools are transparent and that students know how their data is used is crucial. In addition, the decision-making process can be complex because of the diversity of student populations and the need to tailor interventions to meet individual needs, which requires developing effective interventions for all students, despite their varying learning styles, preferences, and needs.

Decision-making in LA is a complex process that requires navigating various factors. One such factor is the need to balance the potential benefits of LA with ethical considerations. It is crucial to ensure that LA is transparent and that students know how their data are used. Additionally, the decision-making process can be complicated due to the diversity of student populations and the need to tailor interventions to meet individual needs. A multidisciplinary approach involving data scientists, educators, and learning designers is needed to address these complexities. Moreover, ethical principles such as transparency, informed consent, and data protection must guide decision-making. By adopting such an approach, educators and data scientists can harness the power of LA to enhance student learning and improve educational outcomes.

Due to various factors, improving the learning experience through LA is complex and challenging. These include the overwhelming volume and complexity of interdependent data, ethical considerations, and the need to tailor interventions to meet individual student needs. To address these complexities, a multidisciplinary approach involving data scientists, educators, and learning designers should be employed to analyze data, design interventions, and evaluate their effectiveness. In addition, ethical principles, such as transparency, informed consent, and data protection, should guide the decision-making process to ensure that the use of LA is aligned with student interests and rights. Educators and data scientists can harness the power of LA to enhance student learning and improve educational outcomes by taking a collaborative approach. The insights and implications for practice highlight the importance of understanding the complexities of decision-making and the value of a collaborative approach to achieve better outcomes.

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Chapter 7
Fostering Problem-Solving Skills and Creativity in Latin America Primary Schools Through System Dynamics

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Abstract There is a growing need to foster problem-solving skills and creativity in Latin America among primary-school students. This chapter highlights the importance of using system dynamics to achieve these goals. Educators can create an integrated learning environment that helps students develop analytical and creative capabilities to tackle complex issues by incorporating collaborative teaching strategies like visualization, structured dialogue, problem-solving activities, and simulations. Developing systems thinking skills is crucial for making informed decisions and taking responsible action in today's complex world. Educators can use system dynamics models and instructional materials to create a dynamic and interactive learning experience that promotes critical thinking, problem-solving, and teamwork. This approach requires clear communication, problem-understanding, creative and critical thinking, and evaluation of solutions. To achieve success, educators must foster an environment that emphasizes collaboration, creativity, openness to new ideas, and interaction. By empowering students to tackle localized problems, educators can create leaders in problem-solving and promote better learning and development outcomes for Latin American students and communities. Overall, this chapter provides insights into the benefits of using system dynamics to foster problem-solving skills and creativity among primary school students in Latin America. The chapter also offers practical guidance for educators on creating an integrated learning environment that promotes critical thinking, problem-solving, and teamwork and ultimately drives better learning outcomes for students.

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Keywords System dynamics · Problem-solving skills · Creativity · Primary school · Latin America · Educational research · Teaching strategies · Collaboration · System thinking · Learning · Critical thinking · Learner-centered learning · Learning environments

7.1 Introduction

In Latin American primary schools, system dynamics has been identified as an essential tool for promoting problem-solving skills and creativity among students (Arndt, 2006). Research has highlighted the effectiveness of system dynamics in helping students develop the analytical and creative capabilities necessary to tackle complex issues (Forrester, 1993). Collaborative teaching strategies, such as visualization, structured dialogue, problem-solving activities, and simulations, have been found to be particularly effective in facilitating learning and promoting problem-solving skills (Arndt, 2006).

System thinking is a critical component of system dynamics that promotes problem-solving skills and creativity among Latin American primary school students (Forrester, 1993). This chapter provides a comprehensive overview of system thinking and its applications in the context of system dynamics in educational settings in Latin America. It also highlights the key components of effective problem-solving and the importance of creating a creative environment that fosters system thinking.

To promote system thinking is essential to place the responsibility of learning in the hands of the learner and connect factual knowledge with its application (Forrester, 1993). This approach seeks to open up a new level of creativity and enthusiastic interest among students. System thinking skills are crucial for making informed decisions and taking responsible action in today's complex world (Forrester, 1993). However, conventional education only sometimes fosters these skills, even though learner-oriented approaches have been found to be more effective (Forrester, 1993).

Various educational methods have been examined to determine the best way to promote system thinking. Combining system dynamics models with additional instructional materials within an integrated learning environment has been found to be the most effective approach (Arndt, 2006). By empowering students to tackle localized problems, educators can create leaders in problem-solving and promote better learning and development outcomes for Latin American students and communities (Arndt, 2006).

The deficiencies in pre-college education in Latin America can be addressed through a practical and unconventional approach, such as System Dynamics with learner-centered learning (Lee, 2015). This chapter provides a comprehensive overview of the potential of systems thinking and its applications in education, including how system dynamics can improve student learning and understanding through simulation, game-based approaches, visualizations, and models.

Educators can create more meaningful and engaging learning environments by integrating system dynamics with other educational theories, such as learning goals and outcomes. Through collaboration, clear communication, creative thinking, and critical reflection, educators can empower students to identify and tackle localized problems and become leaders in problem-solving in the region.

System thinking and system dynamics are powerful tools for creating dynamic and interactive learning experiences in educational environments. By exploring how these tools can be combined with simulations, game-based approaches, visualizations, models, and faith-based teaching, educators and students can gain enhanced learning experiences.

To take a holistic approach to problem-solving, educators in Latin America must emphasize clear communication, understanding of problems, creative and critical thinking, and evaluation of solutions. By considering students' values and interests and empowering them to drive their learning, educators can foster leadership skills in problem-solving to help students be prepared to face increasingly complex challenges and thus contribute to the development of their communities.

Educators in Latin America can improve learning and development outcomes for students by forming teams and engaging in inspiring learning activities (Arndt, 2006). Collaboration and teamwork can help students recognize and manage emerging issues better while developing critical thinking and problem-solving skills. Ultimately, this leads to better learning outcomes for Latin American students and communities.

To foster creative dynamics in classrooms, teachers in Latin America should consider a number of important factors (Arndt, 2006). These include establishing a learning environment emphasizing collaboration and creativity, encouraging openness to new ideas and perspectives, utilizing interactive activities and instructional techniques, integrating teaching with technology, promoting opportunities for critical thinking and problem-solving, and reinforcing student confidence through feedback.

By prioritizing these factors, educators can create a more engaging and dynamic learning environment that fosters problem-solving skills and encourages creative thinking in students. This, in turn, can lead to improved learning and development outcomes for Latin American students and communities (Arndt, 2006).

7.2 Overview of System Thinking and Its Applications in System Dynamics in Education

Systems thinking skills are necessary to act successfully and responsibly in a complex world (Arndt, 2006). Systems thinking, as an approach that seeks to understand phenomena and problems as interconnected and complex systems, requires the development of specific skills such as critical thinking, problem-solving, and others like the ability to see the general picture and understand the interconnections between the parts; ability to identify and understand cause and effect relationships; ability to consider the long-term implications of actions and decisions; Ability to integrate different perspectives and knowledge from various disciplines.

However, conventional education needs to significantly improve these skills, while learner-centered approaches seem more promising. These skills are essential for students to understand the complex problems and decision-making associated with the disruptions of today's world.

To promote systems thinking in the classroom, integrated learning environments that combine system dynamics models with additional teaching materials have been shown to affect learning positively (Arndt, 2006). Guidelines and practices can be used to develop systems thinking in higher education classrooms, allowing students to identify connections, understand interconnections and boundaries, and create and use conceptual models (Elsawah & Ryan, 2022). Rubrics can also be used to measure students' progress in systems thinking development based on their ability to design causal loop diagrams, identify plausible connections, and explain archetypes of systems that can be useful in solving problems.

Systems thinking and system dynamics can also be used by educators, administrators, and pedagogical policymakers to understand the complex interconnections between different educational system components, such as the curriculum, teaching methods, student behavior, and school climate. This holistic view can help identify the root causes of problems and develop practical solutions, such as forecasting behavioral situations in the school system (Groff, 2013).

System dynamics have been successfully integrated into the K-12 education system in the US for over two decades, thanks to the support from various stakeholders (Lyneis, 2000). It is cross-cutting and can be integrated with various subjects, aiding students in understanding complex systems and developing critical thinking and problem-solving skills. While implementing system dynamics in education may not be easy, involving teacher leaders, supportive administrators, and volunteers can lead to successful inclusion in the curriculum.

7.3 The Role of Collaboration in Promoting Problem Solving and Education in Latin America

Latin America faces numerous challenges, including gaps in quality and access to its educational system, hindering socioeconomic progress and well-being in the region. Various organizations worldwide have emphasized addressing these challenges and improving access, coverage, progression, and completion at different educational levels (Cepal, 2021).

Improving the education system requires addressing the challenge of improving 21st-century skills (Suasnábar, 2017). This involves universalizing school coverage and adapting the system's structure, processes, results, and educational policy to new occupations that form the basis of economic growth, social equity, and cultural integration in the twenty-first century.

Collaboration is crucial in promoting problem-solving and education in Latin America, just like 21st-century skills. The construction of knowledge in the classroom is based on collaboration and a constructivist approach to learning, where discussion and reflection lead to brainstorming and collaborative formulation of analysis and solutions (Baucal et al., 2022). Effective teaching strategies and appropriate spaces are necessary to create such knowledge.

Collaboration between governments, educators, and other stakeholders can help address the lack of access to quality education, particularly in disadvantaged communities. Collaboration can involve sharing resources and expertise, developing effective teaching strategies, and creating partnerships to support students and their families.

In addition to improving access to education, collaboration can promote problem-solving skills among students. By working together on projects and assignments, students can learn to think critically and creatively, develop practical communication skills, and develop strong problem-solving skills. This can prepare them to tackle the complex problems facing their communities and the world (Peña-López, 2017).

7.4 Strategies for Fostering Creative Environments in Education in Latin America Using System Thinking

Systems thinking offers an effective strategy to promote creative educational environments throughout Latin America. This methodology allows educators to view the educational system as a whole, identifying factors contributing to a creative environment, such as the curriculum, teaching methods, and overall school culture.

To implement systems thinking in the classroom, educators can design a curriculum that fosters creativity by emphasizing project-based learning, problem-solving, and critical thinking. Several strategies can be applied, including system modeling, teaching feedback, case studies, problem-solving, and class discussions.

For example, students can learn to model systems using specialized software, such as STELLA or Vensim, analyze feedback loops in systems, analyze case studies involving complex systems, solve complex problems using a systems approach, and engage in class discussions that encourage systems thinking. These resources can help students develop basic systems thinking skills, identify interrelationships between various earth systems, and identify hidden parts of the hydrological system (Assaraf & Orion, 2009).

Project-based learning is another innovative teaching method to help students develop critical thinking skills and systems. Ekselsa et al. (2023) found that project-based learning-containing education for sustainable development moderately developed students' systems thinking skills. By focusing on real-world problems and issues, students can develop a deeper understanding of complex systems and how they can be sustainably managed.

Implementing systems thinking in the classroom requires educators to learn the tools and methods of systems thinking. With appropriate training and support, educators can effectively use systems thinking to foster creative environments throughout Latin America.

7.5 Method

System Dynamics is a methodology applied across different fields, including engineering, economics, and social sciences (Sterman, 2002). This approach is based on the principle that systems are composed of interconnected components that affect each other over time. To simulate the behavior of these systems and test various policies and scenarios, System Dynamics employ computer models, as Forrester (1987) explained.

Integrating systems thinking and creativity has become increasingly important in today's world, enabling people to address problems effectively and generate innovative solutions. One way to achieve this integration is through user-centered design, which uses creativity to design solutions focused on user needs (Brown, 2006).

To design a dynamic hypothesis for integrating systems thinking and creativity, we used the System Dynamics methodology. The first step was to identify the components of the system and their interconnections. The second step is to develop a causal loop diagram showing the components' relationships and how they interact over time.

Once the causal loop diagram is developed, the next step is to convert it into a stock-and-flow diagram that shows how the components change over time. This diagram will help us identify the critical feedback loops in the system and how they influence the system's behavior.

After the stock-and-flow diagram is developed, the next step is to develop a computer model of the system using the System Dynamics software. This model enables us to simulate the system's behavior under different policy and scenario conditions and identify the most effective solutions.

Finally, we use user-centered design principles to generate innovative solutions that focus on user needs. By integrating a user-centered design with System Dynamics, we can design solutions that are effective but also creative and user-friendly.

In conclusion, integrating systems thinking and creativity through user-centered design is a powerful approach for addressing complex problems in various fields. Using System Dynamics to design a dynamic hypothesis can help develop practical and innovative solutions that consider system interactions and the needs of the people involved from a holistic perspective and generate more impactful and sustainable results.

7.6 Dynamic Hypothesis

Systems thinking is a multidimensional concept that enhances problem-solving capabilities and creativity through various mechanisms. One such mechanism is the dopaminergic system. The dopaminergic system is a set of neuronal structures and pathways in the brain that use dopamine as the main neurotransmitter. Dopamine is a chemical that plays a crucial role in communication between nerve cells and is associated with cognitive mechanisms such as goal-directed thoughts, novelty seeking, and problem-solving, all essential for creativity (Takeuchi et al., 2010). Additionally, atypical problem-solving approaches can stimulate creativity by encouraging individuals to consider alternative perspectives and solutions (Dane et al., 2011).

Moreover, STEAM education programs based on systems thinking can foster human resources with systems thinking skills and creative problem-solving abilities (Jeon & Lee, 2015). This approach focuses on integrating science, technology, engineering, the arts, and mathematics to promote holistic problem-solving skills that incorporate diverse perspectives fostering creativity and critical thinking.

In managerial contexts, creative problem-solving can be distinguished into divergent exploratory thinking and convergent integrative thinking, which are essential aspects of creativity (Myszkowski et al., 2015). Applied systems thinking, represented by different systems methodologies, can be used to structure problem situations and creatively intervene in the real world to solve practical management problems (Petrovic et al., 2001). This approach emphasizes using systems thinking tools and frameworks for identifying and addressing complex management problems.

Strategic thinking, which includes systems thinking, creativity, and vision, is another mechanism that can be used to solve strategic problems (Liu & Cho, 2019). This approach involves a holistic and long-term perspective that considers multiple factors and possible scenarios to develop innovative solutions.

The interaction of understanding and forecasting thought processes is also important in creative mathematical thinking (Moiseienko, 2023). This approach involves using systems thinking tools and mathematical models to analyze complex problems and generate new insights.

Finally, emotions can also play a role in creativity and problem-solving. Positive emotions can enhance creativity by promoting flexible thinking and broadening attention, whereas negative emotions can impair problem-solving by inducing rumination and reducing cognitive flexibility (Baas et al., 2008).

In conclusion, systems thinking can promote creativity and problem-solve through various mechanisms, including the dopaminergic system, non-typical problem-solving approaches, STEAM education programs, applied systems thinking, strategic thinking, creative mathematical thinking, and emotions. These mechanisms offer diverse and innovative approaches to addressing complex problems in different contexts and meet user needs.

The dynamic hypothesis of creativity proposes that the capacity to think systemically enhances problem-understanding and creative problem-solving capabilities through a series of interconnected cycles: R1, R2, and R3 (as seen in Fig. 7.1). This

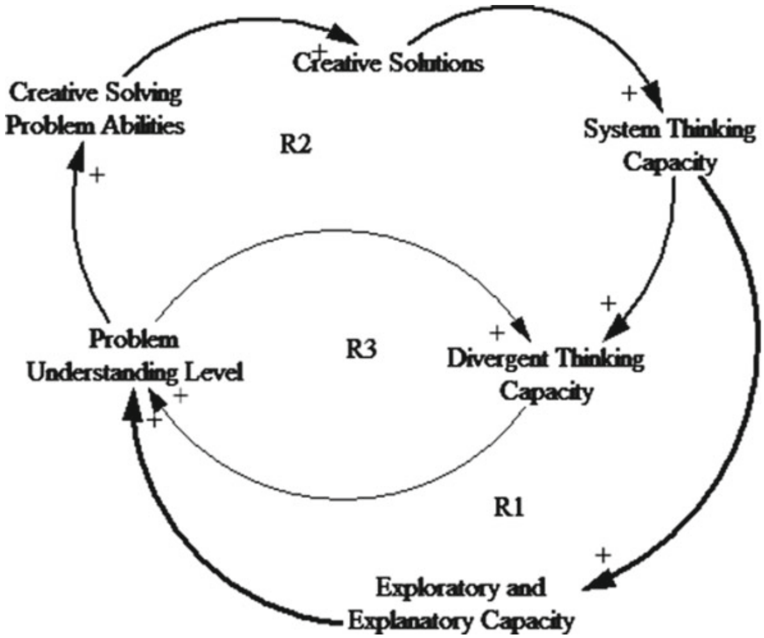

Fig. 7.1 Dynamic Hypothesis about how to promote creative solving abilities from system thinking

hypothesis draws on several references that highlight the importance of creativity and problem-solving skills in various contexts and the need to foster and develop these skills through education and collaboration.

Each cycle is explained below:

R1: Studies have shown that increasing the capacity for systems thinking enhances the capacity for both exploratory and integrative convergent thinking, which is helpful in analyzing complex problems and improving problem understanding. Convergent thinking has been found to be more effective for low-risk takers (Shen et al., 2018). In contrast, verbal convergent thinking predicts performance on single and multiple solution tasks. Cancer et al. (2022) examined the contributions of executive functioning and divergent thinking to creative problem-solving.

R2: Developing systems thinking skills promote a deeper and more complete understanding of problems and their contexts, leading to the ability to generate multiple solutions and different perspectives. Lumsdaine and Lumsdaine (1995) found that teaching creative problem-solving to engineering students improved their thinking and problem-solving skills. Hidayat and Evendi (2022) observed that applying a mathematical problem-solving model improved students' creative thinking abilities. Norris et al. (2022) discovered that a scenario's presentation to students influences their subsequent problem-solving approach, thus complicating the assessment of systems thinking.

R3: Divergent thinking, characterized by the ability to generate multiple original solutions to a problem, is directly linked to problem-solving capacity. A person with developed divergent thinking skills has a more remarkable ability to find practical and innovative solutions to problems as they can explore different perspectives and creative approaches. Divergent thinking can also help overcome mental rigidity and preconceived ideas that hinder problem-solving abilities. Studies have shown that divergent thinking is positively related to problem-solving skills (Cancer et al., 2022; Tucha et al., 2010; Zebehazy et al., 2020; Zhou et al., 2020) as it enables the pursuit of new ideas and contributes to innovation (Best et al., 2015).

7.7 Conceptual Model Validation

The authors' dynamic hypotheses and causal diagrams were validated through a rigorous process involving the assessment of both behavioral and structural validity of the simulation model, utilizing established guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010).

Behavioral validity was evaluated by assessing the model's ability to reproduce the system's behavior accurately. The structural validity was assessed by evaluating the model's feedback structure, time delays, and parameter values. The authors also ensured their diagrams accurately represented the system under investigation by validating them against the relevant literature and modeling discussions.

As illustrated in Fig. 7.2, the endogenous and exogenous variables that shape or determine the boundaries of a system are described comprehensively. The system boundaries were defined based on the criterion of belongingness, meaning that variables that affect and are affected by the system or are exogenous to the system but affect it were included. Endogenous variables included the capacity for systemic thinking, divergent and convergent thinking, education and training, complexity in problem-solving, organizational support, decision-making frameworks, available information and data, time and resource constraints, creative environments, inspiration stimulation, cognitive tools and techniques.

To validate their dynamic hypotheses and causal diagrams, the authors of this study adopted established structures and concepts from previous studies, as summarized in Table 7.1. These structures and concepts were used to ensure the structural validity of the dynamic hypotheses and causal diagrams and assess their ability to represent the system under investigation accurately.

In particular, the authors used structures and concepts from existing studies to assess the feedback structure, time delays, and parameter values of their dynamic hypotheses and causal diagrams. By adopting these established structures and concepts, the authors have contributed significantly to the literature on fostering problem-solving skills and creativity through systems thinking.

Table 7.1 provides an overview of the structures and concepts adopted from three existing works: Jeon et al. (2015), Moiseienko (2023), and Qudrat-Ullah and BaekSeo (2010). These structures and concepts validated the dynamic hypotheses and causal

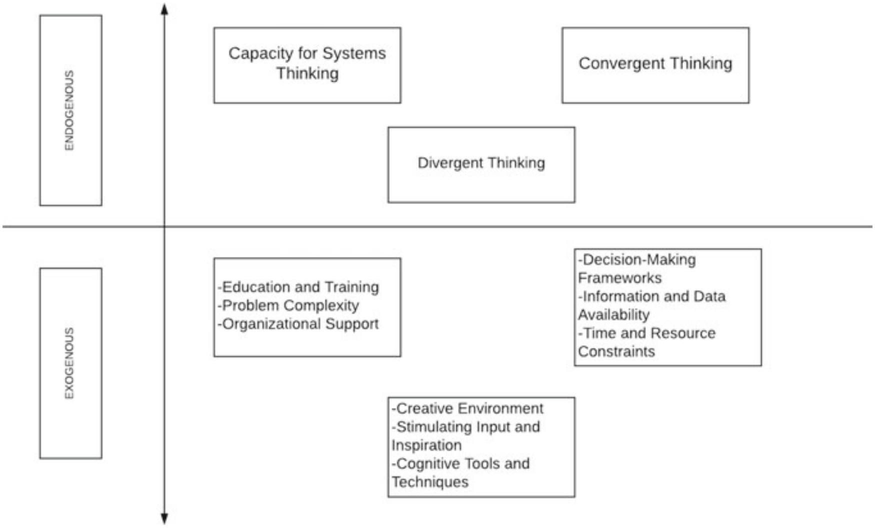

Fig. 7.2 The following is a selection of significant endogenous variables for this study, closely linked to a set of exogenous variables. These exogenous variables play a crucial role in the endogenous variables' existence and sustainability. It is important to note that endogenous variables depend on their associated exogenous variables to receive the necessary support and function effectively

Table 7.1 Structures adopted from the existing work

Structures/concepts	Remarks
Jeon, Jooyeon, and Jinsil Lee, 2015. "Development of an STEAM Program Based on Systems Thinking for Elementary School Students." Journal of the Korean Association for Science Education 35(5): 1042–1053	The structural formulation was adopted
Moiseienko, Anton. 2023. "Interaction of Thought Processes of Understanding and Forecasting in Creative Mathematical Thinking." Journal of Creative Behavior. Advance online publication. https://doi.org/10.1002/jocb.579	The structural formulation was adopted
Qudrat-Ullah, H., and BaekSeo S. (2010). "How to do structural validity of a system dynamics type simulation model: The case of an energy policy model". Energy Policy, 38(5): 2216–2224	The structural formulation was adopted

diagrams developed to foster problem-solving skills and creativity through systems thinking.

7.8 Discussion

The dynamic hypothesis of creativity proposes that a person's ability to think systemically enhances their problem-understanding and creative problem-solving capabilities through a series of interconnected cycles (Cancer et al., 2022). Cycles R1, R2, and

R3 promote the development of systems thinking, deeper problem understanding, and divergent thinking, which are all critical components of effective problem-solving. Studies have shown that individuals who can think systemically have a more holistic understanding of problems and their contexts, leading to the ability to generate multiple solutions and perspectives (Shen et al., 2018). Divergent thinking, in particular, is directly linked to problem-solving capacity as it enables individuals to pursue new ideas and contribute to innovation (Best et al., 2015).

To foster effective problem-solving and creativity, educators need to take a holistic approach that involves clear communication, understanding of problems, creative and critical thinking, collaborative environments, and evaluation of solutions (Dane et al., 2011). This approach encourages individuals to work together, share ideas, and consider alternative perspectives to develop creative solutions. Studies have shown that engaging in inspiring learning activities can empower students to recognize and manage emerging problems, resulting in improved learning and development outcomes (Nonthamand & Na-Songkhla, 2018). Collaborative teaching strategies that allow the development of systems thinking are crucial for facilitating learning and enabling students to develop analytical and creative abilities (Lumsdaine & Lumsdaine, 1995).

System dynamics, as an educational tool, has been shown to promote problem-solving skills and creativity among Latin American elementary school students (Hovmand & Hovmand, 2014). Collaborative teaching strategies that allow systems thinking to develop are crucial for facilitating learning and enabling students to develop analytical and creative abilities. Using simulations, game-based approaches, visualizations, and models can enhance student learning and understanding.

It is important to note that the effectiveness of system dynamics as an educational tool depends heavily on the quality of the instructional design and training of teachers. Therefore, providing adequate training and support to teachers is crucial for the successful implementation system dynamics in primary schools. Additionally, further research is needed to assess the long-term impact of system dynamics on students' problem-solving skills and creativity and to explore potential cultural differences in the effectiveness of this approach in different regions of Latin America.

In conclusion, the interconnected cycles of the dynamic hypothesis of creativity explain how creative problem-solving through systemic thinking can improve the ability to understand problems and develop creative solutions. By fostering and developing these skills through education and collaboration, individuals can enhance their problem-solving abilities and contribute to developing innovative solutions in various contexts. Using system dynamics and systems thinking tools in education can promote problem-solving skills and creativity among students, prepare them for the challenges of the modern world, and contribute to the development of a more innovative and sustainable society.

7.9 Conclusion

This chapter highlights the importance of using system dynamics in Latin American educational settings to promote problem-solving skills and creativity among elementary school students. Collaborative teaching strategies that allow systems thinking development are crucial for facilitating learning and enabling students to develop their analytical and creative abilities (Arndt, 2006). The research emphasizes the need for pedagogical strategies that promote systems thinking in elementary school students in Colombia.

To achieve the most effective results, it is essential to combine the implementation of system dynamics and systems thinking tools with additional didactic materials within an integrated learning environment (Elsawah & Ryan, 2022). Using simulations, game-based approaches, visualizations, and models can enhance student learning and understanding. This approach provides students with a hands-on learning experience that encourages them to explore and understand complex systems.

Educators must take a holistic approach to problem-solving that involves clear communication, understanding of problems, creative and critical thinking, and evaluation of solutions (Groff, 2013). Educators can empower students to recognize and manage emerging problems by engaging in inspiring learning activities. This approach results in improved learning and development outcomes, including developing critical thinking and problem-solving skills (Lyneis, 2000).

As our dynamic hypothesis describes (Fig. 7.1), integrating system dynamics, systems thinking, and creative problem-solving approaches into education can enhance students' problem-solving abilities, promote creative thinking, and prepare them for the challenges of the modern world. Collaborative teaching strategies that foster systems thinking, combined with didactic materials, simulations, and models, can provide students with a hands-on learning experience that promotes analytical and creative abilities. Educators can empower students to recognize and manage complex problems by taking a holistic approach to problem-solving, resulting in improved learning and development outcomes.

7.10 Insights and Implications for Practice

Collaborative teaching strategies facilitate learning and enable students to develop their analytical and creative abilities (Arndt, 2006). Educators should adopt a holistic approach to problem-solving that involves clear communication, understanding of problems, creative and critical thinking, and evaluation of solutions (Groff, 2013). By integrating systems thinking tools such as cause and effect diagrams, Botg's, simulations, and dynamic models, educators can promote systems thinking and problem-solving skills among students.

To achieve the most effective results, additional teaching materials should be integrated into an integrated learning environment that emphasizes collaboration and creativity (Elsawah & Ryan, 2022). Using simulations, game-based approaches, visualizations, and models can enhance students' learning and understanding, allowing them to explore and understand complex systems.

Educators should establish a learning environment that encourages openness to new ideas and perspectives, uses interactive activities and instructional techniques, integrates instruction with technology, promotes opportunities for critical thinking and problem-solving, reinforces student confidence, and provides feedback. Educators can empower students to recognize and manage emerging problems by creating an engaging and supportive learning environment, resulting in improved learning and development outcomes.

In summary, to promote systems-thinking and problem-solving skills among students, educators should focus on collaborative teaching strategies, adopt a holistic approach to problem-solving, integrate systems-thinking tools with additional teaching materials, and establish an engaging and supportive learning environment. By implementing these practical tips, educators can prepare students for the challenges of the modern world, promoting critical thinking, problem-solving, and creativity.

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Chapter 8
Exploring Gender Inequality and Practical Solutions for an Equitable Environment for Women in Scientific Vocations

Jorge-Andrick Parra-Valencia and Martha Lizette-Massey

Abstract Despite progress towards gender equality in science and education, women remain underrepresented in decision-making roles, and unconscious bias in recruitment and promotion processes remains a persistent challenge. Systems thinking provides a helpful framework for identifying the complex causes of gender inequality and developing realistic strategies and solutions. The dynamic hypothesis of gender inequality proposes the existence of four feedback loops, each with four cycles of reinforcement, that contribute to structural inequality between men and women in science. To effectively address gender inequality, a multifaceted approach is needed that targets the various feedback loops reinforcing gender disparities and addresses the structural factors that shape social inequalities. This could include combating unconscious bias, reducing gender-based stereotypes, and increasing access to resources. Continued efforts toward gender equality and equality of opportunity are crucial for creating a more equitable and inclusive scientific community. By applying systems thinking and taking a comprehensive approach to address gender inequality, we can progress towards a more just and equitable society.

Keywords Gender inequality · Scientific vocations · System thinking · Personal obstacles · Social obstacles · Strategies for change · Analyzing implications · Equitable environment · Women · Problem solving · Complex system · Effective strategies

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8.1 Introduction

Women in research and academia face significant challenges that hinder their career development and limit their advancement of scientific vocations. These challenges include a lack of representation in decision-making roles, unconscious bias in recruitment and promotion processes, unequal access to resources, such as mentoring and networks, inadequate recognition of their scientific contributions, and unequal compensation and salary gaps. These issues are compounded by systemic discrimination, insufficient career pathways, gender-based violence, harassment, and other forms of abuse in science disciplines, which perpetuate gender stereotypes and prevent women from reaching their full potential.

Various studies, including those from Ceci (2007), Rossi (1965), White (1970), and Tripp-Knowles (1995), have identified societal discouragements, innate differences in ability between the sexes, differences in aspirations, a lack of opportunities and acceptance, and a lack of understanding of the obstacles that women face in science academia as barriers to women's progress in scientific vocations. To address these obstacles and create a more equal and inclusive environment for women in scientific vocations, a multifaceted approach must consider multiple factors at play.

Systems thinking, an approach to problem-solving that examines the interconnectedness of components and their effects in a complex system, can be valuable for identifying the causes of gender inequality and developing realistic strategies and solutions. By examining the individual components of a system, such as societal discouragements, innate differences in ability between the sexes, and differences in aspirations, systems thinking can help identify the feedback loops and structural factors that contribute to gender inequality and develop practical solutions to address them. Additionally, systems thinking can be employed to analyze the implications of projects and help better align goals for creating an equitable environment for women in scientific vocations.

A range of strategies can be employed to create a more equitable and inclusive environment for women in research and academia. These include establishing quotas for women in leadership roles, providing anti-bias training, increasing access to resources to facilitate career growth, shared parental leave systems, incentives and recognition for female researchers, salary equity plans, affirmative action initiatives, specialized pathways in science careers, zero tolerance for gender-based violence, and gender-sensitive education programs to reduce stereotypes. Implementing these measures in conjunction with one another can create a more equitable and just environment for women in scientific vocations.

In conclusion, systems thinking can be a robust approach to identifying and addressing gender inequality in scientific vocations. By understanding women's obstacles, examining feedback loops contributing to gender inequality, and implementing effective strategies, we can create a more equitable and inclusive environment for women in research and academia.

8.2 Definition of Gender Inequality in Scientific Vocations

Gender inequality in scientific vocations refers to an uneven distribution of opportunities, rights, outcomes, and status based on gender identity. The Organization for Economic Cooperation and Development (2009) defines gender equality as promoting the freedom of all individuals to develop their abilities and make choices without being limited by gender stereotypes, rigid gender roles, or biases. Women in scientific vocations face various obstacles, including societal discouragements, differences in aspirations, lack of opportunities and acceptance, and lack of understanding of the obstacles they face in science academia. Studies from Ceci (2007), Rossi (1965), White (1970), and Tripp-Knowles (1995) have identified personal and social barriers, including innate differences in ability between the sexes, as contributing factors to these obstacles.

In Latin America, gender and income inequalities contribute to an even wider gap in opportunities and preparedness for boys and girls. According to Busso and Messina (2020), Latin America is one of the most unequal regions in the world regarding income, with significant disparities in knowledge and emotional development among children from different socioeconomic backgrounds. These disparities become more pronounced as students progress through their school years and face job opportunities. Women in Latin America face enormous barriers to success, which leads to a lack of interest in STEM. To address these barriers and create a more equal and inclusive environment for women in scientific vocations, strategies must consider multiple factors, including gender and income inequalities, cultural norms, and biases. By addressing these factors and promoting gender equality, we can create a more just and equitable society that benefits all individuals regardless of their gender identity.

8.3 What Are the Obstacles that Women Face in Scientific Vocations?

Women in scientific vocations face numerous obstacles that hinder their career development and limit their advancement. Ceci (2007) suggests that these obstacles are likely a combination of societal discouragements, innate differences in ability between the sexes, and differences in aspirations. These factors can lead to a lack of opportunities and acceptance for women in scientific vocations, as White (1970) noted. Additionally, personal obstacles such as the need for great motivation, thick skin, exceptional ability, and some unusual socialization patterns can further limit women's progress in scientific fields, as Rossi (1965) suggested. Tripp-Knowles (1995) argues that a lack of understanding of women's obstacles in science academia exacerbates these challenges. Overall, these papers suggest that personal and social obstacles contribute to gender inequality in scientific vocations and that a multifaceted approach is needed to address them. This approach should include strategies to combat unconscious bias, reduce gender-based stereotypes, and increase access to resources to create a more equitable environment for women in scientific vocations.

8.4 System Thinking and Gender Inequality

Systems thinking is an approach to problem-solving that considers the interconnectedness of components and their effects in a complex system. When applied to gender inequality in scientific vocations, systems thinking can be a valuable tool for identifying women's obstacles and developing effective strategies to address them. By examining the individual components of a system, such as societal discouragements, innate differences in ability between the sexes, and differences in aspirations, systems thinking can help to identify the causes of gender inequality and develop realistic solutions. Furthermore, systems thinking can be employed to analyze project outcomes and align goals for an equitable environment for women in scientific vocations (Lewis, 2016).

Gender inequality in scientific vocations is a multifaceted issue that requires a comprehensive approach. Systems thinking can be used to identify the feedback loops and structural factors that contribute to gender inequality in scientific vocations, such as unconscious bias, gender-based stereotypes, and unequal access to resources. Through systems thinking, we can better understand the complex dynamics that perpetuate gender inequality and develop practical solutions to address them.

Lewis (2016) argues that systems thinking can help to shift the focus from individual factors to the more extensive system that underlies gender inequality in scientific vocations. By taking a holistic view of the system, we can identify the interrelated components and feedback loops that contribute to gender inequality and develop strategies that address the root causes of the problem. Moreover, systems thinking can help to identify unintended consequences of interventions and evaluate their effectiveness in promoting gender equality.

In conclusion, systems thinking is a powerful tool for addressing gender inequality in scientific vocations. By using this approach, we can identify the complex interconnections that contribute to gender inequality and develop effective strategies that address the root causes of the problem. By taking a holistic view of the system, we can promote a more equitable environment for women in scientific vocations and ensure that everyone has equal access to opportunities, rights, outcomes, and status.

8.5 Method

We used systems thinking to develop a dynamic hypothesis that captures the key variables and feedback loops contributing to gender inequality in scientific vocations. This involved building a causal loop diagram that visualizes the interconnections between variables and feedback loops and developing equations that capture the system's dynamics over time. We then validated the dynamic hypothesis using data and feedback from stakeholders, including field experts and women working in scientific vocations.

We used system dynamics to design a dynamic hypothesis to explain gender inequality and develop solutions to address it.

Defining the problem: The first step in using system dynamics to address gender inequality is clearly defining the problem. This involves identifying key variables and feedback loops contributing to gender inequality in scientific vocations. Examples of key variables include societal discouragements, innate differences in ability between the sexes, differences in aspirations, and a lack of opportunities and acceptance.

Building a causal loop diagram: Once the problem is defined, the next step is to build a causal loop diagram (CLD) that captures the key variables and feedback loops contributing to gender inequality. CLD should include positive and negative feedback loops that influence the system over time. The purpose of CLD is to provide a visual representation of the key factors that contribute to gender inequality and how they interact with one another.

Develop a dynamic hypothesis: Based on CLD, the next step is to develop a dynamic hypothesis that explains how gender inequality arises and how it can be addressed. The dynamic hypothesis should include a causal loop diagram and equations that capture the system's key variables and feedback loops. The hypothesis should also include a set of scenarios that allow testing of the effects of different interventions on the system.

Validating the hypothesis: Once the dynamic hypothesis has been developed, it should be validated using data and feedback from stakeholders. This may involve running simulations to test the effectiveness of different interventions and solicit feedback from experts in the field. The validation aims to ensure that the dynamic hypothesis accurately captures the key factors that contribute to gender inequality and that the proposed interventions are likely to be effective.

Implementation and monitoring of interventions: Once the dynamic hypothesis is validated, the next step is implementing and monitoring interventions to address gender inequality. This may involve implementing policies to reduce unconscious bias, promote gender-based stereotypes, and increase access to resources for women in scientific vocations. The effectiveness of these interventions should be monitored over time, using data and feedback from stakeholders to ensure that they have the desired effect.

Refine the hypothesis: As new data and feedback become available, the dynamic hypothesis should be refined to reflect the changing system dynamics. This may involve updating the causal loop diagram and equations to reflect new feedback loops or modifying the scenarios to include additional interventions.

Communicate and disseminate findings: Finally, the findings of the system dynamics analysis should be communicated and disseminated to stakeholders and the broader scientific community. This may involve publishing research papers, presenting findings at conferences, and engaging policymakers to promote evidence-based interventions to address gender inequality in scientific vocations.

8.6 Results

The dynamic hypothesis in Fig. 8.1 explains how the reinvestment of strategic resources, such as capital, financial resources, relationships, knowledge, health, pleasant environments, and skills, can contribute to differences between two groups in scientific vocations (Lampón et al., 2020). The reinvestment rate is crucial in this process, as it determines the rate at which the resource is increased. The initial difference in the reinvestment rate between groups can result in minor differences that accumulate over time, leading to inequity behavior (Sterman 2000).

Inequity occurs when one group has a greater reinvestment capacity than another group, whether in terms of wealth or ability to reinvest resources. Minor initial differences in wealth or reinvestment rates can lead to more significant differences over time due to exponential and geometric growth. This behavior is known as the Matthew effect, where those with more resources are more likely to gain additional resources (Merton, 1968).

To address gender inequality in scientific vocations, it is essential to understand the dynamics of the inequity archetype and identify effective strategies to reduce its effects. Teachers, administrators, and policymakers can play a crucial role in understanding when and how significant gaps occur in the dynamics of the archetype. For example, studies can be conducted to understand why there are differences in the development of scientific skills and vocations between different groups (Lampón et al., 2020).

It is essential to recognize that their choices do not solely determine individuals' success but are also influenced by initial conditions of strategic resources and the environment. Individuals from disadvantaged backgrounds may need more access to valuable resources, such as education, advice, and financial capital, limiting their options

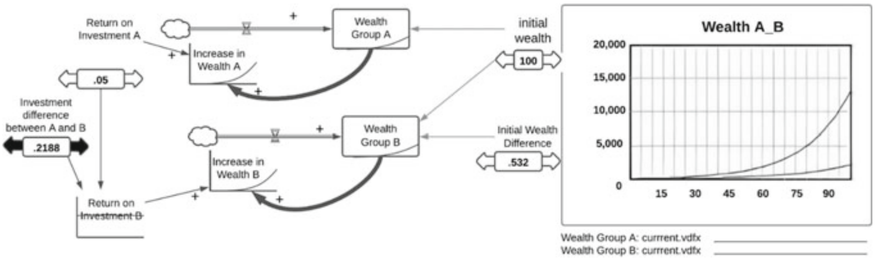

Fig. 8.1 The dynamic hypothesis explains the differences between two groups when talking about the reinvestment of a strategic resource

and decision-making abilities. The environment also plays a crucial role in shaping individuals' success. An environment that fosters innovation and entrepreneurship is more conducive to business success than an environment that does not (Shane, 2009).

Furthermore, it is essential to recognize that a system conditions societal inequity. Inequalities in access to valuable resources, such as education and financial capital, can perpetuate inequality in people's success. Therefore, it is necessary to consider other factors, such as the initial conditions of strategic resources and the environment, when addressing gender inequality in scientific vocations (Lampón et al., 2020).

In conclusion, the dynamic hypothesis developed through systems thinking provides insights into the root causes of gender inequality in scientific vocations. The hypothesis identifies the dynamics of the inequity archetype, the Matthew effect, and the influence of initial conditions and the environment on individuals' success. By understanding these dynamics, we can identify effective strategies to reduce the effects of gender inequality and create a fairer and more equitable environment for all individuals.

Gender inequality in education and science is a persistent issue that has been extensively studied. The gender gap is particularly evident in STEM disciplines, where women are underrepresented and face numerous barriers to entry and advancement (Hanson et al., 1996; Riedler et al., 2021). The causes of gender inequality in higher education are complex and multifaceted, with societal expectations, cultural norms, and institutional biases all playing a role (Buchmann, 2009).

Research has indicated that gender stratification is greater in science occupations than in science education, indicating that factors beyond training contribute to inequality in high-status science careers (Hanson et al., 1996). Despite efforts to narrow the gender achievement gap, women continue to be underrepresented in STEM careers, which contributes to gender inequalities in income (Amato, 2021).

Gendered high school course selection has been identified as a precursor to gendered careers, with self-concept and intrinsic value mediating the relationship between course selection and career choice (Nagy et al., 2008). While there is a national interest in women's underrepresentation in STEM, gender inequality in the social sciences has received less attention (Casad et al., 2022).

Ensuring gender equality in higher education is a priority worldwide, particularly in science disciplines, as gender has been linked to achievement and participation in certain professions (Dilli & Westerhuis, 2018; Egne, 2014). Countries with greater gender equality in science education have been found to have higher entrepreneurial activity in knowledge-intensive sectors and high-growth aspirations (Dilli & Westerhuis, 2018; Riedler et al., 2021).

Gender differences in interests vary by STEM field, with the largest gender differences favoring men observed in engineering disciplines and gender differences favoring women in social sciences and medical services (Su & Rounds, 2015). Overall, gender inequality in education and science is a complex issue that requires ongoing attention and efforts to address.

The first cycle, R1, applies to both men and women, where societal expectations increase the capacity for reinvestment with delay. For instance, societal expectations

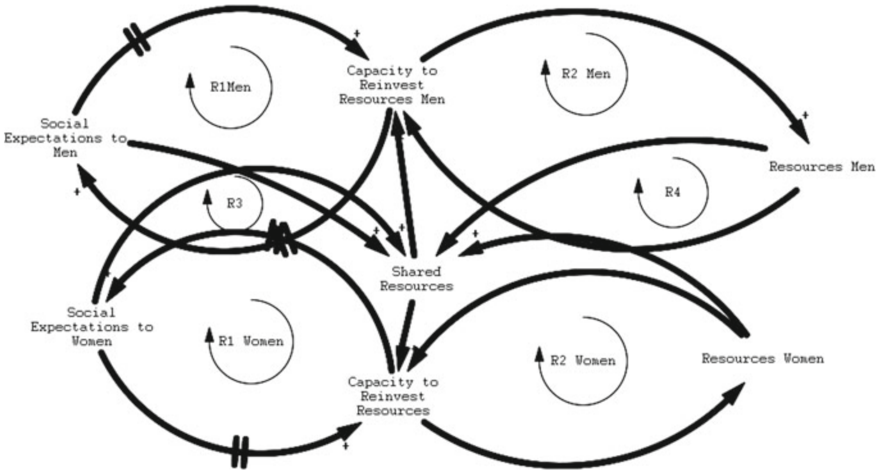

Fig. 8.2 Presents the dynamic hypothesis explaining how gender inequality develops between men and women in science. This hypothesis identifies four feedback loops, each consisting of four reinforcement cycles

that men are better suited to STEM careers can lead to increased investment in their education and training. In contrast, women may be discouraged from pursuing STEM careers (Hanson et al., 1996). This reinforcement can create a feedback loop in which men have a greater capacity for reinvestment, further increasing their resources and opportunities.

The second cycle, R2, increases the resources by augmenting the reinvesting ability. As a result, increased resources further enhance the capacity for reinvestment. This feedback loop can lead to a growing disparity in resources between men and women, as men may have greater access to resources, such as funding, mentorship, and networking opportunities (Riedler et al., 2021).

The third cycle, R3, is linked to the differential expectations of men and women, which provides better access to resources for the group with higher expectations, similar to the Matthew effect. This cycle can lead to a self-fulfilling prophecy in which men are perceived as more competent and receive more resources and opportunities. At the same time, women are overlooked and have limited access to resources (Merton, 1968). This feedback loop can create a significant barrier for women in science, as they may be perceived as less competent or committed to their careers than men.

Finally, Societal expectations can significantly impact how resources are distributed in science, leading to a feedback loop that favors men over women (Tellhed et al., 2016). This is because societal expectations can lead to men receiving more investment in their education and training in STEM careers, while women may be discouraged from pursuing those careers (Wang et al., 2015). This can create a feedback loop in which men can reinvest more remarkably, further increasing their resources and opportunities (Tellhed et al., 2016). In addition, differential expectations of men and women can lead to men being perceived as more competent and therefore receiving more resources and opportunities. In contrast, women are overlooked and have limited access to resources (Saw et al., 2018). This can create a significant barrier for women in science, as they may be perceived as less competent or committed to their careers than men (Cabay et al., 2018).

Research has shown that women are underrepresented in STEM careers, despite obtaining higher course grades in math than boys and being just as likely to be enrolled in advanced math courses in high school (Wang et al., 2015). The degree of women's underrepresentation varies by STEM fields (Saw et al., 2018). Studies have also shown that various factors, including the role of formal education, informal education, and community, contribute to the lack of participation in STEM and STEM careers (Wiebe et al., 2018). Furthermore, women in doctoral programs in STEM leave without finishing at higher rates than men and turn away from academic and research careers (Cabay et al., 2018).

The social climate can also undermine or strengthen women's motivation and career aspirations in STEM fields (Tellhed et al., 2016). Therefore, it is essential to provide STEM encouragement and career development programs that engage girls from an early age (Mohtar et al., 2019). Such interventions can have longer-lasting effects and are associated with lower costs than interventions that begin later in childhood (Saw et al., 2018). Additionally, it is essential to address gendered educational and occupational pathways entrenched in many countries (Saw et al., 2018).

Shared resources generated by men and women are allocated based on expectations, with greater sharing occurring when expectations are higher. This creates structural inequality, as higher performance and contribution expectations for men versus women in science lead to disparities in resource allocation, accumulation, and capacity development. For example, men may receive more credit for their contributions to research projects, whereas women's contributions are undervalued or overlooked (Casad et al., 2022). This feedback loop can further perpetuate gender inequality in science by limiting women's opportunities to develop skills, advance their careers, and access resources.

In conclusion, the dynamic hypothesis provides insights into how gender inequality develops between men and women in science. The feedback loops identified in the hypothesis highlight the role of societal expectations, differential access to resources, and allocation of shared resources in perpetuating gender inequality. Addressing these barriers requires systemic change, including more significant investment in education and training for women in STEM, the increased representation of women in leadership positions, and cultural shifts that challenge gender bias and stereotypes (Egne, 2014). Addressing these issues can create a more equitable and inclusive environment for women in science, promoting innovation and progress. It is essential to address these expectations and provide interventions that engage girls from an early age to increase their participation in STEM careers (Mohtar et al., 2019).

8.7 Conceptual Model Validation

This section validates the authors' dynamic hypotheses and causal diagrams. The validation process involved assessing the behavioral and structural validity of the simulation model using established guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010).

Behavioral validity was evaluated by assessing the model's ability to reproduce the behavior of the system it represented. The structural validity was assessed by evaluating the model's feedback structure, time delays, and parameter values. The authors validated the diagrams against relevant literature and modeling discussions, ensuring they accurately represented the system under investigation.

Figure 8.3 provides a comprehensive description of the endogenous and exogenous variables that shape or determine the boundaries of a system. The endogenous variables in the dynamic hypothesis include capacity for reinvestment, location of shared resources, social expectations, and perception of competition. In contrast, exogenous variables include family and social environment, social and cultural norms, political and legislative policies, historical and global influences, social norms and expectations, media representation, education and training, professional affiliations, cultural attitudes, role models, social networks and connections, labor market conditions, policy and practice organization, government regulations and funding, institutional support, and social values and priorities.

Overall, the validation process confirmed the accuracy and reliability of the study's dynamic hypotheses and causal diagrams. By providing a comprehensive and detailed description of the variables involved in shaping the system under investigation, there is a better understanding of the factors contributing to gender inequality and provides valuable resources for policymakers and researchers working to address this critical issue.

Table 8.1 provides an overview of the structures and concepts adopted from the existing literature to validate the causal loops and dynamic hypothesis presented in this chapter on gender inequality. The table shows how various concepts were incorporated into the causal theories and how the structure of the investigated system was developed.

The validation process was based on the established guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010), which involve assessing the behavioral and structural validity of the simulation model. The model's ability to reproduce the behavior of the represented system was evaluated to ensure its behavioral validity and the model's feedback structure, time delays, and parameter values.

This study provides a comprehensive overview of the structures and concepts adopted from existing literature to validate causal loops and dynamic hypotheses related to gender inequality. By incorporating these structures and concepts, this study contributes to a better understanding of the dynamics of gender inequality. It provides a valuable resource for policymakers and researchers addressing this critical issue.

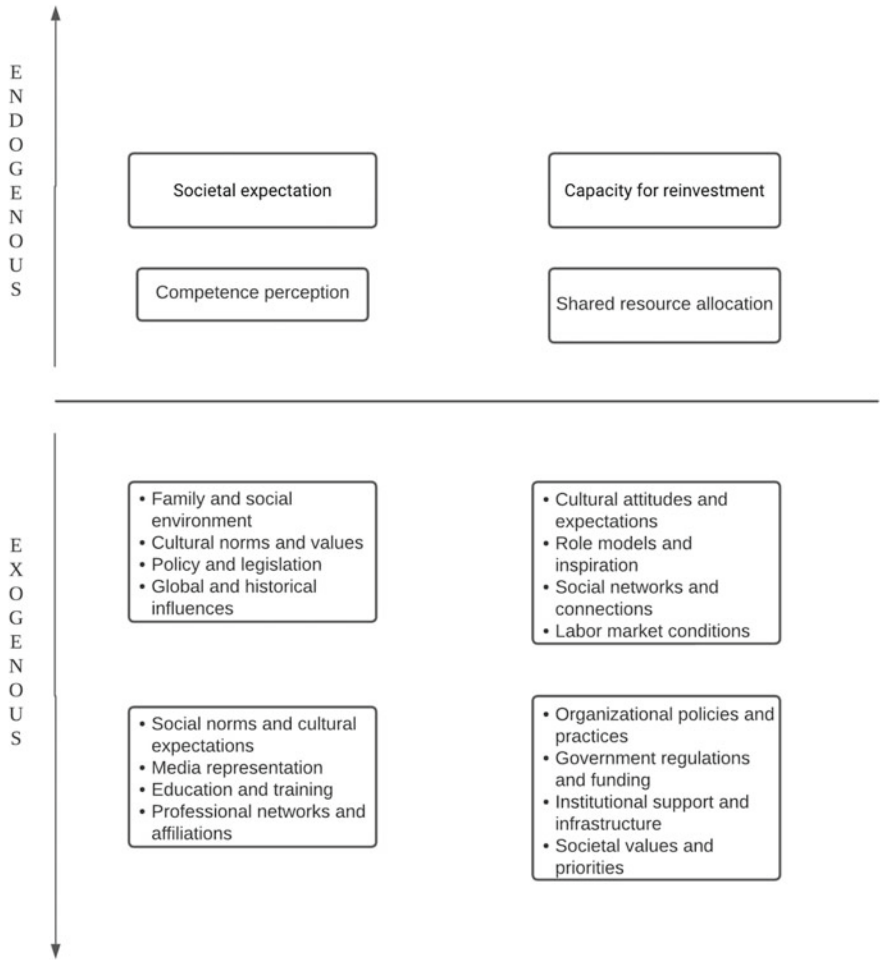

Fig. 8.3 Endogenous and exogenous variables

Table 8.1 provides a valuable reference for researchers interested in the dynamics of gender inequality. The table highlights the importance of adopting established structures and concepts from the existing literature to ensure the accuracy and reliability of simulation models. Following the guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010).

Table 8.1 summarizes the structural validation process based on the concepts included in the literature. The table shows the structures and concepts adopted from existing works and brief remarks on each structure.

The first structure, adopted from Lampón et al. (2020), focused on promoting gender inclusivity in academia and was included in the study as a structural reference. The second structure, from Riedler et al. (2021), highlights the importance of

Table 8.1 Structures adopted from the existing work

Structures/concepts	Remarks
Lampón, Jesús F., et al. "Towards a gender-inclusive academia: A call to action for the neuroscience community." European Journal of Neuroscience 52, no. 3 (2020): 2537–2546	A structural structure was adopted
Riedler, B., N. Stéphenne, E. Aguilar-Moreno, M. Jagaille, A. Monfort-Muriach, G. Fiore, and N. Antoniou. 2021. "Towards Gender Equality in Education and Career in the Earth Observation and GI Sector." The International Archives of the Photogrammetry Remote Sensing and Spatial Information Sciences XLIII-B5-2021: 21–27	A structural structure was adopted
Tellhed, U., M. Bäckström, and F. Björklund. 2016. "Will I Fit in and Do Well? The Importance of Social Belongingness and Self-Efficacy for Explaining Gender Differences in Interest in STEM and HEED Majors." Sex Roles 75 (3–4): 148–160	A structural structure was adopted
Wang, M., J.L. Degol, and F.-F. Ye. 2015. "Math Achievement Is Important, but Task Values Are Critical, Too: Examining the Intellectual and Motivational Factors Leading to Gender Disparities in STEM Careers." Frontiers in Psychology 6: 36	A structural structure was adopted
Cabay, M., B.L. Bernstein, M.B. Rivers, and N. Fabert. 2018. "Chilly Climates, Balancing Acts, and Shifting Pathways: What Happens to Women in STEM Doctoral Programs." Social Sciences 7 (2): 23	A structural structure was adopted
Alkire, Sabina, Ruth Meinzen-Dick, Amber Peterman, Agnes R. Quisumbing, Greg Seymour, and Ana Sofia Vaz. 2013. The Women's Empowerment in Agriculture Index. https://doi.org/10.35648/20.500.12413/11781/ii1g1i	A structural structure was adopted
Egne, Ruth. "The leaky pipeline in the scientific career." EMBO Reports 15, no. 7 (2014): 673–676	A structural structure was adopted

gender equality in education and careers in the Earth's observation and geographical information sectors. The third structure, proposed by Tellhed et al. (2016), emphasizes the significance of social belongingness and self-efficacy in explaining gender differences in STEM and HEED majors.

The fourth structure, from Wang et al. (2015), examines the intellectual and motivational factors leading to gender disparities in STEM careers, emphasizing the critical role of task values. The fifth structure, from Cabay et al. (2018), explores the challenges faced by women in STEM doctoral programs, including child climates, balancing acts, and shifting pathways. The sixth structure, from Alkire et al. (2013), presents the Women's Empowerment in Agriculture Index, which measures women's empowerment in agriculture-related activities.

Finally, the seventh structure, from Egne (2014), discusses the leaky pipeline in scientific careers, highlighting the challenges faced by women in pursuing scientific careers. All of these structures were included in the study as references to validate the model's feedback structure, time delays, and parameter values, ensuring the accuracy and reliability of the developed dynamic hypotheses and causal diagrams.

Overall, Table 8.1 provides valuable insights into the literature on gender inequality in various sectors, highlighting the importance of promoting gender inclusivity and equality in education and career opportunities. By adopting structural references from established works, this study contributes to a better understanding of the factors contributing to gender inequality, providing a valuable resource for policymakers and researchers working to address this critical issue.

8.8 Discussion

The dynamic hypothesis of gender inequality in science identifies four feedback loops that contribute to the persistent disparities between men and women. The first cycle, R1, is driven by societal expectations that reinforce gendered notions of suitability for STEM careers, resulting in men receiving increased investments in their education and training. On the other hand, women may be discouraged from pursuing STEM careers, leading to a feedback loop in which men have a greater capacity for reinvestment, further increasing their resources and opportunities. (Hanson et al., 1996).

The second cycle, R2, is linked to increased resources, which augment the ability to reinvest. This feedback loop can lead to a growing disparity in resources between men and women, as men may have greater access to resources such as funding, mentorship, and networking opportunities. This further enhances the capacity for reinvestment and perpetuates the cycle (Riedler et al. 2021).

The third cycle, R3, is related to the differential expectations of men and women and provides better access to resources for the group with higher expectations. This cycle can create a self-fulfilling prophecy in which men are perceived as more competent and receive more resources and opportunities, whereas women are overlooked and have limited access to resources. This feedback loop can create a significant barrier for women in science as they may be perceived as less competent or committed to their careers than men (Merton, 1968).

Finally, societal expectations significantly impact the distribution of resources in science, leading to a feedback loop that favors men over women. This is because societal expectations can lead to men receiving more investment in their education and training in STEM careers, whereas women may be discouraged from pursuing those careers. This can create a feedback loop in which men can reinvest remarkably, further increasing their resources and opportunities. In addition, the differential expectations of men and women can lead to men being perceived as more competent and therefore receiving more resources and opportunities, while women are overlooked and have limited access to resources (Cabay et al., 2018; Saw et al., 2018; Tellhed et al., 2016; Wang et al., 2015).

Despite efforts to address gender inequality in science, significant disparities have persisted at all academic levels (Gupta & Sharma, 2002; West et al., 2013). Motherhood is a significant factor in perpetuating gender inequality in science, as women often face challenges in balancing their careers and family responsibilities (Staniscuaski et al., 2020). These challenges can lead to lower productivity, fewer opportunities for advancement, and limited access to resources, thus reinforcing the feedback loops identified in the dynamic hypothesis.

Addressing gender inequality in science requires a multifaceted approach that targets various feedback loops, including societal expectations, differential access to resources, and the allocation of shared resources based on expectations. This approach should involve organizational interventions that promote gendered knowledge and equality of opportunity in science. It is essential to recognize the structural factors that shape social inequalities and implement policies that promote equality of opportunity in science, such as addressing biases and stereotypes that limit women's opportunities, promoting work-life balance, providing mentorship and networking opportunities, and increasing the representation of women in leadership positions. By addressing these issues, we can create a more equitable and inclusive environment for women in science, promoting innovation and progress, while reducing the forgone growth in per capita income caused by gender inequality.

8.9 Conclusion

In conclusion, the dynamic hypothesis of gender inequality in science highlights the pervasive and multifaceted nature of gender disparities. The four feedback loops identified by this hypothesis demonstrate how social expectations, differential access to resources, and structural inequalities contribute to the continued underrepresentation of women in science and academia.

Despite efforts to address gender inequality, progress has been slow, with motherhood and societal inequalities perpetuating such disparities. To effectively address gender inequality, a multifaceted approach that targets various feedback loops and addresses the structural factors that shape social inequalities is required.

Organizational interventions, policies that promote work-life balance, and addressing implicit biases and stereotypes are some ways to address gender inequality. By continuing to work towards gendered knowledge and equality of opportunity, we can progress toward a more equitable and inclusive scientific community.

As our dynamic hypothesis describes (Fig. 8.2), gender inequality in science and education is a complex issue that requires sustained efforts and a multifaceted approach. By understanding the dynamic hypothesis of gender inequality and addressing the underlying factors contributing to gender disparities, we can create a more equitable and inclusive scientific community.

8.9.1 Insights and Implications for Practice

Systems thinking can provide a comprehensive and strategic approach to addressing gender inequality in science and education (Zippel & Ferree, 2018). The dynamic hypothesis of gender inequality in science can serve as a valuable framework for identifying the feedback loops contributing to the problem and developing effective interventions and policies (Larivière et al., 2013).

To better understand the root causes of gender inequality, decision-makers can prioritize identifying and analyzing the systemic factors contributing to gender disparities in science and education. This can involve examining existing social and cultural norms, policies and laws, and organizational cultures perpetuating gender inequality (Zippel & Ferree, 2018). Conducting a thorough systems analysis and developing a system map of the components and stakeholders involved can provide a more comprehensive understanding of the issue and inform decision-making.

To address gender inequality, decision-makers can develop and implement policies and programs that aim to mitigate or eliminate systemic root causes and address the issue of gender inequality. For example, policies that promote work-life balance, provide equal access to resources and opportunities and address implicit biases and stereotypes can help create a more equitable and inclusive environment for women in science and education (Zippel & Ferree, 2018).

To ensure that the proposed solutions are effective, decision-makers can continuously monitor and assess the implementation of policies and programs. Regular evaluations and gathering feedback from stakeholders can help identify areas for improvement and ensure that desired changes elicit corresponding changes in the broader system (Larivière et al., 2013).

In conclusion, using systems thinking to address gender inequality in science and education can provide practical insights and recommendations for decision-making. By prioritizing the identification and analysis of systemic root causes, developing and implementing effective policies and programs, and continuously monitoring and assessing the implementation of solutions, we can work towards creating a more equitable and inclusive environment for women in science and education.

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Part IV
Bridging the Digital Gap with Systems Thinking

Chapter 9
Leveraging AI Tools for Enhanced Digital Literacy, Access to Information, and Personalized Learning

Jorge-Andrick Parra-Valencia and Martha-Lizette Massey

Abstract The digital divide remains a significant challenge for many communities worldwide. However, recent advancements in AI technology offer a unique opportunity to address this divide by enhancing digital literacy, promoting access to information and resources, and facilitating personalized learning experiences. This chapter explores how machine learning algorithms, natural language processing, and other AI-driven technologies can be leveraged to provide more effective and efficient training tailored to individualneeds and learning styles. Additionally, AI tools can provide more accessible and relevant information to individuals regardless of their level of digital competence. By utilizing AI tools to improve digital literacy, promote access to information and resources, and facilitate personalized learning experiences, we can create a dynamic feedback loop that contributes to closing the digital divide. This chapterproposes that this feedback loop can lead to a cycle of empowerment, where the accumulation of knowledge and resources reinforces the ability to learn and acquire more resources. Finally, this chapter provides recommendations on how to effectively and responsibly use AI tools to address the digital divide.

Keywords Digital gap · AI tools · Digital literacy · Access to information · Personalized learning · Machine Learning · Natural language processing · Digital proficiency · Digital education · Technology · Digital Inclusion · Equity · Digital divide · Education technology · Digital training · Feedback loop

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9.1 Introduction

The unequal distribution of access to and use of digital technologies among various groups of people, commonly referred to as the digital gap or divide, remains a significant challenge in today's society (Fraillon et al., 2020). Research has shown that income inequality is a significant factor in the digital divide, with those in lower socioeconomic classes having less access to digital technologies (Fuchs, 2008; Mills & Whitacre, 2003). In addition, there is a consistent gap between home Internet usage in metropolitan and non-metropolitan areas in the United States (Mills & Whitacre, 2003), and gender is believed to play a role (Joiner et al., 2006). Despite efforts to bridge the digital divide, such as initiatives to decrease inequalities between groups of different socioeconomic backgrounds (Soomro et al., 2020), challenges remain, including the rural–urban Internet access gap in countries like Indonesia (Hadi, 2018).

However, recent developments in AI technology offer a promising approach for addressing the digital gap and improving digital inclusion. AI tools can potentially promote access to information and resources, enhance digital literacy, and facilitate personalized learning experiences (Fuchs, 2008; Fraillon et al., 2020; Soomro et al., 2020). By leveraging the power of AI tools, we can work towards creating a more equitable society where everyone has equal access to digital technologies and can fully participate in the digital world. In this chapter, we explore the potential of AI tools to address the digital gap and provide recommendations on how policymakers, educators, and technology developers can work together to promote digital inclusion.

9.2 Enhancing Digital Literacy Through AI Tools

Digital literacy is an essential skill for participation in social and economic life; however, many individuals still lack adequate digital skills (Fitriani, 2023). AI-powered platforms can significantly enhance digital literacy by providing personalized feedback and guidance for digital training (Wood et al., 2021; Voulgari et al., 2021). These platforms can be efficient and effective and lead to better learning outcomes (Cingolani et al., 2022; Mhlanga, 2020a, 2020b). AI tools can also be used to design and evaluate systems to improve digital literacy in educational settings (Voulgari et al., 2021). Moreover, AI can assist with research and writing a research paper or novel (Warren, 2023).

However, there are potential limitations and challenges associated with the use of AI-powered digital training platforms. Reliable internet connectivity is necessary to access these platforms (Fitriani, 2023), and concerns about accessibility and inclusivity must be addressed to ensure that AI-powered digital training is accessible to a diverse range of learners (Nazaretsky et al., 2021). Ethical concerns also arise, such as the potential for AI to be used unethically in authoritarian governance. It is essential to ensure that AI is used both responsibly and ethically (Geis et al., 2019).

Despite these challenges, AI-powered platforms offer the potential to enhance digital literacy and contribute to closing the digital gap (Mhlanga, 2020a, 2020b). However, implementing AI-powered digital training platforms must be both responsible and equitable, considering the needs and concerns of all learners (Cingolani et al., 2022). Therefore, it is crucial to address the potential limitations and ethical concerns associated with AI-powered digital training platforms (Krügel et al., 2022; Geis et al., 2019) to maximize societal benefits. In conclusion, AI-powered platforms have the potential to enhance digital literacy and bridge the digital divide (Williamson & Eynon, 2020), and it is important to use AI tools in a responsible and ethical manner to realize these benefits.

9.3 Promoting Access to Information and Resources

Artificial Intelligence (AI) has transformed the way information is accessed and processed, making it more accessible and relevant to users. Natural Language Processing (NLP) is one of the most significant contributions of AI (Chen & Decary, 2019). NLP algorithms can interpret written or spoken language, thereby allowing machines to extract relevant information, categorize it, and provide insights. This technology is used in search engines, such as Google and Bing, to provide users with more accurate search results by analyzing the context and intent of the search query (Wiljer & Hakim, 2019). Additionally, chatbots and virtual assistants use NLP to understand and respond to user queries (Deng & Lin, 2023).

Machine Learning (ML) is another AI-powered technology that can make information more accessible (Kuleto et al., 2021). ML algorithms can analyze large amounts of data to identify patterns and relationships, which can help categorize and organize information. This can be particularly useful when dealing with large datasets or complex information structures, where manual organization can be time consuming and error prone. Predictive analytics, where algorithms are trained to make predictions based on historical data, is another application of ML (Pandey et al., 2021).

AI-powered technologies can also personalize information, making it more relevant to individual users. Recommendation systems used by e-commerce sites and streaming services use ML algorithms to suggest products or content based on a user's previous interactions and preferences (Moriuchi, 2020). This personalization improves user experience and increases the likelihood of engagement and conversion.

In conclusion, AI-powered technologies have made information more accessible and relevant through NLP, ML, and personalized recommendation systems. These technologies can potentially impact almost every aspect of our lives, from healthcare to education (Pokrivčáková, 2019a, 2019b; Luckin & Cukurova, 2019a, 2019a; Moriuchi, 2020; Wiljer & Hakim, 2019; Kuleto et al., 2021). By leveraging AI tools, we can promote access to information and resources, democratize knowledge, and improve people's lives worldwide.

9.4 Method

Systems Thinking and System Dynamics are powerful tools for understanding complex systems, such as the digital gap, and for supporting better decision-making. Systems Thinking is a holistic approach to problem solving that emphasizes the interconnections between different components of a system and the feedback loops that govern their behavior (Sterman & Dynamics, 2000). System Dynamics, on the other hand, is a method for modeling and simulating complex systems over time using feedback loops and causal relationships to understand system behavior (Forrester, 1961).

To define the dynamic hypothesis for the study of AI tools in education using Systems Thinking and System Dynamics, we followed the steps outlined below:

Identifying the research problem: We clearly defined the problem at hand, which is the study of AI tools in education and their potential impact on student learning outcomes, as well as the factors that contribute to the equitable distribution of these tools.

Develop a conceptual model: We developed a conceptual model that describes the key components of the system and their interrelationships using causal loop diagrams to show the feedback loops that govern the system behavior.

The conceptual model is translated into a dynamic hypothesis. We translated the conceptual model into a dynamic hypothesis that describes how the key components of the system interact over time to produce the observed patterns of behavior and outcomes. This hypothesis is based on the literature and captures the key feedback loops and causal relationships that underlie a system's behavior.

Validation of the hypothesis: We validated the dynamic hypothesis using structural and literature-based methods. The structural validation method we used was based on the work of Qudrat-Ullah and BaekSeo (2010a), which involves comparing the structure of the model with the underlying theory and data to ensure that the model accurately represents the system being studied. We also conducted a literature-based validation by comparing the dynamic hypothesis with existing literature on AI tools in education to ensure that it is consistent with current knowledge and theory.

Using this hypothesis to generate insights and inform interventions, we used the validated hypothesis to create insights into the system's behavior and the potential effects of different interventions. These insights can inform policy and practical decisions and guide further research. Using Systems Thinking and System Dynamics in this manner, we gained a deeper understanding of the impact of AI tools in education and developed more effective strategies for addressing the digital gap. These methods enabled us to capture the complexity of the system and its interconnections and to predict the long-term effects of different interventions without necessarily developing a simulation model.

9.5 Dynamic Hypothesis

The dynamic hypothesis for the study of Leveraging AI Tools for Enhanced Digital Literacy, Access to Information, and Personalized Learning is based on systems thinking and System Dynamics methodologies. The hypothesis describes the critical components of the system, their interrelationships, and how they interact over time to produce the observed patterns of behavior and outcomes.

9.5.1 Systemic Study of the Use of AI in Engineering Education

Reference mode is an approach used in research to explain the behavior of a problematic situation over time. An initial conjecture is constructed regarding the possible behavior of key variables that describe problematic behavior and its future performance (Long & Meadows, 2018).

This approach involves identifying the key variables influencing problematic behavior and constructing a model that illustrates how these variables interact over time. The initial conjecture is based on a prior understanding of the behavior of the system and the researcher's experience in the field.

Once the reference mode is constructed, it can be used to compare and evaluate the actual behavior of the system with its expected behavior. This allows deviations to be identified and a better understanding of the underlying causes of problematic behavior (Long & Meadows, 2018) (Fig. 9.1).

First, the variables of the level of critical thinking in relation to the use of conversational chats in engineering education were analyzed. To understand these possible behaviors, lines 1 and 2 are defined, representing past and possible future developments resulting from the use of conversational bots in engineering education, which

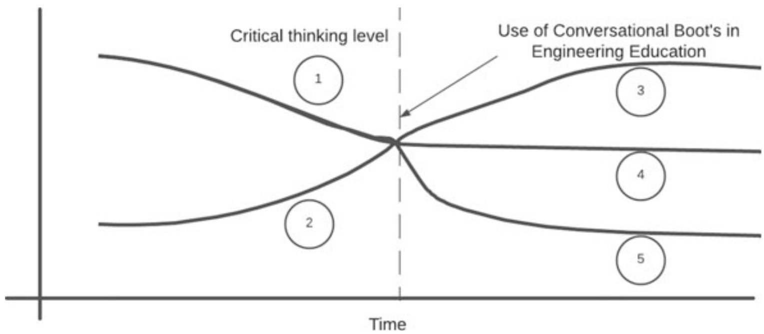

Fig. 9.1 Reference mode on the possible changes in critical thinking behavior resulting from using artificial intelligence tools in education

are reflected in lines 3, 4, and 5. Two options are proposed regarding how the past can affect the level of critical thinking: a significant decrease and a possible improvement, although the latter is more difficult to verify empirically. Some authors support the idea of a decrease in the level of critical thinking, whereas others suggest that it is increasing.

The use of conversational AI tools in engineering education can have both positive and negative effects on critical thinking skills. Therefore, it is important to conduct detailed studies to understand how these tools affect critical thinking development and its potential long-term consequences (Coker, 2022). Some authors suggest that the use of AI tools, such as ChatGPT, can improve critical thinking skills (Rusandi, 2023), whereas others argue that it leads to a decrease in critical thinking (Spector & Ma, 2019).

Critical thinking is a vital skill that enables individuals to analyze, evaluate, and synthesize information to make informed decisions. However, over time, there has been a decline in students' critical thinking skills. One cause of this decline is the traditional education system, which focuses on rote memorization rather than the development of critical thinking skills (Rimiene, 2002). Another reason is the lack of emphasis on critical thinking skills in the curriculum (Kamysheva, 2021). Effective teaching strategies are also lacking (Bardeny, 2023).

To address the decline in critical thinking, solutions such as incorporating critical thinking skills into the curriculum (Gencer & Doğan, 2020) and implementing effective teaching strategies (Triyani et al., 2019) have been proposed.

The use of conversational AI tools has been suggested as a potential way to improve critical thinking skills (Porter & Grippa, 2020; Rusandi, 2023). Real-time feedback provided by AI has been shown to have a positive effect on group dynamics and individual behavior (Porter & Grippa, 2020). The use of AI tools may also help students distinguish accurate information from rumors and misinformation (Porter & Grippa, 2020).

However, AI cannot replace creativity and critical thinking (Funmi & Xu-sheng, 2020). The human mind remains crucial for scientific advancement (Boone, 2023). The use of AI tools for moral improvement raises ethical concerns, highlighting the need for new evaluation methods that emphasize creativity and critical thinking (Funmi & Xu-sheng, 2020).

In conclusion, conversational AI tools have the potential to improve critical thinking skills among students and researchers. However, it is crucial to consider the limitations of AI and its ethical concerns when using it for moral improvement. Critical thinking should serve as a tool to integrate AI in teaching and as an antidote to the threats that AI poses to the teaching profession in the era of machine learning (Funmi & Xu-sheng, 2020).

The dynamic hypothesis presented in Fig. 9.2 suggests that the potential strengthening or weakening of critical thinking skills with the use of AI tools, particularly conversational bots, is closely tied to students' ability to exercise critical thinking. Developing critical thinking skills is essential in various fields, and the use of AI tools can either improve or impair these skills depending on the level of critical

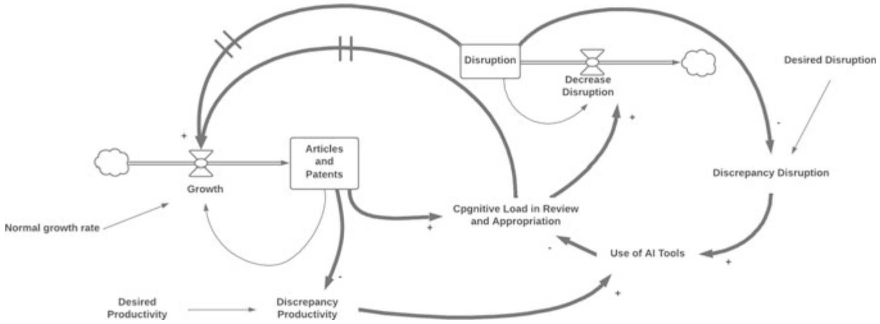

Fig. 9.2 Shows the effect of using AI tools in reducing disruption in published research outcomes

thinking involved. Therefore, it is crucial to ensure that AI tools are effectively used to enhance critical thinking skills (Chukwuyenum, 2013).

Figure 9.2 illustrates a structure that explains both the growth of articles and patents as well as the effect of increased productivity resulting from the use of artificial intelligence. However, this increased productivity can also generate a cognitive burden that may affect the ability to review and comprehend the literature, leading to a decrease in the disruption caused by data as production levels increase. This reduction in disruption may come at the cost of deductive reasoning capabilities, which may be affected by the lack of critical thinking skills applied when using AI tools. Therefore, it is essential to strike a balance between the use of AI tools and development of critical thinking skills to avoid compromising the quality of research outcomes.

Generative AI tools, especially conversational bots, have been linked to the potential strengthening or weakening of students' critical thinking skills. According to Chukwuyenum (2013), students with high critical thinking skills can increase the depth, speed, and accuracy of their critical thinking using AI tools. Additionally, Jaiswal et al. suggested that AI can relieve humans in routine tasks, allowing them to engage in creative activities. However, the level of critical thinking skills is crucial for determining the impact of AI on critical thinking. Suppose the level of critical thinking is low. In that case, the use of AI tools can accelerate the deterioration of critical thinking skills, leading to a progressively weakened condition in their ability to think critically (Chukwuyenum, 2013).

Developing critical thinking skills is essential in various fields, including engineering, medicine, and mathematics, to name a few. Chukwuyenum (2013) literature review found that critical thinking skills correlate with students' academic success in the first two years of medical school and with (Medical College Admission Test) scores. Similarly, Sulastri (2023) notes that the accounting learning process requires students to have critical thinking skills. Aswin et al. also found that intrapersonal intelligence and motivation for learning are factors that influence students' critical mathematical thinking skills.

AI can replicate intelligent behavior and critical thinking equivalent to that of humans. However, developing critical thinking skills is crucial to ensure that AI tools are used effectively. Verma and Verma noted that the role of AI in the future medical field requires critical thinking skills equivalent to those of a human. Furthermore, Azizah found that critical thinking skills involve integrating knowledge by analyzing information and determining solutions to existing problems according to data and facts to produce correct decisions.

AI tools can also improve critical thinking skills as presented on Fig. 9.3. Rusandi (2023) discussed the role of AI as a ChatGPT in education and research, focusing on developing critical thinking skills and maintaining academic integrity. Spector and Ma (2019) emphasized the importance of research and critical thinking skills for the next generation, from AI to human intelligence. Additionally, Aswin et al. found that motivation for learning influences students' critical mathematical thinking skills.

The dynamic hypothesis proposed in this chapter suggests that mental representations and processes are not static but instead constantly change and adapt in response to new information and experiences. To investigate the validity of this hypothesis, we conducted a literature review. The implications of these results for learning, memory, and cognitive development are discussed in detail in the following sections.

The digital gap can be addressed by leveraging AI tools to enhance digital literacy, promote access to information and resources, and facilitate personalized learning experiences. As AI tools become more widely available and accessible, they have the potential to create a dynamic feedback loop that can contribute to closing the digital gap.

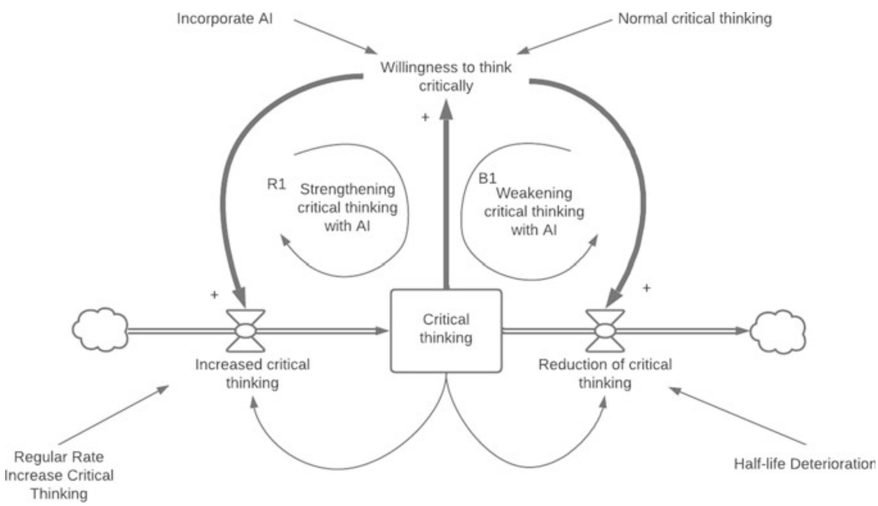

Fig. 9.3 Dynamic hypothesis on the change in critical thinking over time based on willingness to think critically and its relationship with the incorporation of AI tools

First, AI tools can help improve digital literacy by providing intuitive and engaging interfaces that make learning accessible and engaging. By using AI-powered platforms, individuals can receive personalized feedback and guidance that caters to their learning styles and needs. This can help close the digital literacy gap by providing more effective and efficient training for individuals who may have limited access to traditional educational resources.

Second, AI tools can help promote access to information and resources by leveraging the power of machine learning algorithms to analyze large datasets and make information more accessible and relevant. Through natural language processing and other AI-powered technologies, individuals can more easily access and interpret information, regardless of their level of digital proficiency.

Overall, by leveraging the power of AI tools to enhance digital literacy, promote access to information and resources, and facilitate personalized learning experiences, we can create a dynamic feedback loop that contributes to closing this digital gap. As more individuals access effective digital training and resources, they become better equipped to participate in the digital economy and contribute to creating an equitable and inclusive society.

Several studies have supported the use of AI tools to address this gap. For instance, Chounta et al., (2021a, 2021b, 2021c) found that teachers in Estonian K-12 education perceived AI as a valuable tool to support their teaching practice. Mhlanga (2020a, 2020b) investigated the impact of AI on digital financial inclusion and found that AI can help improve access to financial services for underserved populations.

AI tools have also been shown to enhance digital literacy. González-Padilla (2023) suggests that AI-powered platforms can provide personalized feedback and guidance that caters to individual learning styles and needs, which can help to close the digital literacy gap. Fu et al., (2020a, 2020b) found that AI-enabled digital learning applications could facilitate language learning and improve learners' continuous learning intentions.

AI tools can also promote access to information and other resources. Van Beekveld et al., (2017a, 2017b) suggest that machine learning algorithms can analyze large datasets and make information more accessible and relevant. Additionally, Zielinski et al. (2023) caution that while ChatGPT may prove a useful tool for researchers, it represents a threat to scholarly journals because ChatGPT-generated articles may introduce false or plagiarized content into the published literature. Sanders et al., (2018a, 2018b) suggest that future research is investigating ways to use AI to learn and provide tailored resources and support that cater to individuals' specific needs and interests.

The dynamic hypothesis presented in Fig. 9.4 outlines the reproduction of tangible or intangible resources, which depend on the ability to produce these goods (Lindstädt & Fauser, 2004). This ability, in turn, depends on the learning capacity, which is influenced by educational technology (Shen et al., 2021). In the context of this article, we consider Artificial Intelligence (AI) tools as a form of educational technology that, when used, allows us to increase learning speed (Pokrivčáková, 2019a, 2019b). This, in turn, improves our ability to produce tangible and intangible resources

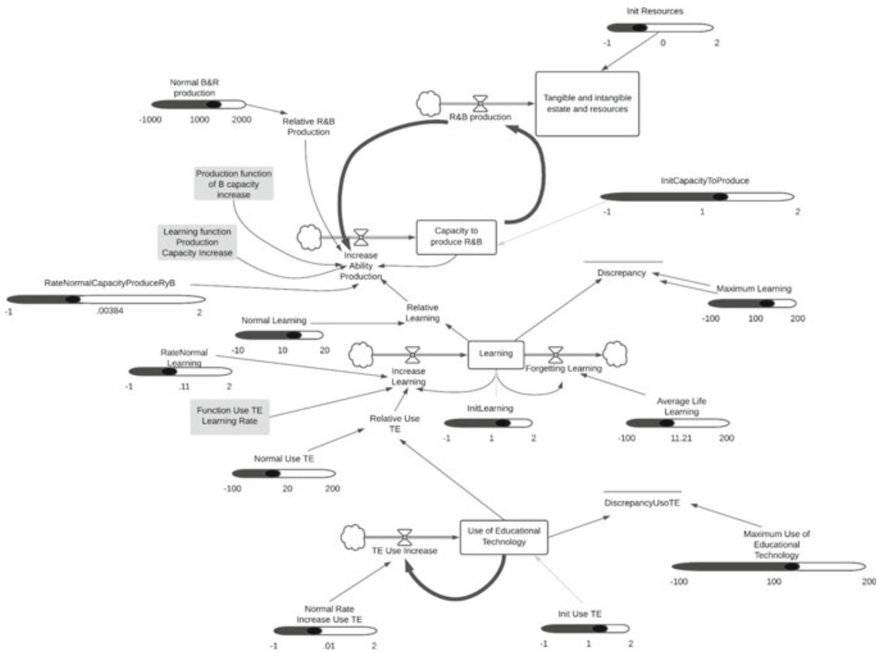

Fig. 9.4 First Dynamic Hypothesis. We integrate Resources, Capabilities, Learning, and the use of information Technology to explain the effect of AI later on

that can accumulate and empower individuals to create and change their environment (Chounta et al., 2021a, 2021b, 2021c). Therefore, AI tools are essential for increasing our capacity for learning, which ultimately changes our ability to accumulate resources and improve access to tangible and intangible resources (Luckin & Cukurova, 2019a, 2019a).

The integration of AI tools into education has been shown to have a positive impact on teaching, learning, assessment, references, and collaboration (Shen et al., 2021). Additionally, AI-powered technologies can be used to predict central lymph node metastasis in thyroid carcinoma (Zhu et al., 2021) and to determine the direction and speed of a powered wheelchair (Naidoo et al., 2019). However, the use of AI in education also raises ethical challenges that must be addressed (Chounta et al., 2021a, 2021b, 2021c). The integration of AI in education should be done with caution, considering ethical considerations and the need for interdisciplinary research (Luckin & Cukurova 2019a, 2019a).

The dynamic hypothesis presented on Fig. 9.5 is based on four reinforcement cycles and two fundamental processes. The first process involves converting information into knowledge through learning, which can be accelerated by using artificial intelligence tools (Lei et al., 2010). The second process involves reinvestment

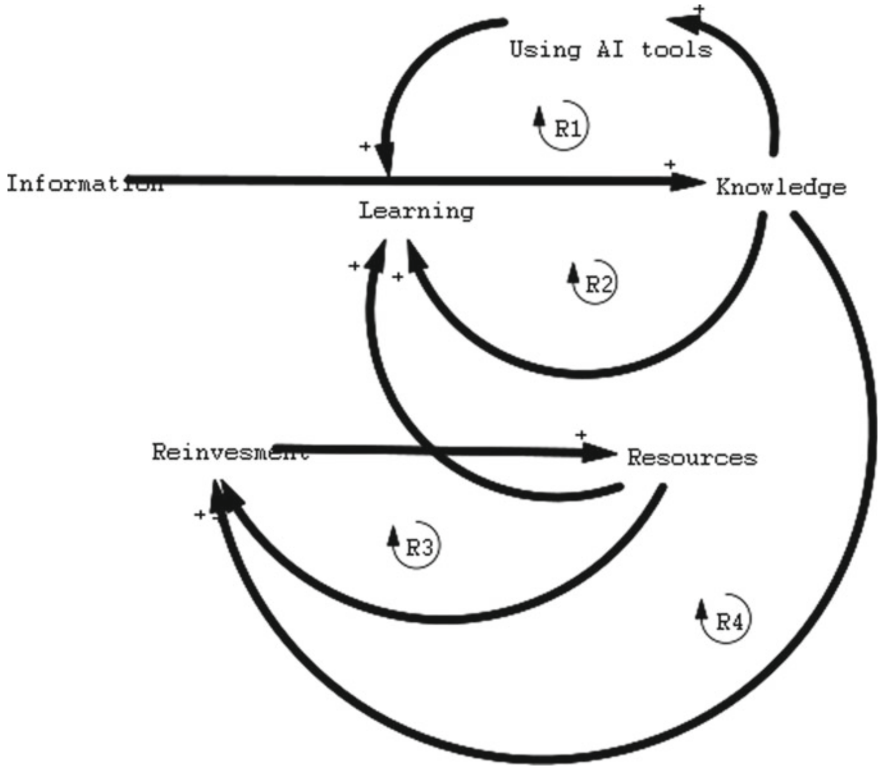

Fig. 9.5 Dynamic Hypothesis in a Second Version. AI tools increase the Speed of Learning and Reinvesment of Resources mostly based on Information Technology

to obtain additional resources. Cycle R1 connects knowledge to the use of artificial intelligence tools, which increases learning and subsequently enhances knowledge. The basic learning cycle follows, where knowledge is multiplied and more resources improve learning ability. This allows reinvestment in Cycle R3 to obtain more resources. In Cycle 4, the speed of reinvestment can be increased through knowledge, leading to even greater resources and improved learning capacity (van Gelder, 1998).

This dynamic development generates an empowering cycle, enabling individuals to learn more quickly and acquire resources more quickly. It reinforces the accumulation of tangible and intangible resources and knowledge. This hypothesis is based on the idea that learning and reinvestment are interconnected and can lead to a positive feedback loop, which can enhance the ability to learn and acquire resources (Myers & Cory 2013).

The use of artificial intelligence tools can accelerate the learning process and enhance knowledge. Using AI-powered platforms, individuals can receive personalized feedback and guidance that caters to their individual learning styles and needs

(Fu et al., 2020a, 2020b; González-Padilla 2023). This can help to close the digital literacy gap by providing more effective and efficient training for individuals who may have limited access to traditional educational resources. In addition, machine learning algorithms can analyze large datasets and make information more accessible and relevant, thereby promoting access to information and resources (Van Beekveld et al., 2017a, 2017b).

In conclusion, the dynamic hypothesis presented in this study is based on four reinforcement cycles and two fundamental processes. The hypothesis suggests that the accumulation of knowledge and resources can lead to an empowering cycle, which can reinforce the accumulation of tangible and intangible resources and knowledge. The use of artificial intelligence tools can accelerate the learning process and enhance knowledge, which can contribute to closing the digital gap. This hypothesis is based on the idea that learning and reinvestment are interconnected and can lead to a positive feedback loop, which can enhance the ability to learn and acquire resources.

9.6 Challenges and Limitations

The use of AI tools for digital inclusion has gained popularity in recent years, but several challenges and limitations must be addressed. Privacy and data security concerns, biases and ethical considerations, infrastructure and connectivity issues, and the need for transparency and accountability are some of the challenges that need to be addressed to ensure that AI-powered digital inclusion technologies are accessible, effective, and equitable.

To address these challenges, it is crucial to prioritize transparency and accountability in the design and deployment of AI-powered digital inclusion technologies. This includes involving communities in the design and implementation of AI-powered platforms (Cave and Éigeartaigh 2018, pp. 54–63), promoting the equitable distribution of AI tools and resources (Mhlanga 2020a, 2020b, 45), and ensuring that privacy and data security concerns are adequately addressed (Shinners et al., 2019, pp. 1097–1108). Additionally, the explainability and interpretability of AI outcomes are important to ensure that the decisions made by AI-powered platforms are transparent and accountable (Bigot & Rouet, 2007).

Investing in infrastructure to improve connectivity in underserved areas and ensuring that vulnerable and marginalized communities have access to AI-powered digital inclusion technologies are crucial (Moulin et al., 2021, pp. 1058–1065). Moreover, it is important to engage critically with digital health and related technologies, such as AI, IoT, and CPS, to ensure that they are used ethically and responsibly (Jacobides et al., 2021a, 2021b, pp. 183–204). Calibrating the algorithms of AI design tools to provide solutions that meet expected design standards is also crucial to ensure that AI-powered platforms are effective and equitable (Weber-Lewerenz 2021, pp. 1–15).

In conclusion, addressing the challenges and limitations associated with the use of AI tools for digital inclusion requires implementation of potential solutions and mitigation strategies. By involving communities in the design and implementation of AI-powered platforms (Cave and ÓhÉigeartaigh 2018a, 2018b, pp. 54–63), prioritizing transparency and accountability (Shinners et al., 2019, pp. 1097–1108), promoting equitable distribution of AI tools and resources (Mhlanga 2020a, p. 45), and critically engaging with digital health and related technologies (Jacobides et al., 2021a, 2021b, pp. 183–204), we can ensure that AI-powered digital inclusion technologies are accessible, effective, and equitable for all.

9.7 Conceptual Model Validation

The dynamic hypothesis in this study was validated through a rigorous examination of its feedback structure by validating its diagrams against the relevant literature and modeling discussions. The endogenous and exogenous variables that shape or define the system boundaries are comprehensively described in Fig. 9.6, and the criterion of belongingness was used to define the system boundaries. This criterion includes variables that affect and are affected by the system or are exogenous to the system but affect it.

Endogenous variables were described in detail, including their ability to increase production, learning, and associated capabilities and resources. The exogenous variables, which included the use of artificial intelligence, resources, and information technology in general, were related to the endogenous variables but were not explicitly used to demonstrate the dynamics surrounding the ability to learn, reinforce the appropriation of tangible or intangible resources, or achieve educational objectives.

The approach used to validate the dynamic hypothesis was consistent with the guidelines provided by Qudrat-Ullah and BaekSeo (2010a) to ensure the structural validity of a System Dynamics simulation model. Using both structural and literature validation methods, the authors were able to ensure that the dynamic hypothesis accurately represented the system being studied and was consistent with current knowledge and theory. This enabled the authors to generate insights into the system and inform policy and practical decisions.

Figure 9.6 comprehensively describes the endogenous and exogenous variables that shape or define system boundaries. The selected endogenous variables included the ability to increase production capacity, learning, and learning flow. These endogenous variables are closely linked to exogenous variables that play crucial roles in their existence and sustainability. It is worth noting that endogenous variables are completely dependent on their associated exogenous variables to receive the necessary support and function effectively.

In addition to the selected endogenous variables, Fig. 9.6 includes several exogenous variables not explicitly considered in this study, such as socioeconomic conditions, access to technology, and access to infrastructure. These exogenous variables are important to consider, as they can affect the system's behavior and the study's

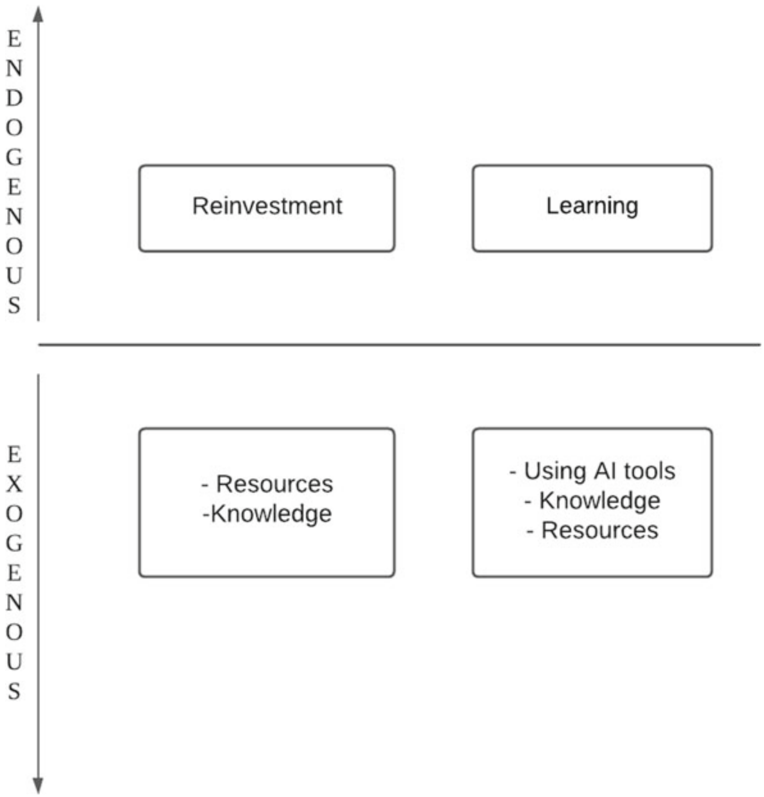

Fig. 9.6 Endogenous and Exogenous Variables that Shape the System Boundaries

outcomes. By comprehensively describing both endogenous and exogenous variables, Fig. 9.6 provides a clear understanding of the system's boundaries and factors contributing to its behavior and outcomes.

Table 9.1 provides a list of structures and concepts adopted from existing studies that have been used to develop the dynamic hypothesis for our study. The selection of studies was based on their relevance to our research topic, which focused on the use of artificial intelligence (AI) tools and critical thinking skills to promote better learning outcomes.

Consistent with the literature, our study recognizes the potential of AI tools to promote better learning outcomes while also acknowledging the importance of critical thinking skills (Funmi & Xu-sheng, 2020; Porter & Grippa, 2020; Spector & Ma, 2019). We aimed to strike a balance between the use of AI tools and the development of critical thinking skills to avoid compromising the quality of research outcomes (Boone, 2023; Chukwuyenum, 2013).

Our study emphasizes the need to develop students' critical thinking skills in higher education (Kamysheva, 2021), and explores the use of online discussions to

Table 9.1 Structures adopted from the existing work

Structures/concepts	Remarks
"Separation or Integration? Can network carriers create distinct business streams on one integrated production platform?" (Lindstädt & Fauser, 2004)	Causal structure was adopted
Teaching and Learning With Artificial Intelligence. In Emerging Technologies and Pedagogies in the Curriculum.	Structural formulation was adopted
"Preparing Teachers for the Application of AI-powered Technologies in Foreign Language Education." (Pokrivčáková, 2019)	Structural formulation was adopted
"Exploring Teachers' Perceptions of Artificial Intelligence as a Tool to Support Their Practice in Estonian K-12 Education." (Chounta et al., 2021a, 2021b, 2021c)	Structural formulation was adopted
"Designing Educational Technologies in the Age of AI: A Learning Sciences-driven Approach." (Luckin & Cukurova, 2019a)	Structural formulation was adopted
"Application of Machine Learning Algorithms to Predict Central Lymph Node Metastasis in T1-T2, Non-Invasive, and Clinically Node Negative Papillary Thyroid Carcinoma." (Zhu et al., 2021)	Structural formulation was adopted
"Beyond Two-Point Statistics: Using the Minimum Spanning Tree as a Tool for Cosmology." (Naidoo, et al., 2019)	Structural formulation was adopted

improve critical thinking skills (Gencer & Doğan, 2020). We recognize that the use of AI tools can generate a cognitive burden that may affect the ability to review and comprehend literature, leading to a decrease in disruption caused by data as production levels increase (Boone, 2023). Therefore, our study focused on the effect of chatbots on critical thinking skills using a quasi-experimental design (Rusandi, 2023).

By adopting the structures and formulations proposed in the studies listed in Table 9.1, we aim to build on existing knowledge and provide a more comprehensive understanding of the subject matter. Our study aimed to contribute to the existing literature on the use of AI tools to promote better learning outcomes while ensuring the development of critical thinking skills.

9.8 Discussion

The responsible and equitable use of AI tools is essential for digital inclusion (Dignum 2023a, 2023b). By following best practices, such as involving communities in the design and implementation of AI-driven platforms, promoting transparency and accountability, and maintaining a balance between human and artificial intelligence, we can ensure that the benefits of these technologies are accessible to all and that potential risks are mitigated (Berendt et al., 2020).

Furthermore, the Dynamic Hypothesis suggests that AI-driven digital inclusion technologies have the potential to enhance critical thinking skills, improve access to information, and provide personalized learning experiences. However, it is crucial to ensure that the use of AI tools does not impair critical thinking skills and that they are effectively used to enhance them. The development of critical thinking skills is essential in various fields, and AI tools can either improve or impair these skills, depending on the level of critical thinking involved (Chukwuyenum, 2013).

Moreover, the use of AI tools in managing complex tasks, particularly in the context of digital training, access to information, and personalized learning experiences, has become increasingly prevalent. However, it is essential to use AI tools responsibly and effectively to ensure that the benefits of these technologies are accessible to all and that the potential risks are mitigated. The best practices include involving communities in the design and implementation of AI-powered platforms, promoting transparency and accountability, and maintaining a balance between human and artificial intelligence (Kamrowska-Załuska, 2021).

In summary, the responsible and equitable use of AI tools can enhance digital literacy, access to information, and personalized learning experiences while promoting critical thinking skills and bridging the digital divide. It is important to recognize the potential of these technologies to empower individuals and communities and to ensure that their use remains ethical and inclusive (Letaief et al., 2022). By following the best practices and considering the findings of the Dynamic Hypothesis, we can harness the potential of AI tools to promote digital inclusion and enhance critical thinking skills.

9.9 Conclusion

In conclusion, this chapter highlights the importance of responsible and equitable use of AI tools for digital inclusion. As discussed, following best practices such as involving communities in the design and implementation of AI-driven platforms, promoting transparency and accountability, maintaining a balance between human and artificial intelligence, and monitoring the effectiveness and equity of AI-driven digital inclusion technologies are essential to ensure that the benefits of AI technologies are accessible to all and potential risks are mitigated.

The dynamic hypothesis presented in this chapter suggests that leveraging AI tools in digital training, information access, and personalized learning experiences can accelerate the learning process, promote digital inclusion, and bridge the digital divide. This hypothesis proposes that the accumulation of knowledge and resources can lead to an empowering cycle, which can reinforce the accumulation of tangible and intangible resources and knowledge. According to this hypothesis, AI tools can enhance knowledge and contribute to the accumulation of resources, thereby increasing the ability to reinvest in further learning.

As emphasized throughout this chapter, it is important to use these technologies responsibly and equitably, considering users' needs and concerns, promoting transparency and accountability, and maintaining a balance between human and artificial intelligence. As noted by Kshetri, the responsible and ethical use of AI technologies is crucial to ensure that the benefits of these technologies are accessible to all, and potential risks are mitigated.

By following best practices and leveraging AI tools in a responsible and equitable manner, digital inclusion can be promoted to create a more inclusive society. However, it is important to continue monitoring the effectiveness and equity of AI-driven digital inclusion technologies as well as to address any potential biases and unintended consequences that may arise from their use.

Overall, this chapter demonstrated that AI-driven digital inclusion technologies have the potential to contribute to closing the digital gap and promoting digital inclusion. However, realizing this potential requires the responsible and equitable use of these technologies as well as ongoing monitoring and evaluation. By doing so, we can ensure that the benefits of AI technologies are accessible to all, and help create a more inclusive and equitable society.

9.10 Insights and Implications for Practice

This chapter offers practical recommendations for decision-makers seeking to promote digital inclusion and close the digital divide using AI tools. It emphasizes the importance of responsible and equitable use of AI technologies, which can be achieved by following best practices, such as involving communities in the design and implementation of AI-powered platforms, promoting transparency and accountability, maintaining a balance between human and artificial intelligence, and monitoring the effectiveness and equity of AI-powered digital inclusion technologies.

The dynamic hypothesis presented in this chapter suggests that AI tools can play a crucial role in promoting digital inclusion. The hypothesis proposes that the accumulation of knowledge and resources can lead to a cycle of empowerment that can reinforce the accumulation of tangible and intangible resources and the acquisition of knowledge. The use of AI tools can accelerate the learning process and improve knowledge, contributing to the accumulation of resources and the ability to reinvest in additional learning.

This chapter further highlights the potential of leveraging AI tools in digital training, access to information, and personalized learning experiences to promote digital inclusion and close the digital divide. However, it emphasizes the importance of using these technologies responsibly and equitably, considering the needs and concerns of users, promoting transparency and accountability, and maintaining a balance between human and artificial intelligence.

Overall, the chapter concludes that the responsible and equitable use of AI-powered digital inclusion technologies is crucial for promoting digital inclusion and creating a more inclusive society. Decision makers can promote digital inclusion and bridge the digital divide by following the best practices and leveraging AI tools responsibly and equitably.

Based on the discussion in this chapter, several insights and practical implications can be drawn for decision-makers seeking to promote digital inclusion and close the digital divide using AI tools.

First, decision makers should prioritize the responsible and equitable use of AI technologies to ensure that their benefits are accessible to all while mitigating potential risks. This can be achieved by following best practices such as involving communities in the design and implementation of AI-powered platforms, promoting transparency and accountability, maintaining a balance between human and artificial intelligence, and monitoring the effectiveness and equity of AI-powered digital inclusion technologies.

Second, decision makers should consider leveraging the potential of AI tools to accelerate the learning process, improve knowledge, and promote digital inclusion. The dynamic hypothesis presented in this chapter suggests that the accumulation of knowledge and resources can lead to a cycle of empowerment that can reinforce the accumulation of tangible and intangible resources and the acquisition of knowledge. Therefore, the use of AI tools in digital training, access to information, and personalized learning experiences can help promote digital inclusion and bridge the digital divide.

Third, decision makers should be mindful of the potential biases and unintended consequences that may arise from the use of AI technologies. For example, AI algorithms may perpetuate existing biases or create new ones. Therefore, it is important to use these technologies responsibly and equitably, considering the needs and concerns of users, promoting transparency and accountability, and maintaining a balance between human and artificial intelligence.

In conclusion, decision makers play a crucial role in promoting digital inclusion and closing the digital divide using AI tools. By prioritizing the responsible and equitable use of these technologies, leveraging their potential to promote digital inclusion, and being mindful of their potential biases and unintended consequences, decision makers can help create a more inclusive and equitable society.

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Chapter 10
Navigating the IT Professional Shortage with System Thinking: Practical Insights for Better Decision Making

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Abstract The shortage of skilled IT professionals is a growing problem with various contributing factors. Managerial practices that lead to turnover and recruitment issues, a need for more appropriately trained individuals, low enrollments in relevant programs, ICT skill shortages, inadequate budgeting and planning, and a lack of trained personnel are all contributing factors. This chapter proposes a systems thinking approach to address the IT professional shortage, providing practical insights for better decision-making. This chapter explores the key principles of systems thinking and how they can be applied to the IT job market, with examples of organizations that have successfully implemented this approach. It also provides practical insights for organizations seeking to address the IT professional shortage and recommendations for implementing systems thinking in their approach. Finally, it discusses the importance of adopting a system-thinking approach to address IT professional shortages and other complex problems. The chapter concludes with a call for a systemic vision of digital competencies and skills to effectively address the digital talent gap and promote a stronger digital economy.

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Keywords IT professional shortage · System thinking · Digital talent · Managerial practices · Recruitment · Training · Enrollment · ICT skills · Budgeting · Planning · Digital competencies · Digital economy · Practical insights

10.1 Introduction

The digital economy has acquired digital talent as a crucial aspect of its economic competitiveness. The term 'digital economy' refers to the increasing importance of technology and digitization in the global economy (World Economic Forum, 2016). However, the digital divide between developed and developing countries continues to widen, with strategic technological investments often contributing to digital competitiveness (World Bank, 2016).

Colombia faces a significant challenge in building its digital talent pool. According to the World Ranking of Digital Competitiveness, Colombia ranks 59th out of the 64 main economies worldwide (IMD World Competitiveness Center, 2020). This low ranking highlights the urgent need for a country to invest in digital talent development.

The shortage of Information Technology (IT) professionals is a growing problem around the world and can be attributed to a number of factors that may vary depending on the geographic and sectoral context. These factors contribute to the challenges faced by organizations in recruiting and retaining skilled IT professionals.

First, inefficient management practices can contribute to employee turnover and lack of retention, which in turn can affect the quality of recruiting and training new IT professionals. Second, the ever-evolving nature of technology means IT professionals must keep up with the latest technologies and trends. Lack of proper training can contribute to a lack of up-to-date skills and knowledge. Third, low enrollment in relevant IT programs can affect the number of IT professionals available. This may be due to a lack of awareness of available career opportunities or a negative perception of the industry. Fourth, the lack of IT skills in the workforce may be due to a lack of education, training, or experience in the field of technology. Fifth, a lack of adequate investment in IT technology and training can limit the ability of organizations to retain and train IT professionals. Finally, a lack of trained and experienced IT staff can make it difficult to identify and hire new IT professionals.

Addressing these factors can help organizations improve their ability to attract, retain, and train qualified IT professionals and reduce the digital talent gap faced by many developing countries, including Colombia. (Cappelli, 2000a, 2000b; Forth, 2006; Roberts, 2000a, 2000b, 2000c; Walstrom, 2008).

This chapter proposes a systemic representation of the fundamental structure of the digital talent supply system and evaluates the ICT mission initiative that is part of a systemic vision of education at all levels to address the effective digital talent gap in Colombia. The systemic representation of the digital talent supply system will provide a holistic view of the problem, identify critical strategic resources and propose solutions to close the IT talent supply gap.

The dynamic hypothesis explains the behavior of the gap and identifies public policy recommendations to combat it, understanding the dynamic hypothesis as a simulation model that allows analyzing how the variables of a system interact over time, identifying patterns and trends, and proposing solutions to improve system performance. In this case, the dynamic hypothesis is used to analyze the digital talent gap in Colombia and propose public policy recommendations to combat it. The results suggest that a systemic view of education at all levels is required to address the digital talent gap effectively. The proposed policy recommendations include a role for the ICT Mission in ensuring the provision of strategic resources to maintain digital talent throughout the system. The objective of public policy should be to achieve digital talent security that allows the country to provide digital talent, which is increasingly necessary to produce goods and services in the context of growing international demand (MINTIC, 2020a, 2020b; ANDI, 2020a, 2020b).

This chapter aims to provide practical insights for better decision making and policy design in navigating the shortage of IT professionals using a system-thinking approach. It will explore the key principles of systems thinking and how they can be applied to the IT Professional shortage, providing structures to improve comprehension and decision-making. It also provides practical insights for organizations seeking to address the IT professional shortage and recommendations for implementing systems thinking in their approach. The chapter concludes with a call for a systemic vision of digital competencies and skills to effectively address the digital talent gap and promote a stronger digital economy.

10.2 Method

In this chapter, a combination of System Dynamics and System Thinking methods are employed to analyze the shortage of skilled IT professionals in Colombia (Forrester, 1995). System Dynamics allows us to study the dynamic changes of different variables that constitute a system over time and understand the underlying feedback mechanisms (Forrester, 1995). This approach utilizes the fundamental elements of System Dynamics, including the design of a dynamic hypothesis that explains the change in the fundamental variables over time and the flows that determine the change in these variables.

The System Dynamics methodology involves several steps, including conceptualization, designing the dynamic hypothesis and reference modes, mathematical modeling, simulation, and evaluation of the utility of the model (Forrester, 1995). By utilizing the expertise of experts, scientific and academic materials, and technical reports, System Dynamics enables us to identify the strategic variables of the resource, identify feedback structures, and suggest policies to improve the problematic behavior of the system.

A literature review was conducted to shed light on the labor market of IT professionals in Colombia. This review identified several key factors that influence the supply and demand of IT professionals, such as education and training, immigration policies, industry trends, and economic conditions. These factors were explored in previous studies by Angel (1991) and Theodore et al. (2015), Eeckhout (2018), and Neugart and Richiardi (2018).

To synthesize the insights gained from the literature review, a preliminary causal loop diagram was created to illustrate the interrelationships and feedback loops that shape IT professionals' labor market.

Overall, this review provides a foundation for further research on the labor market of IT professionals in Colombia and highlights the need for a holistic understanding of the various factors that shape this market.

Once the preliminary causal loop diagram was developed, the study used System Dynamics modeling to refine the diagram and simulate the behavior of the IT professionals' labor market over time (Angel, 1991; Eeckhout, 2018; Neugart & Richiardi, 2018; Theodore et al., 2015). The system dynamics model incorporates feedback loops and time delays to capture the complex dynamics of the labor market. The model was validated using historical data and expert opinions to ensure that it accurately captured the behavior of IT professionals' labor market and could be used to make policy recommendations (Angel, 1991; Eeckhout, 2018; Neugart & Richiardi, 2018; Theodore et al., 2015). The causal loop diagram is a visual tool that helps us understand the interactions among the different variables in the system.

This study provides practical decision-making and policy design recommendations based on insights derived from a dynamic hypothesis using the System Dynamics methodology. This research demonstrates how System Dynamics modeling can assist policymakers and organizations in comprehending the complex dynamics of the labor market and devising effective strategies to address the shortage of IT professionals.

Systems thinking is a holistic approach to examining complex problems and systems that focuses on the interactions among system components and the patterns that emerge from these interactions (York et al., 2019, 2742–2751). It is a learning strategy in which theoretical systems concepts are deliberately used to explain and predict natural phenomena (Verhoeff et al., 2018). Systems thinking is not simply an engineering approach; it is a philosophy for solving many practical problems, such as joined-up government, social work, climate change, and terrorism (Blockley, 2010, 189–199).

Systems thinking considers all possible influencing factors in a system and establishes their interconnectedness through modeling (Jonker et al., 2017). It is a process of thinking using systems ideas to represent better a problematic situation (Paquibut, 2017, 161–170). Systems thinking is a rapidly expanding approach to creating and maintaining large complex systems (Holden, 2014, 22–28). It helps policymakers reconceptualize health problems and contexts, goals, potential policy solutions, and methods (Haynes et al., 2019, 65–76).

Researchers have constructed tools that provide an operational definition for systems thinking in chemistry education and serve as a guide for the design, analysis, and optimization of systems thinking activities (York & Orgill, 2020).

The shortage of Information Technology (IT) professionals is a persistent problem that impacts the industry and society. To address this issue, systems thinking can be used as a framework to understand the complex interactions and feedback loops that contribute to the shortage. This chapter outlines the steps of a systems thinking approach to studying the shortage of IT professionals.

The first step is to clearly define the problem by identifying its scope, contributing factors, and impact on the industry and society. Stakeholders involved in the problem, including employers, employees, educational institutions, professional associations, and government agencies, should be identified. The second step is to analyze the system that produces and employs IT professionals, examining factors such as education and training programs, job market, hiring practices, and career paths. Feedback loops that contribute to the shortage should also be identified.

The third step is to develop interventions to address the shortage of IT professionals, at both individual and systemic levels. For example, improving education and training programs, increasing the diversity and inclusivity of the workforce, and aligning government policies with industry needs can all be effective interventions. Finally, the outcomes of the interventions should be evaluated to measure their effectiveness, and impact on the shortage, and identify areas for further improvement.

Overall, systems thinking is a powerful tool that can be used to analyze complex systems and problems effectively. By considering the interconnectedness of all factors and using theoretical concepts, researchers and decision-makers can better understand the issues they face and develop effective solutions.

In summary, the combination of system dynamics and systems thinking methods is a powerful approach for studying the labor market of IT professionals and developing evidence-based policy recommendations to address shortages in the IT professional labor market. By providing a dynamic perspective on the labor market, System Dynamics modeling can help policymakers and organizations better understand the complex dynamics of the labor market and develop effective strategies to address shortages among IT professionals (Hafeez & Aburawi, 2013; Olejniczak, 2018).

10.3 Results

The digital divide is defined by two fundamental elements: the demand for digital talent, still with the most conservative expectations, shows that the country cannot satisfy the demand for digital talent for professionals in information technology. The current shift towards a service exacerbates this problem- and a knowledge-based economy and the situation worsens on the demand side (see Fig. 10.1).

Figure 10.2 illustrates the possible baseline behaviors that represent the evolution of the supply and demand variables for digital talent over time, which are crucial in determining the future behavior of the digital gap. The reference mode is based on mental models and provides insights into how the digital gap may behave in the future based on the identified supply and demand variables.

The demand for digital talent has grown dramatically in the digital era. However, the supply of digital talent has failed to keep up with demand, creating a digital skills gap. In order to meet this challenge, it is essential to understand the basic structure

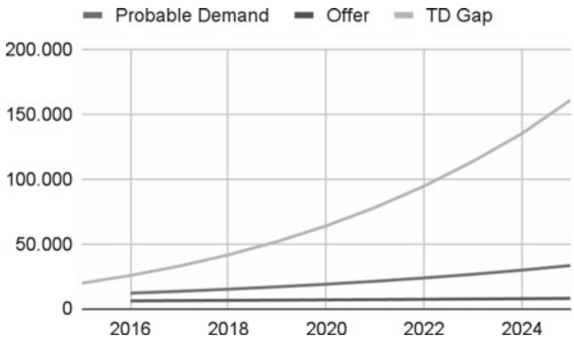

Fig. 10.1 Data and projection of the digital talent short age in Colombia. (Fedesoft, 2015)

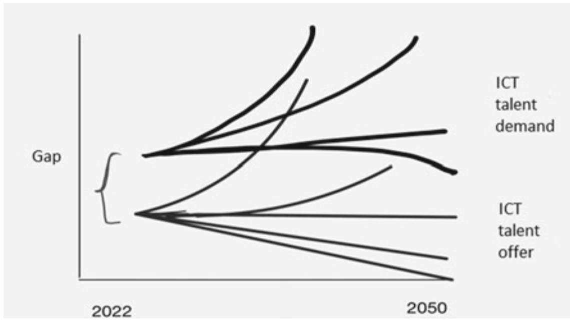

Fig. 10.2 Reference mode behavior of the information technology shortage

of digital talent production and the factors contributing to the digital skills divide. This chapter explores the structure of digital talent production and highlights key elements that policymakers can consider to reduce the digital skills gap (Anderson, 2018).

Producing digital talent is based on a complex education and training system that requires years of development. It encompasses a range of educational institutions, from elementary schools to universities, and vocational training centers that provide learners with the skills they need to become digital professionals. In addition, the digital industry plays an essential role in building the necessary skills to succeed in this sector (OECD, 2019).

Creating digital talent involves several steps, including basic training, specialized training, and continuous learning. Founding education gives learners a necessary understanding of math, science, and computer science. Specialized training focuses on developing specific digital skill sets like coding, data analytics, and digital marketing. Lifelong learning is critical to tracking new technologies and trends in the digital industry (World Economic Forum, 2020).

Despite significant investments in the generation of digital talent, the digital skills gap still needs to be addressed. There is a need for more qualified digital professionals who can meet the demands of the digital industry. The digital skills gap results from several factors, including a lack of investment in digital education, inadequate training programs, and a mismatch between the skills demanded by the digital industry and those provided by the education system (Anderson, 2018).

There are several vital elements that policymakers need to address to reduce the digital skills gap. One is an early investment in digital education. This investment should aim to provide learners with basic skills in mathematics, science, and computing. Secondly, policymakers should promote specialized training programs that provide learners with specific digital skills in high demand in the digital industry. Finally, lifelong learning programs should be promoted to ensure that digital professionals remain up-to-date on new technologies and trends (European Commission, 2016).

The demand for digital talent will continue to grow, and policymakers must act to reduce the digital skills gap. This study focused on the structure of digital talent production and the factors contributing to the digital skills gap. Policymakers must invest in digital education, promote specialized training programs and encourage lifelong learning to close the digital skills gap. By taking these actions, policymakers can ensure that the supply of digital talent meets the requirements of the digital industry and promotes economic growth and competitiveness (World Economic Forum, 2020).

Figure 10.2 illustrates the possible reference behaviors that show changes over time for the digital talent supply and demand variables that define the future behavior of the digital gap. Based on these dynamics, several basic structures have been considered to derive a series of basic learning that should be considered to define how public policy has contributed to and can continue to reduce the digital gap.

As shown in Fig. 10.3, a program must primarily recruit people for ICT training, which is generally oriented towards advanced digital talent training. It is important to note that digital talent development consists of three levels: core, standard, and advanced. In advanced training, it is necessary to have both the availability of places in the program and people with the capacity, willingness, and interest to study and finally finish the program. Hence, the number of students in Misión is affected by the entry and exit of exceptions and degrees.

The structure presented in Fig. 10.3 consists of basic, standard, and advanced levels. One may wonder how many students of previous levels are needed to fuel this system, which in turn fuels the development of the digital talent the country needs. This is not only to address the existing digital gap but also to prepare for

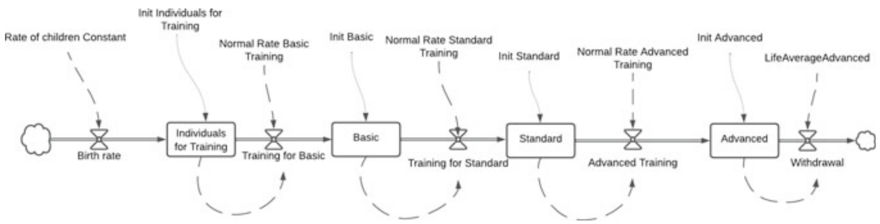

Fig. 10.3 Structure for information technology talent production, including basic, standard, and advanced levels

the previously mentioned perspective of an even greater need for people with digital talent to respond to the demands of the transformation of the global economy.

One of the critical factors in reducing the digital gap is to ensure a steady supply of skilled digital professionals in the workforce. Policy programs are vital for recruiting and training individuals with advanced digital talents. However, the program's success depends not only on the availability of program spaces but also on the willingness and ability of individuals to complete the program. Therefore, it is essential to develop a recruitment strategy that targets individuals with the necessary skills, motivation, and interest in pursuing advanced digital talent training.

It is also critical to regularly monitor and assess the program's effectiveness. In doing so, weaknesses and areas for improvement can be identified, and corrective actions are taken to ensure meeting the program objectives. Analyzing the dynamics of the model developed in this study is a powerful tool for assessing the effectiveness of a strategic program and identifying areas for improvement.

Therefore, a program should have a recruitment strategy that targets individuals with the necessary skills and motivation and an effective monitoring and evaluation system.

As shown in Fig. 10.4, the system should be viewed as a whole, and training at the base of the pyramid should be prioritized. The base of the pyramid consists of individuals who are trained in basic skills, which then progress to standard and, ultimately, advanced skills. These individuals will effectively help bridge the digital divide. Therefore, a large number of individuals are needed at the primary level, with some progressing to the intermediate or standard level and others advancing to the advanced level. Failing to consider this aspect of training, policy, and maintenance of pyramid availability can further exacerbate the digital talent gap.

A preliminary evaluation of the physical phenomenon indicates that if the need to feed the system from the beginning is not considered, it will be very difficult to close the digital gap. Furthermore, it is impossible to close the gap between supply and demand with just a few educational programs. To improve the overall system,

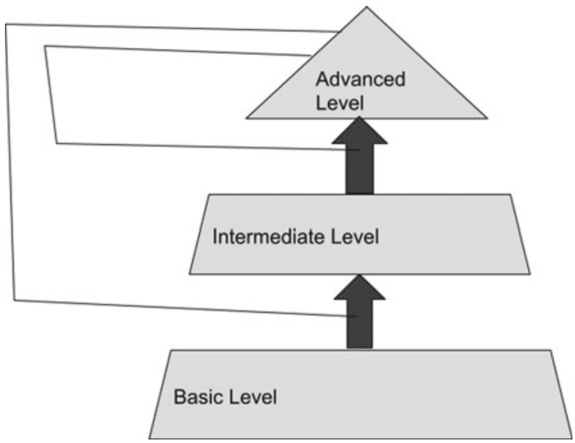

Fig. 10.4 Pyramid system of digital talent training at the basic, standard, and advanced levels

production rates for basic, intermediate, and advanced ICT talent must be increased in order to reduce losses due to dropouts. It also involves working on a program to improve the social perception and satisfaction of information technology talent.

A dropout is a complex problem that cannot be addressed solely in specific or advanced programs. If dropout occurs at this level, it is already too late and will generate a very low availability of ICT talent. At the basic, intermediate, and advanced levels, it becomes relevant to review the factors that determine dropout and to identify the role of these factors or their relationship with the digital gap.

In the literature, Tinto's model stands out as an explanation for dropout based on attributes related to the objectives of education; institutional experiences; personal and normative integration with academic rules, professors, and peers; the quality of student effort; learning achieved by the student; commitment to results; and external conditions such as perceived satisfaction with the career (Nicoletti, 2019). As a policy issue, MisiónICT programs must assume, with much more detail and intensity than has been done so far, the design of dropout-proof programs. It includes ensuring the highest quality and lowest dropout rates from the selection of candidates to that of institutions that offer training to guarantee satisfaction. Another essential factor is external satisfaction with the IT professionals.

Studies of dropouts in information technology programs have found that social norms, class size, program specificity, perceived boredom, poor teaching, course difficulty, unfriendliness, lack of satisfaction, inflexibility, academic workload, grades, sense of belonging, negative experiences, lack of self-confidence, the time required to complete studies, focus on high positions, quality of studies, and external factors define the conditions that affect school dropout in these programs (Giannakos, et al., 2017).

Nicoletti (2019) presents a model of dropping out and perseverance that revisits the theoretical model of Tinto. This model highlights the importance of integration, engagement, and satisfaction with student retention and the role of external factors, such as institutional support, in reducing dropout rates.

Furthermore, addressing the issue of dropouts requires a multifaceted approach, which includes improving teaching quality, providing flexibility in course delivery and scheduling, promoting students' sense of belonging, and enhancing institutional support (Giannakos et al., 2017). By addressing these factors, educational programs can increase both retention and overall satisfaction among students pursuing careers in information technology.

The shortage of skilled IT professionals in Colombia is a complex phenomenon influenced by several key factors, including education and training, immigration policies, industry trends, and economic conditions (Angel, 1991; Eeckhout, 2018; Neugart & Richiardi, 2018; Theodore et al., 2015). These factors interact in complex ways, creating feedback loops and time delays that influence IT professionals' labor market dynamics.

To gain a deeper understanding of the dynamics of IT professionals' labor market, the study utilized the System Dynamics methodology and conducted a literature review. This study identified potential policies that could help address the shortage of skilled IT professionals in Colombia, such as investments in education and training programs, changes in immigration policies to attract more IT professionals, and incentives for companies to hire and retain IT professionals (Hafeez & Aburawi, 2013; Olejniczak, 2018). This System Dynamics model demonstrated that these policies could have a significant impact on increasing the supply of skilled professionals and reducing shortages.

The labor market is a complex system that involves the interaction between labor supply and demand. However, while research has traditionally focused on the supply side of the labor market, the demand side, particularly the hiring decisions made by employers, has received less attention in sociological research (Bills et al., 2017). The allocation and reallocation of human resources, ensuring a balance between supply and demand for work in the long term, is the primary function of the labor market (Lee, 2020). Labor market information, including quantitative and qualitative data related to supply and demand in the labor market, is essential for evidence-based skill development and career counseling (Lee, 2020).

The impact of digital economic development on the demand and supply of the labor market is a topic of interest. Chen (2022) found that the labor market has been affected to some extent by the digital economy, highlighting the need for policies and strategies to address the challenges and opportunities presented by this phenomenon.

This study utilizes the System Dynamics methodology and literature review to provide evidence-based policy recommendations for addressing the shortage of skilled IT professionals in Colombia. These insights can be useful for policymakers, organizations, and stakeholders involved in the IT industry in Colombia and other countries facing similar challenges. Furthermore, This study highlights the importance of considering both the supply and demand sides of the labor market and the need for labor market information for evidence-based decision-making.

The labor market for Information Technology (IT) is complex and affected by various factors, including the demand for skilled workers, education and experience of the labor force, job availability, immigration policies, and economic conditions (Lee, 2020; Michaillat & Saez, 2015; Sun, 2022). The relationship between labor supply and labor prices is intricate, and the labor market mechanism ensures that both labor supply and demand adjust to equalize supply and demand (Michaillat & Saez, 2015). However, the demand side of the labor market, particularly the hiring decisions made by employers, has received less attention in sociological research (Bills et al., 2017). The employment relationship comprises both the demand and supply sides as well as the matching processes that bring these together (Bills et al., 2017).

The B1 supply cycle in Fig. 10.5 represents an increase in labor prices in the IT sector with a delayed response. The supply of digital talent in IT is not immediately responsive and may take days to decades to adjust. Nonetheless, an increase in the supply of skilled workers ultimately reduces market prices, supported by previous studies. Labor market equilibrium is achieved when the quantity of labor supplied equals the quantity of labor demanded at a certain wage rate (Michaillat & Saez, 2015).

The B2 demand cycle in Fig. 10.5 shows that labor price in the IT sector is closely related to demand. As labor prices increase, demand may be reduced, whereas higher

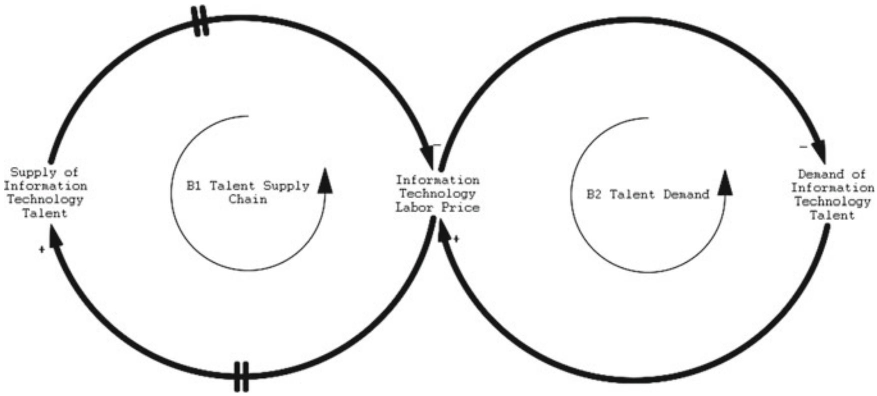

Fig. 10.5 Information technology labor market representation using feedback loops B1 and B2

demand can lead to an increase in price. However, external factors can influence this cycle, such as changes in the economy's central commodity, from natural resources to goods and services, where IT is fundamental. This shift can increase demand above what is usually expected, an exogenous or external demand shock.

The shortage of IT talent in the labor market is a significant challenge, resulting from a decline in the number of students graduating with a bachelor's degree in computer science and an increase in the demand for trained IT employees. This shortage can lead to a mismatch between IT graduates and the needs of the labor market, resulting in an inability to find employment and job misplacements (ElSharkawy et al., 2022). The labor market mechanism plays a critical role in ensuring a balance between supply and demand for work in the long term (Michaillat & Saez, 2015).

The labor market for IT is complex and influenced by various factors, including B1 and B2 demand cycles, as shown in Fig. 10.5. The relationship between labor supply and labor prices is affected by the demand for skilled workers, the education and experience of the labor force, job availability, immigration policies, and economic conditions. The labor market mechanism plays a crucial role in ensuring a balance between supply and demand for work in the long term. However, the shortage of IT talent is a significant challenge that can lead to job misplacement and unemployment, and both the supply and demand sides of the labor market need to be considered when addressing this issue.

Supply chains are critical to the Information Technology (IT) industry, as they help ensure organizations access the necessary digital talent. Figure 10.6 depicts the basic supply structure of the IT industry and illustrates three levels of digital skills: basic, intermediate, and advanced.

The basic level of digital skills includes individuals with fundamental knowledge, such as proficiency in Microsoft Office, basic computer literacy, and familiarity with common software applications. The intermediate level comprises individuals with

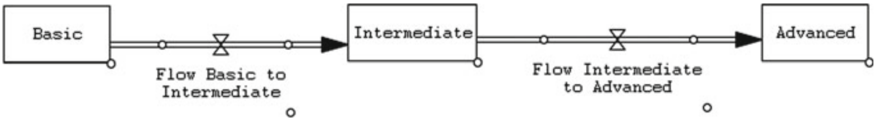

Fig. 10.6 Information technology's basic supply structure describes basic, intermediate, and advanced level of digital skills

more advanced skills, such as experience with coding languages, network administration, and software development. Finally, the advanced level includes individuals with expertise in fields such as cybersecurity, cloud computing, and artificial intelligence (AI).

The supply chain for IT professionals involves recruiting, training, and retaining individuals with the necessary digital skills at each level. Organizations can recruit individuals with basic digital skills through job fairs, community colleges, and training programs (ElSharkawy et al., 2022). Once recruited, individuals can be trained to develop intermediate and advanced digital skills through a combination of on-the-job training, mentorship programs, and formal education (Lockwood & Ansari, 1999). Retaining skilled IT professionals is critical for organizations, and factors such as job satisfaction, compensation, and work-life balance play a significant role in retaining talent (Michaillat & Saez, 2015).

The demand for digital talent is increasing, and the supply chain for IT professionals must be sustainable to meet this demand (Lee, 2020). The shortage of IT talent in the labor market is a significant challenge, and efforts need to be made to address this issue (ElSharkawy et al., 2022). Organizations can work with educational institutions and government agencies to develop training programs that provide individuals with the necessary digital skills (Michaillat & Saez, 2015). Additionally, organizations can focus on retaining skilled IT professionals by creating a positive work environment that fosters job satisfaction and provides opportunities for career growth (Lockwood & Ansari, 1999).

The supply chain of IT professionals involves recruiting, training, and retaining individuals with the necessary digital skills at each level. Figure 10.6 illustrates the basic supply structure of the IT industry and highlights three levels of digital skills. The shortage of IT talent in the labor market is a significant challenge that requires a sustainable supply chain for IT professionals. Efforts need to be made to address this issue, and organizations should work with educational institutions and government agencies to develop training programs and create a positive work environment that fosters job satisfaction and provides opportunities for career growth.

Figure 10.7 presents a causal model of dropout behavior and highlights the B3 satisfaction desertion feedback loop. This feedback loop emphasizes the impact of satisfaction on dropout behavior and how it can influence the availability of digital talent.

As shown in Fig. 10.7, the digital talent gap leads to an increase in salaries, boosting satisfaction with careers in information technology. However, this can also result in fluctuations in the enrollment and retention rates of IT programs. Specifically,

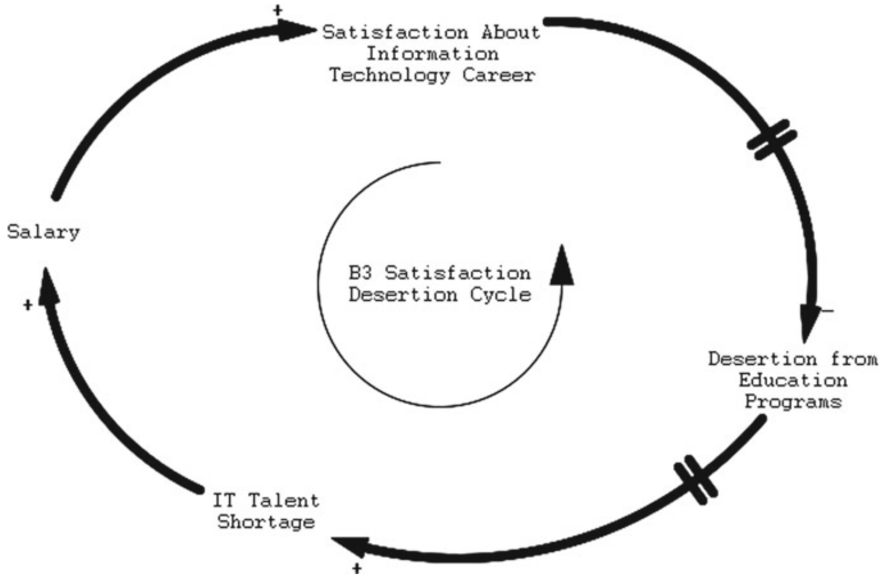

Fig. 10.7 Causal model of dropout behavior, which describes the interplay between digital talent gap, salaries, career satisfaction, and enrollment/retention rates in IT programs

high satisfaction levels may increase enrollment, whereas high dropout rates can exacerbate the digital talent gap.

This figure illustrates the complex interplay between the digital talent gap, salaries in the IT industry, satisfaction with careers in information technology, and enrollment and retention rates in IT programs. The figure highlights how the digital talent gap can impact these variables, which, in turn, can affect each other in a feedback loop. Specifically, the figure shows how changes in salaries and career satisfaction can lead to fluctuations in enrollment and retention rates in IT programs, which can directly impact the digital talent gap.

As discussed earlier, the digital talent gap is a significant challenge, and efforts must be made to address this issue. One way to address this challenge is to provide training programs that offer individuals the necessary digital skills. However, dropout behavior can undermine the effectiveness of these training programs, and it is crucial to understand the factors that influence dropout behavior.

The delay between satisfaction and incentives is a factor that affects dropout behavior. Although there are incentives due to the high salaries expected by trained students, satisfaction with these programs generates a delay in observing the results of these incentives in the number of students trained and reintegrated as a result of satisfaction with the incentives. This delay can lead to oscillations in the system, indicating that although there is pressure for digital talent security, it will be challenging to avoid cycles of high availability (ElSharkawy et al., 2022).

Another factor that affects dropout behavior is the availability of graduates ready to access the programs. The ability to have graduates ready to access the programs can generate oscillations in the system. As dropout decreases due to delays, the digital talent gap also decreases, which can lead to an increase in the availability of graduates. However, this increase in the availability of graduates could lead to a decrease in dropout behavior, resulting in a new cycle of high availability (Michaillat & Saez, 2015).

To design effective training programs that reduce the digital talent gap and improve student satisfaction, it is crucial to understand the factors contributing to dropout behavior, such as the delay between satisfaction and incentives and the availability of graduates ready to access the programs.

Figure 10.8 illustrates a causal model of dropout behavior, reintegration, and delay in IT training programs, highlighting B4's feedback loop. The B3 and B4 balance cycles propose that a shortage of digital talent leads to increased salaries and greater perceived satisfaction with information technology careers, which can reduce the dropout rate in IT programs. However, it should be noted that these cycles are theoretical models that require further research to determine their validity and usefulness in addressing the digital talent gap.

Student satisfaction is crucial to student persistence as it can reduce dropout rates (Suhre et al., 2006). Online education programs have used data-mining approaches

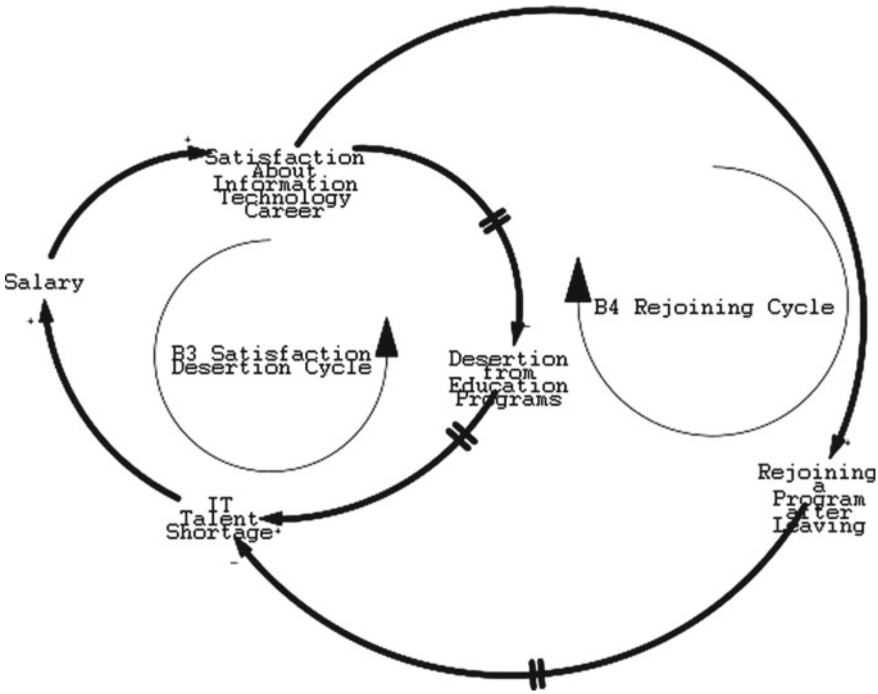

Fig. 10.8 Causal model of dropout behavior, reintegration, and delay in IT training programs

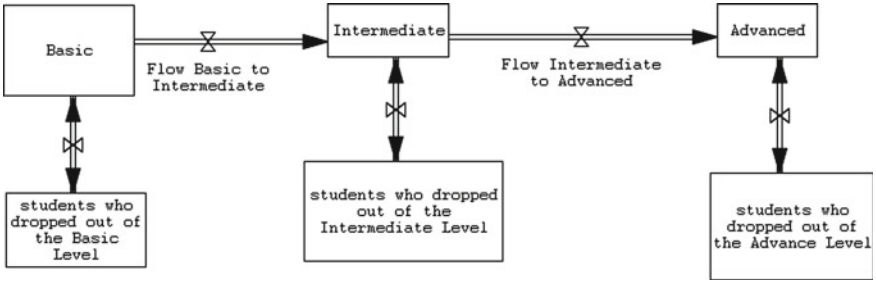

Fig. 10.9 Causal model of dropout behavior with reintegration and delay at each level of digital skills

to predict student dropouts (Yukselturk et al., 2014). The quality of the learning system, information, and service can also influence student satisfaction and, in turn, the student dropout rate (Machado-da-Silva et al., 2014).

It is important to recognize that the B3 and B4 balance cycles presented in Fig. 10.8 are theoretical models that have not been thoroughly studied or tested in the literature, and evidence supporting these models is limited (Yukselturk et al., 2014). Therefore, further research is required to determine the validity and usefulness of these models in addressing the digital talent gap.

Figure 10.9 presents the causal model of dropout behavior with an added feature that considers dropout at each level of digital skill: basic, intermediate, and advanced. The physics of the system reveals that although deserters may occur at different levels of digital talent, they have the potential to return to the training process under favorable conditions. Therefore, it is crucial to consider the possibility of reintegration for these deserters as they may contribute to reducing the digital talent gap by returning to training programs.

Incorporating the delay factor, we can see that there may be a delay between the perception of satisfaction, generation of incentives, and availability of graduates ready to access the programs. However, if the conditions are favorable, students who have dropped out can reintegrate and continue their training, reducing the dropout rate at each level of digital skills and increasing the availability of digital talent.

Understanding the system's dynamics, including the possibility of reintegration, is critical for designing effective programs to reduce dropout rates and increase the availability of digital talent. The causal model of dropout behavior with reintegration and delay provides a framework for addressing the challenges of the digital talent gap and improving the effectiveness of training programs.

Incorporating dropout and reintegration elements into the model highlights the greater inertia and memory of the system for these factors. This means that the effects of program satisfaction resulting from the digital talent gap or satisfaction with information technology professionals on dropout are larger than initially assumed. The model simulations provide valuable insights into the impact of dropouts on the entire system and emphasize the importance of sustainability in digital talent formation.

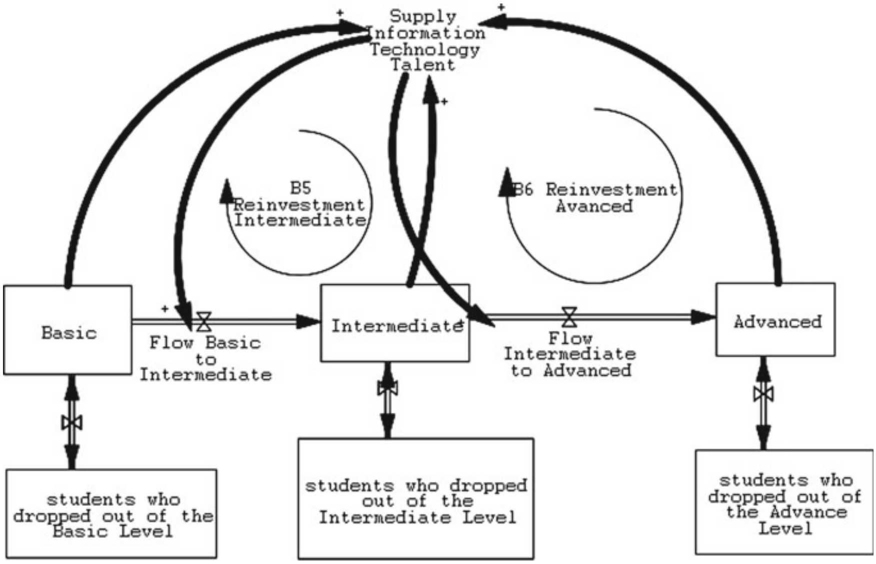

Fig. 10.10 Information technology education chain production with feedback loops about reinvestment

The B5 and B6 feedback loops have been identified as critical elements in developing digital skills on Fig. 10.10 (Bejaković & Mrnjavac, 2020). These loops operate under the principle that the more experts a system has, the more experts should be dedicated to teaching new ones. Research experts have noted that failing to invest in this feedback loop can hinder a system's ability to produce digital talent (Carlisle et al., 2021). This decline could widen the digital skills gap, limit the system's sustainability, and negatively impact economic growth and job creation (Bejaković & Mrnjavac, 2020).

To ensure the system's sustainability and reduce the gap in digital skills, investing in the B5 and B6 feedback loops is imperative. This investment should prioritize the development of digital skills at all levels of education and training, from basic to intermediate and advanced (Bejaković & Mrnjavac, 2020). By doing so, the system can maintain a steady flow of digital talent and adapt to the ever-changing demands of the digital economy (Bejaković & Mrnjavac, 2020).

The lifespan of individuals in the market is a crucial consideration in reducing the digital talent gap. A shorter lifespan makes it more challenging to reduce this gap because individuals must be replaced with relevant talent levels. Therefore, it is essential to provide individuals with relevant skills and abilities to learn and adapt to new technologies rather than promoting disposable digital talent formation with very short periods of usefulness. This approach can help to reduce the digital talent gap and promote sustainable digital talent formation.

As discussed earlier, developing digital talent is crucial for the transition to a service-based economy and maintaining accessible levels of goods and services.

This was a matter of national security. Therefore, it is important to connect the availability of digital talent at the basic and standard education levels to achieve sufficient availability at an advanced level to meet growing social and business needs (ElSharkawy et al., 2022).

Incorporating elements of dropout and reintegration into the model highlights the greater inertia and memory of the system for these factors. The lifespan of individuals in the market is crucial for reducing the digital talent gap, and sustainable digital talent formation is essential. Digital talent development is critical for the transition to a service-based economy, maintaining accessible levels of goods and services, and national security. Connecting the availability of digital talent at different educational levels is vital for meeting the growing social and business needs.

This chapter emphasizes the significance of digital talent in transitioning to a service-based economy and national security. Government-promoted ICT training programs should strategically provide teachers with internship opportunities to achieve sufficient availability of digital talent at an advanced level (ElSharkawy et al., 2022). These programs should also aim to improve citizen satisfaction with professions related to information technology by incorporating mechanisms that incentivize transition at each level to motivate future ICT talents to improve their skills.

The chapter concludes that sustained effort is necessary to reduce the digital talent gap, requiring continuous public investment in training programs and policy measures to ensure a sufficient supply of digital talent to meet the growing social and business needs. This effort is particularly important given the increasing demand for digital talent and the threat of a digital talent gap, which could negatively impact the economy and national security (Michaillat & Saez, 2015).

In summary, the provision of digital talent must connect the availability of such talent at primary and standard education levels to achieve sufficient availability at an advanced level. Government-promoted ICT training programs should strategically provide teachers with internship opportunities to improve citizen satisfaction with information technology-related professionals. Using mechanisms that incentivize transition at each level is necessary to motivate future ICT talent to improve their skills. Sustained efforts are necessary to reduce the digital talent gap, which requires continuous public investment in training programs and policy measures (Suhre et al., 2006).

10.4 Conceptual Model Validation

This chapter describes the development and validation of dynamic hypotheses and causal diagrams. The authors validated the diagrams against relevant literature and modeling discussions and assessed their structural validity using the guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010). In this section, the validation process is summarized.

According to Qudrat-Ullah (2008), the behavioral validity of a simulation model can be evaluated by assessing its ability to reproduce the behavior of the system it represents. Qudrat-Ullah and Baek Seo (2010) proposed guidelines for determining the structural validity of a system dynamics-type simulation model, which involve evaluating the model's feedback structure, time delays, and parameter values.

Using these guidelines, we validated the causal diagrams presented in this chapter by assessing their ability to reproduce a system's behavior and evaluating their structural characteristics, such as feedback loops and time delays. The causal diagrams for this study were both valid and reliable.

In summary, the authors developed and validated dynamic hypotheses and causal diagrams in this chapter. The validation process involved assessing the ability of diagrams to reproduce a system's behavior and evaluate its structural characteristics. The causal diagrams were found to be valid and reliable according to the guidelines proposed by Qudrat-Ullah and Baek Seo (2010).

Figure 10.11 illustrates the classification of the variables in the dynamic hypotheses and the causal diagrams presented in this chapter. The variables are categorized into endogenous and exogenous variables based on the guidelines proposed by Qudrat-Ullah and BaekSeo (2010a, 2010b) for structural validity assessment in system dynamics-type simulation models.

Endogenous variables, such as student attrition behavior, student satisfaction, and digital talent availability, were included in the models, while excluded variables consisted of academic support, access to resources, curriculum quality, education quality, learning environments, educational technologies applied in migration, talent attraction policies, and innovation and entrepreneurship in the ecosystem.

By focusing on the endogenous variables that have the most significant impact on the system, we obtained better and more reliable causal diagrams for this study. This approach is consistent with Forrester's (1961) idea that the structure of a model generates its behavior. The qualitative model developed in this study is designed to provide decision-making guidelines by understanding the fundamental elements of the structure that determine the dynamics in the production of talent in information technology.

To achieve this goal, we present a conceptual model and define the endogenous and exogenous variables that determine their boundaries, a crucial step in ensuring the validity and reliability of the model. This process helps exclude irrelevant variables and focuses on those that have the most significant impact on the system being modeled.

Overall, this study aims to provide decision-makers with a valid and reliable tool for making informed decisions regarding talent production in information technology. Classifying the variables presented in Fig. 10.11 is an essential step towards achieving this goal.

Table 10.1 presents the structures and concepts adopted from the existing literature as empirical validations of the causal loops and dynamic hypotheses presented in this chapter. The table includes the authors, publication year, and titles of the works from which these structures and concepts were adopted.

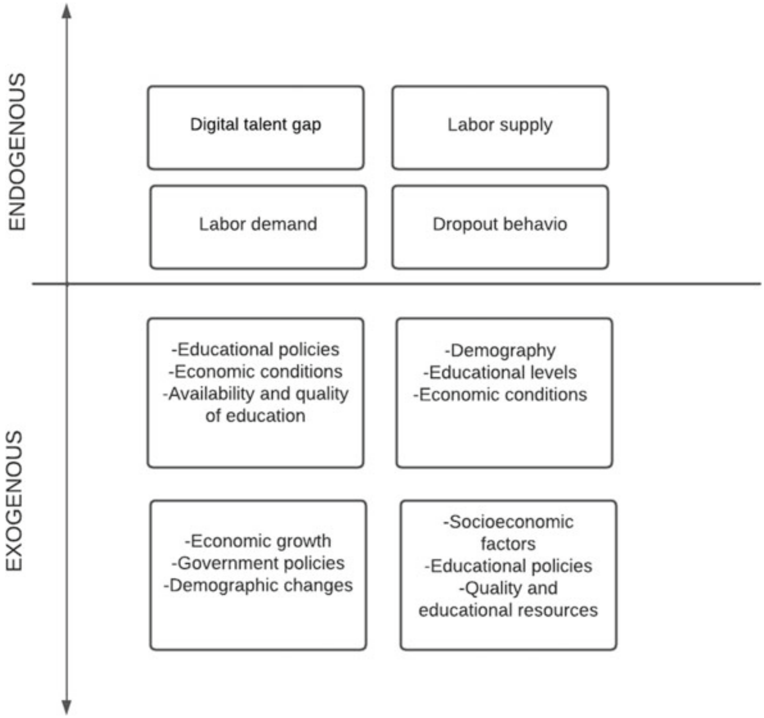

Fig. 10.11 Classification of endogenous and exogenous variables in the dynamic hypotheses and causal diagrams presented in this chapter based on the guidelines proposed by Qudrat-Ullah and BaekSeo (2010)

Table 10.1 presents the structures and concepts adopted from the literature to validate this chapter's causal loops and dynamic hypotheses empirically. The table includes the authors, publication years, and titles of the works from which these structures and concepts were adopted.

The table demonstrates how various concepts, such as the impact of technology education on dropout behavior, the effect of technology education on the availability of digital talent, and the influence of socioeconomic status on dropout behavior, were incorporated into these causal hypotheses. These concepts were adopted by Stromberga et al. (2021) and García et al. (2022), who helped define the model's boundaries and identify the relevant variables that determine the dynamics of talent production in digital technology.

The table also highlights the structure of the digital talent production system and the feedback loops that drive production, availability, and incentives for professionals with digital talent. These structures and concepts were crucial for this research as they provided us with a comprehensive understanding of the dynamics of talent production in the digital technology field.

Table 10.1 Structures and concepts adopted from the existing work in the causal loops diagrams presented in this chapter

Structures/concepts	Remarks
Lee, S. H. (2020). Skills Development Driven by Labor Market Demand. In International Conference on Advanced Information Technologies and Applications (pp. 271–277). Springer	Causal structure was adopted
Michaillat, Pascal, and Emmanuel Saez. 2015. "Aggregate Demand, Idle Time, and Unemployment." The Quarterly Journal of Economics 130(2): 507–569	Causal structure was adopted
Sun, Meng. 2022. "Labor Markets." In Artificial Intelligence, Industry 4.0, and Entrepreneurship: Innovation and Challenges, edited by Ming-Lang Tseng and Ching-Sung Lee, 1–15. IntechOpen	Causal structure was adopted
Bills, David B., Valentina Di Stasio, and Klarita Gërxhani. 2017. "The Demand Side of Hiring: Employers in the Labor Market." Annual Review of Sociology 43(1): 291–310	Causal structure was adopted
ElSharkawy, Mohamed, Ahmed Helmy, and Ahmed Yehia. "The Mismatch between IT Graduates and the Needs of the Labor Market: Evidence from Egypt." International Journal of Human Resource Studies 12, no. 1 (2022): 1–15	Causal structure was adopted
Lockwood, John, and Shahid Ansari. "Information Technology Skills Shortages and the IT Labor Market." Journal of Labor Research 20, no. 4 (1999): 493–502	Causal structure was adopted
Suhre, C., Jansen, E., & Harskamp, E. G. (2006). "Impact of Degree Program Satisfaction on the Persistence of College Students." Higher Education, 2(54), 207–226	Causal structure was adopted
Bejaković, Predrag, and Željko Mrnjavac. 2020. "The Importance of Digital Literacy on the Labour Market." Employee Relations 42 (4): 921–932	Causal structure was adopted

In summary, Table 10.1 provides an overview of the structures and concepts adopted from the existing literature to validate the causal loops and dynamic hypotheses presented in this chapter. The table shows how various concepts were incorporated into causal theories and how the structure of the digital talent production system was developed. By adopting these structures and concepts, this study provides a comprehensive understanding of talent production dynamics in the digital technology field.

10.5 Discussion

The shortage of IT professionals is a significant challenge faced by many countries worldwide, and is attributed to multiple factors, including the increasing demand for IT services, the development of the information economy, and the maldistribution of IT professionals.

Various strategies have been proposed to address this problem. One strategy is to increase the number of IT professionals through online e-learning programs, which have been shown to be effective in improving the knowledge, skills, attitudes, and satisfaction of health professionals. This strategy can be adopted in the IT sector to increase the number of IT professionals.

Another strategy is to attract and retain IT professionals by improving their work conditions and wages. This can be achieved by providing incentives such as bonuses, flexible working hours, and opportunities for career advancement. Providing training and development programs to improve professional IT skills and capabilities can also be effective for retaining IT professionals.

Another strategy is to address the shortage of IT professionals by increasing the number of IT professionals through immigration policies. Immigration policies can be used to attract highly qualified foreigners to sectors facing labor shortages, such as the IT sector. Some OECD countries have adopted this strategy to address the shortage of IT professionals.

Governments, educational institutions, and private organizations can implement these strategies to ensure the availability of IT professionals and promote economic growth and national security. The provision of digital talent must connect the availability of such talent at the primary and standard education levels to achieve sufficient availability at an advanced level. Government-promoted ICT training programs should strategically provide teachers with internship opportunities to improve citizen satisfaction with information technology-related professionals. Using mechanisms that incentivize transition at each level is necessary to motivate future ICT talent to improve their skills. Sustained efforts are necessary to reduce the digital talent gap, which requires continuous public investment in training programs and policy measures (Suhre et al., 2006).

The labor market for IT is complex and is influenced by various factors, including the demand for skilled workers, education and experience of the labor force, job availability, immigration policies, and economic conditions. The labor market mechanism plays a crucial role in ensuring a balance between supply and demand for work in the long term. The shortage of IT talent is a significant challenge that can lead to job misplacement and unemployment, and both the supply and demand sides of the labor market must be considered when addressing this issue (Lee, 2020; Michaillat & Saez, 2015; Sun, 2022).

Figure 10.5 illustrates the B1 and B2 demand cycles, which can impact the relationship between labor supply and labor prices in the IT sector. The shortage of IT talent can lead to fluctuations in enrollment and retention rates in IT programs because of the high salaries and satisfaction levels associated with IT careers. However, factors such as the delay and availability of graduates can also affect dropout behavior and the digital talent gap (ElSharkawy et al., 2022; Michaillat & Saez, 2015).

To address the digital talent gap, investing in the B5 and B6 feedback loops is imperative. This investment should prioritize the development of digital skills at all levels of education and training, from basic to intermediate and advanced (Bejaković & Mrnjavac, 2020). Other strategies to address the shortage of IT professionals include improving work conditions and wages, providing training and development programs, and increasing the number of IT professionals through immigration policies (OECD, 2018).

Sustained efforts are necessary to reduce the digital talent gap, which requires continuous public investment in training programs and policy measures (Suhre et al., 2006). Governments, educational institutions, and private organizations can implement these strategies to ensure the availability of IT professionals and to promote economic growth and national security. The provision of digital talent must connect the availability of such talent at primary and standard education levels to achieve sufficient availability at an advanced level.

In conclusion, addressing the shortage of IT professionals is crucial for countries to meet their growing demand for IT services. Implementing strategies such as online e-learning programs, improving working conditions and wages, and increasing the number of IT professionals through immigration policies, governments, educational institutions, and private organizations can ensure the availability of IT professionals and promote economic growth and national security.

10.6 Conclusion

In conclusion, this chapter highlights the critical role of digital talent in the transition to a service-based economy and national security. Digital talent should be viewed as a system that efficiently understands, intervenes, and supplies strategic digital talent to maintain accessible goods and services. To achieve this, the development of digital talent must be a priority, and simulation exercises have shown that the provision of digital talent must connect the availability of aptitude at the basic and standard education levels to achieve sufficient availability at an advanced level.

To bridge the digital talent gap, this chapter suggests that government-promoted ICT training programs should strategically provide teachers at all three levels of education and create internship opportunities to improve citizen satisfaction with professions related to information technologies. It is also essential to incorporate mechanisms that incentivize transitions at each level to motivate future ICT talent to enhance their training, capabilities, and skills.

To ensure the active participation of women in digital talent roles, gender equity must be considered. Future studies should model the effects of high international salaries on the availability of ICT talent and articulate all modes of ICT training to improve the availability and quality of ICT talent.

Reducing the digital talent gap requires sustained efforts, continuous public investment in training programs, and policy measures. Public policy can contribute to reducing this gap by working on talent recruitment, reducing dropout rates throughout the system, and improving satisfaction with training and professions related to information technologies. By doing so, a country can ensure the availability of digital talent to meet the growing demand for IT services and maintain national security in a service-based economy.

The proposed method is crucial in identifying the provision of digital talent as a system and proposing strategies to address the digital talent gap, specifically in Colombia. This analysis provides actionable recommendations for policymakers, educational institutions, and private organizations to improve the availability and quality of digital talent in the country and to maintain its competitiveness in a rapidly evolving digital landscape.

10.6.1 Insights and Implications for Practice

This chapter emphasizes the importance of digital talent in the transition to service-based economy and national security. The provision of digital talent should be viewed as a system that efficiently understands, intervenes, and supplies strategic digital talent to maintain accessible goods and services. To address the shortage of IT professionals, decision makers should adopt a holistic approach that considers the interconnections and interdependencies of the various components of the digital talent system, from basic education to advanced training.

This analysis provides actionable recommendations for policymakers, educational institutions, and private organizations to improve the country's digital talent availability and quality and maintain its competitiveness in a rapidly evolving digital landscape. Best practices for attracting and retaining IT talent in a competitive market include providing competitive salaries and benefits, offering opportunities for professional development and growth, creating a positive work culture, and prioritizing employee well-being. Upskilling and reskilling existing IT staff can be achieved through training opportunities, mentorship, coaching programs, and promoting a culture of continuous learning.

Effective approaches to workforce planning and succession management involve identifying critical positions and skills, developing a talent pipeline for those positions, and implementing processes to ensure a smooth transition when vacancies occur. To reduce the digital talent gap, it is necessary to provide the system with the necessary tools to reduce dropouts, increase enrollment, identify high-quality programs, prioritize the training of trainers at all levels of the system, and ensure that the level of education meets international standards. Additionally, it is essential to prioritize the social recognition of Information and Communications Technology (ICT) as a strategic profession essential for a country's development.

By leveraging systems thinking, decision-makers can identify leverage points and develop strategies to improve the system's overall functioning. This chapter provides practical strategies for better decision-making in IT talent management, including best practices for attracting and retaining IT talent, strategies for upskilling and reskilling existing staff, effective approaches to workforce planning and succession management, and policy recommendations for reducing the digital talent gap. These insights and implications can guide IT leaders and decision-makers in improving the availability and quality of digital talent, ultimately contributing to a country's competitiveness and national security in a service-based economy.

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Part V
Addressing Agricultural Issues with Systems Thinking

Chapter 11
Leveraging IoT and System Dynamics for Effective Cooperation in Solving Social Dilemmas in Water Management

Beatriz-Eugenia Marin and Jorge-Andrick Parra-Valencia

Abstract This chapter presents an approach to promote practical cooperation in solving social dilemmas in water management by leveraging the Internet of Things (IoT) and System Dynamics. We discuss how System Dynamics can be used as a decision-making tool to consider the complex interdependencies among the different components of the water management system. We also highlight the potential of agent-based models, conflict management practices, game theory, and mathematical models to create more equitable and efficient water policies that encourage stakeholder cooperation. This approach can potentially be applied in multiple cases of water management. In this chapter, we present a specific case of sugarcane production for panela as a reference because of its high water consumption compared to other crops. Using IoT, we can gather and disseminate real-time data, enabling stakeholders to make informed decisions and work collaboratively to optimize water use. Overall, this chapter demonstrates the potential of the IoT and System Dynamics to foster practical cooperation in solving social dilemmas in water management. The proposed approach offers decision-makers a framework for developing more inclusive and collaborative policies that promote equitable and sustainable water use in various contexts.

Keywords Internet of things (IoT) · Systems thinking · Cooperation · Water management · Sugarcane production · System dynamics · Decision-making · Agent-based models · Conflict management · Game theory · Mathematical models · Sustainability

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11.1 Introduction

In recent years, water has become an increasingly complex issue worldwide due to various factors, including climate change, population growth, and resource shortages. To address the various challenges related to water management, there is an urgent need for a coordinated approach to ensure the conservation, use, and sustainable allocation of water resources. Considering that only 0.5% of the water present on earth is fresh and usable, properly managing its distribution becomes a matter of public policy. Agriculture is the activity that demands the most water, consuming 70% of the total available. At certain times of the year, crops are maintained with water from rainfall, but when rainfall is insufficient, farmers must resort to other sources, affecting river flows or groundwater reserves. Three challenges are identified by Saad et al. (2020): water reuse and water pollution monitoring, water pipeline monitoring, and water Irrigation, the last including new methods in cultivating crops (Cassalett et al., 1995; Rosa et al., 2020).

Water management conflicts often arise because of competition between users trying to safeguard access to a vital resource while protecting the natural environment (Priscoli & Wolf, 2009a, 2009b). Without strategies to anticipate, address, and mediate between competing users, intractable water conflicts will likely become more frequent, intense, and disruptive worldwide (Mutahara et al., 2019). Conflict and cooperation are part of the cyclical process of water resource management. The possibility of conflict or cooperation is determined by hydrological, socioeconomic, institutional, political, cultural, and policy contexts (Wolf, 2007). The potential for an outright war between countries over water is low, but cooperation is often missing in disputes over transboundary resources (Ojha et al., 2018).

The management of water conflicts can be improved by adopting an open, confronting, and problem-solving approach to disputes (Lewicki & Sheppard, 1985). Adaptive Learning and Deliberation (ALD) is an effective approach for understanding and addressing conflicts over the local management of forests and water (Yerian et al., 2014). The role of women in water management and conflict resolution is essential, and their contributions to water management are valued, especially through informal initiatives (Tempels & Hartmann, 2022). The OECD Water Governance Principles provide guidelines for good water governance, but these principles can conflict with each other when applied in practice (Hang et al., 2023). The field of water conflict and cooperation deserves re-examination based on new realities, as transboundary river basins are experiencing rapid changes through both physical and economic pathways worldwide (Wolf, 2007).

Cooperation in social dilemmas confronts self-interests with collective interests. Therefore, each actor must consider his own motivations and those of others when dealing with common goods. It has been shown that the strategy of benefits and punishments regulates cooperation. (Pärnamets et al., 2020). Another mechanism of cooperation is by reputation and is based on the beliefs that others have about an actor in the system. These beliefs may arise from physical, social, and other aspects (Manrique et al., 2021). Under this model, reputation increases when there is cooperation or decreases when there is defection; reputation can also increase when switching from defection to cooperation (Pan et al., 2020). Other hypotheses that have been proposed on cooperation strategies are the learning hypothesis, where the initial starting point is confusion and can lead to adaptive learning, and the conditional cooperation hypothesis, where the group influences the individual's behavior by changing his or her behavior. (Andreozzi et al., 2020).

In this study, we seek to continue studying the potential of the Internet of Things (IoT) and System Dynamics to develop new tools for assessing the outcome of cooperative efforts between water users. A cooperative water management evaluation model can be applied to different contexts. Initially, the sugar cane crops for panela have been taken as a reference due to their high demand of the resource, having to resort to irrigation in times of low rainfall. Still, we hope to be able to evaluate other cases where water as a shared resource must be regulated to meet the basic needs of stakeholders. This would improve resource use according to the information received and classify this problem as a social dilemma in imperfect conditions. Water is an exhaustible shared resource, from which its consumption cannot be excluded, as it is used above a sustainable level (Parra, 2012).

The sugar cane crops for panela in the geographic valley of the Cauca River and the North of Santander are growing economies, usually of small farmers who must share water with other crops and households. Valle del Cauca showed that a large portion of water resources are dedicated to sugarcane production, and it is used mainly to make alcohol and refined sugar in large industries, but panela production is lower. However, water must be shared in all cases. This has led to the need for more cooperative approaches to reducing water-usage conflicts regarding panela production (Restrepo & Bedoya, 2015). In the agribusiness sector, sugarcane plantations account for more than 280,000 direct jobs and rank second in the world, behind India. Valle del Cauca and Norte de Santander account for approximately 3.8% and less of the national production, respectively, with similar results in terms of area planted, harvested, and produced in tons (Ministerio de Agricultura y Desarrollo Rural, 2020), demonstrating an ideal situation for the exploration of associated water dynamics, taking advantage of the closeness of the authors with the two regions.

11.2 Literature Review

System Dynamics and IoT Technologies for Water Management

Social dilemmas arise when there are interdependent relationships around a common good, where each party seeks its benefit, probably negatively impacting the community. The decision to cooperate is the main topic in a social dilemma that seeks to provide all its actors, both individually and collectively, with the greatest incentive to generate an environment of mutual trust, reducing the misperception of individuals due to the complexity of the system and interdependence of the actors

(Parra, 2012). Incentives or benefits become the object of exchange rather than quantities of water, and sharing these benefits is a strategy to avoid conflict (Moorthy & Bibi, 2023).

One of the significant challenges in water management is ensuring cooperation among stakeholders to optimize water utilization (Ford, 1997). The system dynamics approach emphasizes group learning, which is vital for promoting cooperation toward achieving a common goal in water management. This approach enables stakeholders to view scenarios from different perspectives and to learn from each other's views to develop sustainable policies. It provides more information to make better decisions and thus guarantees the availability of resources like water. It is also a tool that allows for analyzing complex systems, predicting future outcomes, and formulating policies. It has been successfully applied in water management to develop integrated water resource management plans, define water demands and abstractions, and optimize new services and institutional structures (Badarch et al., 2021; Jacobson et al., 2013).

Water is a crucial natural resource for human civilization, and its management requires robust and advanced approaches, particularly in urban areas. Recent technological advancements, such as the Internet of Things (IoT) and system dynamics modeling, have been integrated into water management to enhance the efficiency and sustainability of this valuable resource (Gautam et al., 2021; Gonçalves et al., 2020; Joshi, 2021; Susetyo et al., 2019).

The importance of water availability lies in the fact that it is a determining factor for the scale and quality of a region's economic and social development. The water resource carrying capacity (WRCC) must be monitored to maintain sustainable development. Jinghuan and Huiran (2010) and Chang (2021) used dynamic system modeling to simulate water availability under demand from domestic use, industry, agriculture, and urban public areas, and the results obtained showed that in the long term, water consumption is not sustainable without cooperation. Water management involves allocating resources to different sectors, such as agricultural, industrial, urban, and environmental. A dynamic approach to systems in water resource management has been developed that accounts for the different demands from these sectors while prioritizing one over the other (Karim & Mohammadghasemi, 2021).

Water management is a critical issue, and integrating IoT technologies can help improve water management systems (Priscoli & Wolf, 2009a, 2009b). IoT can be used to automate water management processes, such as water level monitoring, leakage detection, and water quality monitoring (Gautam et al., 2021; Kamaruidzaman & Rahmat, 2020). The use of IoT in water management can also help increase the efficiency of agricultural and farming processes, such as precision irrigation, which can lead to increased crop yield and decreased costs (Kamienski et al., 2019; Madushanki et al., 2019). Implementing IoT-based water distribution and management systems can help address issues plaguing rural India's water supply chain (Maroli et al., 2020). The use of IoT in water management can also help develop smart cities by aiding in the efficient management of water supply systems (Gautam et al., 2021). Integrating IoT technologies in water management can also help conserve and manage water resources (Kamaruidzaman & Rahmat, 2020). The use of IoT technologies in water management can be improved by developing real-time water monitoring systems based on IoT technology (Skarga-Bandurova et al., 2020).

The IoT has also been integrated into water management to develop smart water management systems that utilize IoT devices and wireless sensor networks (WSN) to monitor and manage water resources in real-time, thereby enhancing the efficiency of water management (Bouziane et al., 2021; Gautam et al., 2021; Gonçalves et al., 2020; Joshi, 2021). These systems can also collect data for big data analytics used in decision-making processes and derive valuable information for predicting future outcomes (Gardner et al., 2005; Maroli et al., 2020; Schultz et al., 2019).

Furthermore, integrating system dynamics modeling, IoT, and WSN has shown promising results in enhancing energy efficiency in water management (Joshi, 2021). The Enhanced Energy Allocating Time Slots Mechanism (EEATSM) has been proposed to optimize energy utilization in smart water management systems (Joshi, 2021).

The integration of dynamic systems with IoT still has a lot of scope for exploration, but in precision farming is finding its greatest utility. Kamienski et al.(2019) proposed robust platforms to make information available and process it in the cloud to apply precision irrigation in agriculture. Pathmudi et al.(2023) identified architectures and devices that offer advantages, particularly in precision irrigation, in reducing water waste.

Creating effective policies to ensure the availability of resources for all subsystems of the environment is another focus of dynamic systems, providing information on the quantity of water for various uses according to the behavior of the stakeholders. System dynamics allows modeling interactions between actors so that decision-makers can create policies using this information, and Kotir et al. (2016) and Laspidou and Ziliaskopoulos (2022) created models to simulate the interactions around a river in some regions of Africa to provide information to generate appropriate policies to maintain sufficient levels of resources.

Interventions in water management have provided opportunities for improvement. For example, Malisa et al. (2020) proposed water reuse using system dynamics modeling to validate known situations and predict their impact in the future, demonstrating the versatility and ease of incorporation of many parameters that can be adapted to different cases.

Other experiences in water management, although they have not used system dynamics, show the essential variables that must be considered in water management practices. Fabbro Neto and Gómez-Martín (2020) studied the Caraguatatuba Water Security Plan in Brazil to compare it with international conflict management practices to create successful strategies. Ismail et al. (2022) also explored the use of technology and data to improve water administration by examining the implementation of IoT and mathematical models. Mathematical models can be developed to provide insights into the potential outcomes of different water-management scenarios. Using optimization methods and simulation tools, policymakers can quickly identify the most effective strategies for managing water resources.

11.2.1 Agent-Based Models for Water Management

Proposals, such as those of Okura et al. (2022) and Reinhard et al.(2022), explored the use of agent-based models and game theory. An agent-based model is a type of simulation that can be used to analyze the impacts of different policy interventions related to water management. In an agent-based model, individual agents, each representing a particular stakeholder or type of water user, are simulated to observe their behavioral and environmental responses to water access, pricing, or other policy changes. This allows for a better understanding of the overall dynamics and effects of different water management approaches (Macal & North, 2009). Bourceret et al. (2022) use agent-based modeling for its ability to incorporate time- and space-scaled patterns based on theories of planned behavior. They identified the characteristics of water protection programs and their interaction with the behavioral characteristics of farmers, demonstrating that the efficiency and effectiveness of policies are positive in most scenarios when farmers are actively involved.

11.2.2 Game-Theory for Water Management

Game theory allows us to examine how changing incentives or strategies can affect the behavior of individuals or groups. In water management, there is the non-cooperative game theory that focuses on the way players make decisions, while the cooperative game theory studies the distribution of benefits obtained through collaboration (Cao et al., 2023).

Using various games, such as the prisoner's dilemma (Doebeli & Hauert, 2005), water decision-makers can look at how different policies might shape user interactions and create greater cooperation or effectiveness in water management. It is common to use this technique with other techniques, such as agent-based models, to validate behaviors. In Okura et al.(2022), conflicts were modeled with agents, and governance concepts under rule-driven cooperation were analyzed using game theory. Noori et al.(2020) used agent-based models, game theory, and genetic algorithms to optimize water allocation in a watershed; the best result was obtained by the cooperative game theory followed by the agent model, highlighting its ease of understanding in the latter.

11.3 System Dynamics and Internet of Things Technologies in Sugar Cane Crops

Worldwide, 2.5 billion people worldwide depend on groundwater for survival, and it has been estimated that 20% of the world's aquifers are overexploited, which affects soil quality (CVC, 2021). Agriculture demands the largest amount of available water, and sugarcane crops can consume between 3000 and 4000 mm per hectare per year (Dingre & Gorantiwar, 2020). In Colombia, the number of hectares dedicated to this crop has increased, mainly for ethanol commercialization, demanding more water and generating conflicts between agricultural and human use (Perez & Alvarez, 2011).

This study focuses on sugarcane crops for the production of panela, which is crucial for the Colombian family basket and has a significant impact on the socioeconomic development of the rural sector (Gil, 2017). As these crops are mostly done manually, they are vulnerable to water scarcity and poor management practices.

To address these challenges, families may need to invest in technologies to manage their crop water consumption effectively. A system dynamics modeling approach can provide helpful information for organizing and collaborating to ensure sustainable water management practices. Additionally, leveraging the Internet of Things (IoT) can enable stakeholders to access real-time information on resource availability and crop needs, thereby facilitating informed decision-making.

Overall, this study highlights the potential benefits of using system dynamics modeling and IoT to promote sustainable water management practices in sugarcane production for Panela, which could have broader implications for the socioeconomic development of the rural sector.

IoT projects have been applied to large sugarcane industries with crops in their best geographies. The main IoT network is in the geographic valley of the Cauca River, from Santander de Quilichao in the Department of Cauca to Virginia in the Department of Risaralda, which takes data from stations located throughout this region and sends them to the cloud where they are processed to be sent as information to different stakeholders. The availability of these lands has facilitated this network (Cenicaña, 2021); however, small producers do not have access to these resources, and their geography differs significantly from that of large companies.

11.4 Method

To model complex systems and grasp their behavior over time, system dynamics modeling methodology is widely employed (Sterman, 2000). The system dynamics modeling process includes the following steps:

First, an issue requiring attention must be identified. This involves defining the system's limits, recognizing key variables, and comprehending their interrelationships (Coyle, 2000). In this study, the main interest is to evaluate how collaboration can increase when more information is available, having as a benefit the availability of the shared resource for all. This information will be captured through an Internet of Things architecture. Sugarcane crops may be a case of interest due to the high water consumption required for their cultivation. Still, the evaluation model is also expected to be used in other environments.

Next, a conceptual model of the system was created. This is achieved by developing a causal loop diagram that shows how key variables are related to one another and how they interact (Forrester, 1961).

Subsequently, numerical values must be assigned to the variables and equations that describe how they change over time, creating a quantitative model (Pidd, 1996). Finally, the model will be tested and validated to ensure its accuracy.

11.5 Results

In the initial phase of this study, we present a construct with three main cycles (See Fig. 11.1) based on the dynamic hypothesis: “More information provided to the user about water availability and consumption, in this case using IoT, increases cooperation around water use.” Under this assumption, the model articulates cooperation with trust to reduce the temptation to drop out. The cycles are as follows:

The first cycle is the perception of damage, which begins with a supply of water and an initial value for the resource, which is influenced by the number of people using the resource, the amount of resource used by each person, and the function that regulates this output, the necessary information on water availability is taken from an IoT architecture, in the case of sugarcane it should capture the water requirements at each stage of crop growth but should also take into account the other resource

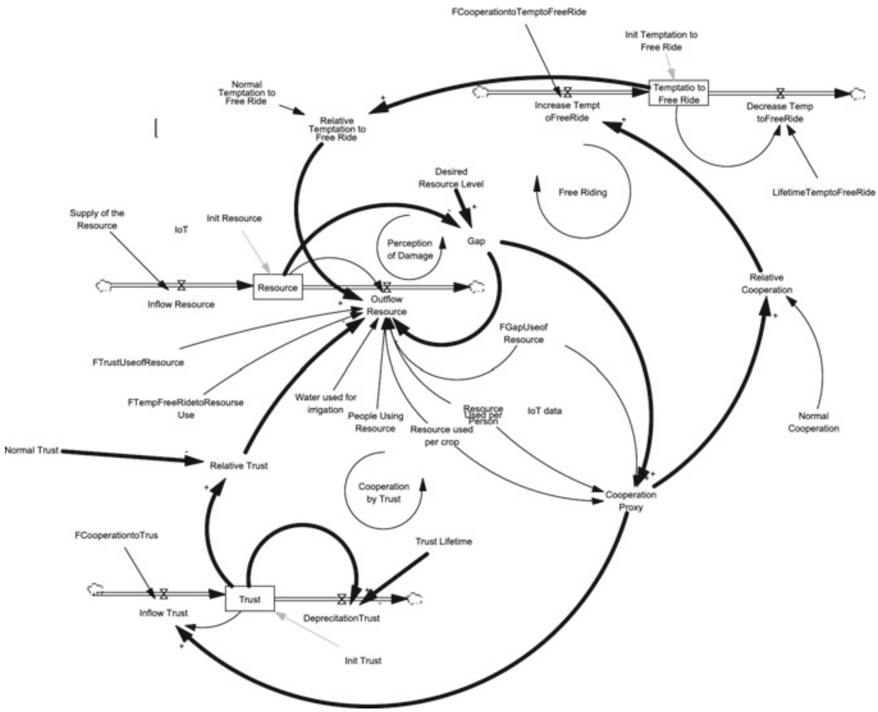

Fig. 11.1 Construct an evaluation of cooperation in water management. Based on Parra (2012)

needs of the other stakeholders. When there is not enough water, the perception of harm increases, and this causes cooperation to increase and consumption per person reduced.

In the second cycle, cooperation is achieved through trust, which grows when people reduce water consumption and is regulated for a lifetime. To determine whether people are reducing water consumption (i.e., cooperating), we used a proxy variable that allows us to increase trust when it is positive. In addition, this cycle had a relative trust variable that increased water savings when there was a high degree of trust.

Finally, we have a free-riding cycle that indicates the temptation to abandon collaborative strategies for resource use. This cycle led to an increase in the water consumption. In this way, we have an outflow of water that can be reduced by cooperation or increased by the temptation to desert. Trust and cooperation determine the temptation to desert. The more trust, the more cooperation, and the less possibility of deserting. The less trust, the less cooperation, and the temptation to desert increases.

11.6 Conceptual Model Validation

This chapter outlines creating and validating dynamic hypotheses and causal diagrams. To ensure the accuracy of the diagrams, the authors compared them with relevant literature and modeling discussions. We evaluated their structural validity according to the guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Seong (2010), which include assessing the model's ability to reproduce a system's behavior and evaluating its feedback structure, time delays, and parameter values.

Causal diagrams were deemed valid and reliable based on these guidelines. The endogenous variables in the model included the outflow resource variable, which tracks the availability of water and creates a perception of damage; the cooperation proxy, which reflects the group's behavior towards water consumption and resource availability; and the relative cooperation variable, which depends on individual's tendencies to cooperate or defect and can increase the temptation to defect. The main variables are described as follows:

- The cooperation proxy can be seen as the behavior assimilated by the group from the information received on the water consumed by each actor and the availability of the resource. There are two options in this variable: trust is increased, which generates greater cooperation, or the temptation to defect is increased.
- The outflow resource variable is the one that records the availability of water for all stakeholders from an initial resource. The behavior of this variable determines the perception of harm.
- Trust is included as an endogenous variable because it can be modified from the cooperation observed by the group and motivates a reduction in consumption.
- The relative cooperation that depends on the individual's normal tendency to cooperate or not, which may increase the temptation to defect.

- Gap is the difference between the desired water level and the water actually available.
- Temptation to free ride refers to the desire not to cooperate and varies directly from the perceived cooperation.
  - Water consumption is the amount of water used regulated by the cooperation proxy.

The exogenous or external variables are:

- Resource is the water available for consumption.
- Normal cooperation is the natural disposition that every human has to cooperate.
- Desired resource level is the amount of water that one would like to have to satisfy all the population's needs.
- People using water is the amount of water that each actor in the system consumes without any regulation (Fig. 11.2).

Table 11.1 provides empirical validations of the causal loops and dynamic hypotheses presented in this chapter. One of the primary dynamic hypotheses presented in the initial phase of the study is that "More information provided to the user about water availability and consumption, in this case using IoT, increases cooperation around water use." This hypothesis is supported by structures and concepts

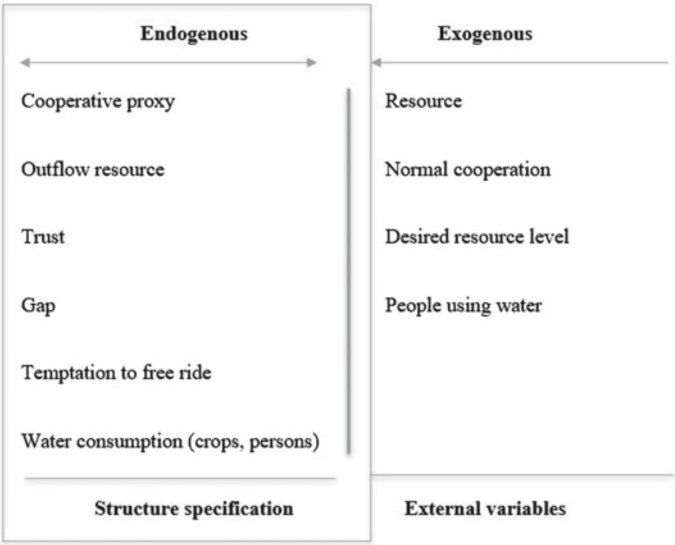

Fig. 11.2 The researchers identify a range of critical internal factors for this study that are directly connected to a group of external factors. These external factors have a vital impact on the internal factors' presence and continuity. It should be emphasized that the internal factors rely entirely on their corresponding external factors to receive essential support and operate efficiently

adopted from various works, including an IoT-based water distribution and management system framework proposed by Maroli et al. (2020), a system dynamics simulation model for sustainable water resources management by Kotir et al. (2016), and a social-ecological framework for promoting water and energy conservation by Gardner et al. (2005). These studies provide structural formulations and frameworks that validate the dynamic hypothesis and support the development of the three primary cycles presented in Fig. 11.1. In the first cycle, the perception of damage is influenced by the necessary information on water availability taken from IoT architecture, as well as the resource needs of other stakeholders. The second cycle, cooperation achieved through trust, is regulated by lifetime and is a proxy variable that allows for an increase in trust when water consumption is reduced. The third cycle, the free-riding cycle, indicates the temptation to abandon collaborative strategies for resource use and is determined by trust and cooperation. The studies cited in Table 11.1 provide valuable empirical evidence for developing and validating the dynamic hypotheses and causal loops presented in this chapter.

Table 11.1 Structure and concepts adopted from the existing work

Structures/concepts	Remarks
Evaluación dinámica sistémica de la cooperación en dilemas sociales a gran escala. Tesis doctoral, Universidad Nacional de Colombia (Parra, 2012)	Causal structure was adopted
Red IoT la autopista de información de la agroindustria de la caña. (Cenicaña, 2021)	Structural formulation was adopted
A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. (Kotir et al., 2016)	Structural formulation was adopted
Using System Dynamics Modelling to visualize the effects of resource management and policy interventions on biodiversity at a regional scale. (Laspidou & Ziliaskopoulos, 2022)	Structural formulation was adopted
Framework for the Implementation of an Internet of Things (IoT)-based Water Distribution and Management System. (Maroli et al., 2020)	Structural formulation was adopted
Utilizing a Social-Ecological Framework to Promote Water and Energy Conservation: A Field Experiment (Gardner et al., 2005)	Structural formulation was adopted
Social Comparison as a Tool to Promote Residential Water Conservation. (Schultz et al., 2019)	Structural formulation was adopted

11.7 Discussion

The results of this study suggest that incorporating real-time information through the IoT into models with system dynamics can generate higher levels of cooperation and trust in dealing with social dilemmas around water management. The construct presented in this study with three main cycles—perception of damage, cooperation through trust, and free-riding–highlights the importance of information sharing and communication in promoting cooperation and reducing the temptation to desert. The use of appropriate technologies and disposal in the right places can provide sufficient parameters to feed the simulation model, which can support decision-making processes and policies in line with the reality of the territories.

Other studies have also shown the potential of IoT in improving water supply chain management, particularly in rural areas. For instance, Maroli et al. (2020) found that IoT can provide more information to users about water availability and consumption, leading to increased cooperation around water use, reduced water consumption, and increased trust. However, the risk of free-riding behavior should also be considered, and interventions must be designed to promote cooperation and minimize free-riding risks.

Social comparisons and attunement labels are two strategies that have been shown to promote residential water conservation. Schultz et al. (2019) found that social comparisons were useful for promoting household water conservation. By contrast, Gardner et al. (2005) demonstrated the effectiveness of augmented feedback approaches in reducing residential water consumption. The use of attunement labels can also reduce residential water and energy use by attracting residents to the environmental impact affordances of various appliances around the house.

The feedback loops presented in this study highlight the importance of information sharing and communication in promoting cooperation and reducing temptation to desert in water management. IoT can provide more real-time information to users about water availability and consumption, leading to increased cooperation, reduced water consumption, and increased trust. However, the risk of free-riding behavior must be addressed through interventions that promote cooperation and minimize free-riding risk. Strategies such as social comparison and attunement labels can also effectively promote residential water conservation.

As Parra (2012) indicated the feedback of information in a system based on shared exhaustible resources should not present delays to generate trust and increase collaboration. The disposal of sugarcane crops for panela presents a challenge in providing information on the time needed, and the use of appropriate technologies and disposal in the right places can provide sufficient parameters to feed the simulation model. Projects such as those developed by Cenicaña (2021) have a scope for large industries. Still, it is also necessary to provide tools to small producers who support their region's economic development.

Kotir et al. (2016) and Laspidou and Ziliaskopoulos (2022), Fabbro Neto & Gómez-Martín, (2020), and Ismail et al. (2022) have been able to provide information oriented to support decision-making in order to create policies in accordance with the reality of the territories. This study is also expected to support these processes.

Incorporating information through Iot into models with system dynamics is expected to generate levels of cooperation based on real-time data, which should increase confidence in dealing with social dilemmas. Trust is the key to encouraging work for the common good, and collaboration depends on the benefits of these interactions.

According to Maroli et al. (2020), implementing an Internet of Things (IoT) -based water distribution and management system can potentially improve water supply chain management in rural India. The study suggests that the IoT can provide more information to users about water availability and consumption, leading to increased cooperation around water use, reduced water consumption, and increased trust. However, this study also recognized the risk of free-riding behavior, which can lead to increased water consumption. Therefore, interventions must be designed to promote cooperation and reduce free-riding risk.

Previous studies have shown that social comparison is useful in promoting residential water conservation (Schultz et al., 2019). Additionally, Gardner et al. (2005) demonstrated the effectiveness of augmented feedback approaches in reducing residential water consumption. This study used social-ecological frameworks to design an intervention to reduce residential water and energy use in a local community. The study used information leaflets, attunement labels, and socially comparative feedback to study the influence on actual energy and water consumption levels in 166 households over a 6-month period. The study suggests that attunement labels designed to attract residents to the environmental-impact affordances of various appliances around the house can reduce residential water and energy use.

In conclusion, the literature suggests that the IoT can improve water supply chain management in rural India. Social comparison and attunement labels can promote residential water conservation, whereas interventions must be designed to promote cooperation and reduce the risk of free-riding behavior (Gardner et al., 2005; Maroli et al., 2020; Schultz et al., 2019).

11.8 Conclusions

Incorporating IoT into models with system dynamics can generate levels of cooperation based on real-time data and increase confidence in dealing with social dilemmas (Parra, 2012). This study highlights the challenge of promptly providing information regarding sugarcane crop disposal for Panela. Appropriate technologies and disposal in the correct places can provide sufficient parameters to feed the simulation model. While large industries have access to projects, such as those developed by Cenicaña (2021), it is essential to provide tools to small producers who also support the economic development of their region. Other studies have been able to provide information to support decision-making and create policies in accordance with the reality of the territories (Kotir et al., 2016; Laspidou & Ziliaskopoulos, 2022; Fabbro Neto &

Gómez-Martín, 2020; Ismail et al., 2022), and this study is expected to support these processes.

Integrating IoT technologies in water management can help address various issues related to water management, such as water level monitoring, leakage detection, water quality monitoring, and precision irrigation. The literature suggests that the IoT can improve water supply chain management in rural regions. Social comparison and attunement labels can promote residential water conservation, whereas interventions must be designed to promote cooperation and reduce the risk of free-riding behavior.

Integrating system dynamics modeling and the IoT has revolutionized water management, making it more efficient and sustainable. The IoT provides real-time data that can be analyzed to make informed decisions, and the system dynamics methodology can then be applied to analyze possible scenarios and develop sustainable policies. Future research should focus on optimizing the integration of these technologies to develop more sustainable water management practices.

Trust is key to encouraging work for the common good, and collaboration depends on the benefits of these interactions. Maroli et al. (2020) highlighted the potential of an IoT-based water distribution and management system to increase cooperation regarding water use, reduce water consumption, and increase trust. However, the study also recognizes the risk of free-riding behavior, which can lead to increased water consumption. Therefore, interventions must be designed to promote cooperation and reduce the risk of free-riding behavior.

The literature suggests that incorporating the IoT into water supply chain management can positively impact water conservation and management. Interventions must be designed to promote cooperation and reduce the risk of free-riding. In addition, providing information and tools to small producers is important for their economic development. Finally, trust is critical in encouraging work for the common good, and collaboration depends on the benefits of these interactions.

- Future Potential of System Dynamics and IoT Technologies

The use of IoT and System Dynamics technologies will continue to play an increasingly important role in water management. As these technologies become more sophisticated and accessible, they will become essential tools for understanding the complexities and dynamics of water resources and for creating effective and equitable policies.

System Dynamics provides a more comprehensive understanding of water management systems. Using agent-based models, game theory, and mathematical models, we can better analyze the potential impacts of different interventions on individual users, as well as overall water availability and use.

Conflict management practices can also help stakeholders with opposing views agree regarding water management decisions. Participants can collaborate through facilitated conversations and structured processes to achieve consensus on equitable and efficient water allocation, pricing, or other strategies.

The future of water management depends on the ability to promote cooperation and collaboration among stakeholders. Owing to technological advances, the Internet of Things (IoT) and System Dynamics (SD) can provide effective tools for fostering better collaboration and communication. By providing data-driven insights into potential policies and fostering collaboration among stakeholders, these technologies will help ensure that our water resources are utilized equitably and sustainably.

The IoT technology enables us to collect and track water consumption and availability data to gain greater insight into the system's dynamics. These data can then be used to evaluate the efficiency of different water management strategies and predict new policie's potential outcomes.

Insights and Implications for Practice.

The dynamic hypothesis assumes that more timely information increases trust and decreases the temptation to misuse resources. Regarding sugarcane crops for panela, geography presents a challenge for capturing this information. However, with the appropriate architecture, it is expected to have a robust model, demonstrating the advantage of using Iot technologies in system dynamics.

This study is part of developing a doctoral thesis that seeks to provide a mechanism to simulate the different conditions of cooperation in water management. Its innovative component is incorporating data through the IoT to provide information on the consequences of collaboration.

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Chapter 12
Exploring the Systemic Causes of Land Inequality with Systems Thinking

Martha-Lizette Massey-Galvis and Jorge-Andrick Parra-Valencia

Abstract This chapter looks at land inequality from a systemic perspective and explores the potential of using cooperation to address it, understanding that the effects of unequal land ownership on quality of life are mixed and that land ownership can have negative effects on the quality of life of the poorest. people. However, the possibility of analyzing the actors involved in the problem of inequity and the role of cooperation between governments, communities, and individuals to generate equitable public policies and solutions tailored to the needs of vulnerable populations allows joint responsibility and accountability among local governments, communities, and individuals. Similarly, cooperation allows for more comprehensive and efficient land reform initiatives and better stakeholder communication and understanding. This understanding can lead to better bargaining and fairer and more equitable regulations, ensuring that vulnerable populations are not left behind. In conclusion, cooperation is an important tool for addressing complex issues of land inequality. Cooperation among governments, communities, and individuals is key to creating public policies and community-led solutions tailored to the specific needs of vulnerable populations. Economic interests and international initiatives remain relevant throughout the process. Finally, this chapter examines other relevant factors, such as economic interests and international initiatives, and emphasizes the importance of a systemic analysis to combat land inequality.

Keywords Poverty reduction · Inequality · Land titling · Land inequality · Land use · System thinking · Public policies · Unequal land ownership · Cooperation · Quality of life · Systemic perspective · Vulnerable populations

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12.1 Introduction

Land inequality is a multifaceted problem influenced by several factors, including land use, soil conditions, inequity in land tenure, disparity in income distribution, lack of access to credit, hindered labor mobility, reduced returns to family labor and conflicting land policies (Cameroon, 2021; Chaves, 2013; Faguet et al., 2018; Mahmood et al., 2016; Suryanta et al., 2022). The concentration of land ownership in a small fraction of the population, commonly known as latifundia, has been a persistent pattern of inequities in land tenure throughout history (Chaves, 2013). Agrarian reform, specifically agrarian reform, has proven to be effective in achieving successful development. Access to land is critical for socioeconomic development, poverty reduction, and environmental sustainability (Chaves, 2013; Faguet et al., 2018; Wardhana, 2020). However, implementing agrarian reform is complex and involves legal, land administration, social, political, cultural, and security aspects (Chaves, 2013; Doly, 2017; Perwitasari et al., 2023). Furthermore, the effects of land reform are highly bimodal and its impact on inequality and land development varies according to the concentration of land ownership (Faguet et al., 2018). Therefore, comprehensive strategies are needed to address land inequality, considering legal, social, political and economic factors to achieve equitable access to land.

A recent example of a comprehensive approach to address land inequality is the launch of a new land policy in Zambia in 2021, which includes providing 50% of land to all women to address gender inequality in ownership. of the earth (Kalinda et al., 2022). However, policy pronouncements are rarely translated into political action, which is a major problem among poor women in all ten Zambian provinces (Kalinda et al., 2022). Similarly, implementing land reform in Indonesia is challenging due to various obstacles, including legal, land administration, social, political, cultural, and security (Perwitasari et al., 2023). Nevertheless, land reform remains an effective tool for their successful development (Perwitasari et al., 2023). In Nepal, redistributive land reform has been shown to increase the income of poor households and reduce inequality, while productivity-enhancing reform has a more significant impact on the economy by raising the productivity of all sectors, including income of all households, while maintaining inequality does not change (Paudel & Saito, 2015). Therefore, redistributive and productivity-enhancing reforms may have a greater impact on equity and efficiency (Paudel & Saito, 2015).

This chapter aims to provide a comprehensive understanding of the complex problem of unequal access to land resources by identifying root causes, analyzing the systemic causes of land inequality and developing strategies to address them, and highlights the importance of cooperation between governments, communities and individuals in the creation of equitable public policies and solutions adapted to the needs of vulnerable populations, it also emphasizes the need to consider economic interests and international initiatives, underscoring the importance of systemic analysis when addressing this issue. Ultimately, this chapter offers information on how systems thinking can be used to develop effective solutions to land inequality (Wegerif & Guereña, 2020a, 2020b).

The importance of land ownership and inequality, and how land is crucial in providing people with a home, food, resources, wealth, and even social standing. Land ownership confers benefits such as societal status, respect, and additional social rights (Bauluz, Govind, & Novokmet, 2020; Wiebe et al., 2019). This chapter argues that public policy and decision-making processes are crucial in addressing land inequality, and discusses the importance of policy interventions to ensure spatially more equitable allocation of infrastructure and public services, policies that ensure smooth migration fluidity, freedom, and an understanding of power relations and institutions to address inequalities (Bebbington, 2008; Kanbur & Venables, 2005).

12.2 Importance of the Study from Systems Thinking Perspective

Systems thinking and system dynamics are essential tools for addressing complex problems and understanding the characteristics of a situation. In most cases, wicked problems result from the dynamic interactions and relationships between multiple system elements. Therefore, systems thinking is fundamental to understanding and solving these problems. One of the most important tools is the dynamic hypothesis, which is a simplified representation of the key components of a system and how they interact to produce complex behavior. By designing a dynamic hypothesis, critical interactions and points of influence in the system can be identified, allowing for a better understanding of the system's dynamic behavior.

In addition, complex systems often have feedback loops that can increase the complexity of a problem and its solution. Therefore, understanding the complexity of the cycle is important for understanding the system's long-term behavior and predicting its future evolution, which will enable delayed information analysis. Delayed information analysis refers to the understanding of how the effects of an action or event can appear in the system long after it occurs. It is vital to understand the dynamics of the systems and how these relationships work over time.

Systems thinking can be applied to close gaps in land inequality by focusing on understanding the systemic causes of land inequality. Systemic analyses of existing structures, policies, and decision-making processes can reveal the underlying dynamics of inequality and offer information on how to address it. System Thinking can also be used to develop strategies to improve communication and collaboration between conflicting parties and to identify opportunities for collaboration that engage all stakeholders in a decision-making process that serves the common good. Finally, systems thinking can be used to develop effective public policies that reduce land inequality and increase cooperation.

The study of land inequality involves the analysis of the complex and dynamic systems involved in its creation and maintenance. This systemic approach allows us to understand the complexity of the social, political, and economic processes that intervene in the distribution of land and natural resources.

A key element in the analysis of land inequality is the understanding of lagging information, that is, the understanding that the effects of actions taken in the present do not manifest immediately but may take years or even decades. Appear. This implies that decisions and policies made today can have significant consequences in the future, highlighting the importance of long-term and informed decision making regarding land distribution.

In addition, the analysis of land inequality also involves understanding the complexities of Earth's cycle. The distribution of land and natural resources is not linear but is influenced by multiple factors, including climate change, market fluctuations, political decisions, and social dynamics. Therefore, it is essential to understand these complexities to understand the characteristics of the situation and make informed decisions about how to address land inequality.

12.3 Definition of Land Inequality

Inequity in land distribution refers to the disparity in the disposition of land and its resources among individuals and groups. This involves differences in the amount and value of land that people can access, the relative strength of their land tenure rights, and the appropriation of the value obtained from land use, and can have a significant impact on livelihoods, access to food, social cohesion, and the environment. It is often driven by structural factors such as power imbalances, discrimination, and historical legacies (Wegerif & Guereña, 2020a, 2020b).

Land inequality refers to the unequal distribution of land among individuals and groups of people. This inequality can manifest itself in terms of direct access to land, control of resources associated with land, or how land is used. Land inequality is closely tied to social and economic deprivation, with some groups having access to much better quality and more productive land, while other groups are left with land of much poorer quality and less potential productivity. In some cases, land inequality can even be linked with other human rights violations, forcing some people to live in an environment of extremely degraded soil and limited access to resources (Erickson, 2004; Wegerif & Guereña, 2020a, 2020b).

The characteristics of land inequality vary from country to country, and even from region to region within the same country. In many cases, land inequality is strongly linked to the political and economic history of the region. In some cases, land inequality can be based on the social and economic segregation of certain groups, while in others, it can be linked to colonial policies or the unequal enforcement of existing land rights (Erickson, 2004).

In most cases, land inequality is deeply entrenched and difficult to address. For starters, land inequality can be difficult to quantify due to varying definitions of what constitutes land inequality and how it is measured. Land inequality is also strongly linked to other systemic issues, like income inequality or exclusionary economic policies, making it difficult to address the root causes. Land inequality is often seen as a purely economic issue and can be viewed as a morally neutral phenomenon.

This further complicates efforts to address the issue, as any attempts to promote land redistribution must overcome this neutrality's moral and political obstacles (Wegerif & Guereña, 2020a, 2020b).

Inequality in access to and control over land, especially in Latin America, constitutes one of the greatest challenges facing the region, being both a cause and a consequence of highly polarized social structures and economic and social inequality. Control of territory continues to be a source of economic and political power, often exercised through repression and violence, while competition for land has intensified with the rapid expansion of activities based on the extraction and exploitation of natural resources. Indigenous, Afro-descendant, and peasant households, especially women, are frequent victims of displacement, loss of livelihoods, and environmental deterioration. Despite this, most governments in the region have maintained a commitment to extractivist as the main driver of their economies, despite territorial conflicts and the unsustainability of the model. Without policies that address this challenge, it will not be possible to reduce economic and social inequality in the region (Guereña & Burgos, 2016).

12.3.1 Importance of Exploring Systemic Causes of Land Inequality

Throughout history, inequality in land tenure has been a complex social problem that has affected most of the world's population. This presents a serious crisis because this inequality has negatively affected the economy, environment, social justice, and political fields. The current static view, in which land inequity has been addressed, has only grown this gap. Therefore, it is necessary to design dynamic models that show scenarios with relevant variables to identify behaviors and allow a better understanding of the phenomenon of inequality in land tenure to finally propose scenarios with potential solutions that allow us to address the consequences of this phenomenon for centuries.

The ambiguities resulting from the different actors involved in decision-making often refer to the low perspective of the behavior of the systems because a broad capacity to understand the social, political, and other variables involved in the problem of inequality is required (Jasanoff, 2005). Understanding and considering the systemic causes of land inequality when looking at solutions and applying systems thinking to address the underlying issues is important. Such solutions might include developing and implementing programs and policies to reduce income inequality, reforming land access and control, and creating more equitable and transparent land markets. Additionally, attempts to overturn historical injustices are an important part of any long-term solution. By adopting a systematic approach, it is possible to promote greater equality and social justice in distributing, controlling, and using land resources.

12.3.2 Archetype of Inequity

In system dynamics, archetypes are recurring patterns found in many complex systems (Tapia & Valenti, 2016, 54885). The "Matthew Effect" archetype describes a situation in which those with more resources or power in a society gain more and more resources and power, while those with fewer resources gain less and less (Tapia & Valenti, 2016, 54885). This archetype occurs when available resources are allocated unequally, leading to those who already have more resources being able to get even more, while those with fewer resources are left behind (Tapia & Valenti, 2016, 54885). The economic and social inequality that results from this archetype can have negative effects on the stability and sustainability of the system as a whole (Tapia & Valenti, 2016, 54885).

The relationship between poverty and educational inequality has been analyzed in the agenda of studies on poverty (García & Derteano, 2019). In addition, the effect of economic crises on inequality of educational opportunities has been studied (García & Derteano, 2019; Tapia & Valenti, 2016). Early childhood care policies are considered a key social investment to mitigate social inequalities (Tapia & Valenti, 2016).

The archetype of inequality allows us to explain the inequality between two different groups (populations with wealth and without wealth, men and women, etc.). It concludes that the increase in the resources of each group depends on its ability to multiply those resources when there is a difference between groups by the capacities that each one has to multiply these resources, the gap will exponentially widen as those resources multiply. Finally, the archetype indicates that, to improve the management of inequality between groups, it is necessary to improve access to resources and the capacity to conserve them because of the feedback structure that generates them. In turn, each resource is either degenerated or consumed. The success of each group will depend on how it manages and manages the resource to conserve it for a longer period, making it more efficient, multiplying it, or reinvesting it. The principle of this archetype revolves around the reference to the model of "The Matthew Effect' (see Fig. 12.1), which dates back many years, where it was observed that an initial advantage tends to generate more advantages and disadvantages. This occurs between individuals or groups, and The Matthew Effect" refers to the concept that those with more resources and advantages are more likely to receive more opportunities and success. In contrast, those with fewer are more likely to struggle and face barriers to success. This term was coined about the Bible verse "For to everyone who has more shall be given, and shall have abundance; but from him who has not, even what he has will be taken away," which is sometimes referred to as the "principle of Matthew" (from the Gospel of Matthew in the New Testament). Daniel Rigney explores this concept in various aspects of modern society, from economics to education. Land tenure refers to the tendency of those who already own land or land to get more, while those who do not have that property are disadvantaged and continue to accumulate it. That is, landowners in rural areas with large areas can use their influence to expand their land or operations, while small farmers or non-landowners

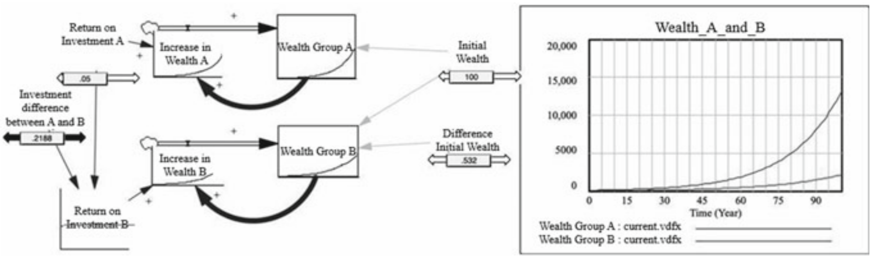

Fig. 12.1 The Inequality archetype, is based on Sterman's work (2022)

would not have the same influence and would be disadvantaged. This inequality in land distribution is directly influenced by economic and social inequality (Rigney, 2010; Sterman, 2022).

12.3.3 Laws and Regulations

Land inequality is a complex and important issue that affects all countries worldwide. Factors contributing to this problem include wealth, power, gender, health, the environment, and poverty. Land inequality has significant implications for the stability and sustainable development of society. It is directly linked to global crises, such as climate change and pandemics, perpetuating the wealth and power of a few (Wegerif & Guereña, 2020a, 2020b). Constitutional protection of property rights can undermine efforts to ensure material equality, particularly in cases where land was acquired through colonialism (Osterling, 2015).

Land and property taxes exist in every country and are often crucial for financing local governments, where autonomous spending can be controlled. The effectiveness of a decentralized policy depends on the design and control of land tenure taxes. Land taxes are a way to increase public finances. Property tax is a complex and controversial tax often viewed as a capital tax and a tax on housing services. Its incidence is unclear, and it is often considered an unfair tax. Despite its many problems, property tax remains an important source of revenue for local governments and can also influence land use patterns. However, property taxes must be appropriately designed from an economic perspective to be effective. The effectiveness of property tax systems in Latin America varies significantly among the countries in the region. Some countries, such as Chile and Colombia, have implemented relatively effective property tax systems, whereas others, such as Mexico, have been less successful in collecting property taxes. Latin American countries often have lower collection rates than others, partly because of their lack of administrative capacity and tax evasion. In addition, property tax systems in Latin America often have inadequate exemption and valuation rates, limiting their ability to generate income (Bird & Slack, 2005).

Vulnerable populations, including small and marginalized farmers, landless workers, tribal communities, and women, are most affected by land inequality. These groups lack access to land and resources, resulting in them being subject to exploitation, poverty, and insecurity. Small farmers and landless workers are often relegated to marginal or leased land, restricting their ability to earn a decent living. This results in little to no economic growth and limited opportunities for upward mobility (Wegerif & Guerena, 2020).

Tribal communities have historically been marginalized because of their distinct culture and way of life. Their land rights have often been violated and pushed to the margins of society. They face significant challenges in accessing land, resources, and education, thus restricting their economic and social development (Behera & Minz, 2020).

Women also suffer from inequality in land ownership. Despite being responsible for most agricultural activities, they have limited access to land and are often excluded from land ownership. This makes them dependent on men for their livelihoods, which restricts their agency and ability to make decisions that affect their lives (Wegerif & Guereña, 2020a, 2020b).

In summary, socially and economically disadvantaged sectors lacking access to land, resources, and opportunities for economic and social mobility are the most vulnerable to land inequality (Bebbington et al., 2008; Dutt & Mukhopadhyay, 2009; Kanbur & Venables, 2005; Klasen et al., 2016; Lockwood, 2020; Symonds, 2020; Wegerif & Guerena, 2020).

12.4 Method

In this chapter on land inequality, we employed a literature review method to investigate current research and theories on unequal land ownership distribution (Wegerif & Guereña, 2020a, 2020b). In addition to the literature review, we used systems thinking and system dynamics methodologies to develop a dynamic hypothesis that provides a deeper understanding of the underlying causes of land inequality and identifies potential solutions.

A literature review was conducted to gather information and data on the historical and contemporary dynamics of land inequality on a global scale, and the factors implicated in its creation and perpetuation. This involved a thorough analysis of the existing literature, including academic journals, books, reports, and online databases, to identify key themes and trends (Boone, 2014; Deininger & Byerlee, 2011).

Through the application of systems thinking and system dynamics methodologies, we identified key variables and feedback loops that contribute to the persistence of land inequality. These methodologies allowed us to develop a causal loop diagram that illustrates the complex interrelationships between various factors and feedback mechanisms that perpetuate land inequality (Sterman, 2000).

The causal hypothesis that we developed posits that disparities in land distribution are closely associated with the economic, political, and social dynamics involved in their creation and perpetuation, such as the lack of resource reinvestment in disadvantaged areas (Deininger & Byerlee, 2011; Wegerif & Guereña, 2020a, 2020b). This hypothesis serves as a theoretical framework for comprehensively examining and understanding land inequality, enabling a deeper understanding of its underlying causes, and identifying potential solutions.

To ensure the validity and reliability of our findings, we used a systematic approach in our literature review, following established guidelines for conducting a comprehensive search and analysis of the relevant literature (Booth et al., 2016). We employed a rigorous screening process, which involved assessing the relevance and quality of each source to ensure that only the most relevant and high-quality literature was included in our analysis (Cook et al., 2018).

Overall, integrating systems thinking and system dynamics methodologies with the literature review method is an effective and efficient way to investigate the complex issue of land inequality. By synthesizing existing research and theories and applying these methodologies, we developed a dynamic hypothesis that provides a deeper understanding of the underlying causes of land inequality and identifies potential solutions to address this critical issue.

12.5 Applying System Thinking Towards Bridging Gaps

Land inequality is a complex and pervasive issue that affects communities worldwide. Applying system-thinking principles can help us understand the underlying causes of land inequality and identify effective solutions to bridge this gap. By taking a systemic approach, we can analyze the feedback loops and interdependencies that contribute to the unequal distribution of land ownership. In this section, we aim to provide a comprehensive understanding of land inequality by examining its historical and contemporary dynamics. By integrating the insights gained from systems thinking, we identify potential solutions that address the root causes of land inequality and promote equitable land ownership.

Understanding the cycles that generate inequity:

The dynamic hypothesis developed in this section provides a comprehensive understanding of the causes of land inequality, and identifies potential solutions to bridge this gap. The hypothesis integrates system-thinking principles and a literature review of the historical and contemporary dynamics of land inequality on a global scale. It posits that the unequal distribution of land ownership is closely associated with the economic, political, and social dynamics that contribute to land creation and perpetuation.

According to the literature, reinvestment rates among individuals can increase investment and resource acquisition regardless of land ownership. However, historical factors such as privileged access to land ownership have contributed to the concentration of land ownership among certain groups with access to more resources, perpetuating land inequality. The younger population is typically more economically active, leading to an increase in the landowner population. However, youth and old age are influenced by cultural norms, expected behaviors, rights, and aspirations, which can limit access to training and development opportunities for those who do not own the land.

Individuals without access to land face significant inequality in their access to resources and economic opportunities, leading to cycles of poverty and vulnerability. The relationship between land inequality and life cycles can also affect the options available to young and old age. In addition, a country's history can contribute to the transmission of wealth from generation to generation, perpetuating land inequality.

Although redistributive agrarian reforms have been successful at specific historical points, they require unique political and social conditions. In Latin America, agrarian reforms have not effectively addressed land inequality due to short-term political aims and lack of consideration of key socioeconomic factors affecting the intended beneficiaries.

Figure 12.2 highlights five feedback loops that reinforce or balance land inequality. By applying system-thinking principles, we can identify the key variables and interdependencies that perpetuate this issue.

R1. "Reinvestment" depicts the reinforcing feedback loop, where individuals' disposable reinvestment rates can increase investment and resource acquisition, leading to greater land ownership. However, privileged access to land ownership has contributed to the concentration of land ownership among certain groups with access to more resources, thus perpetuating land inequality.

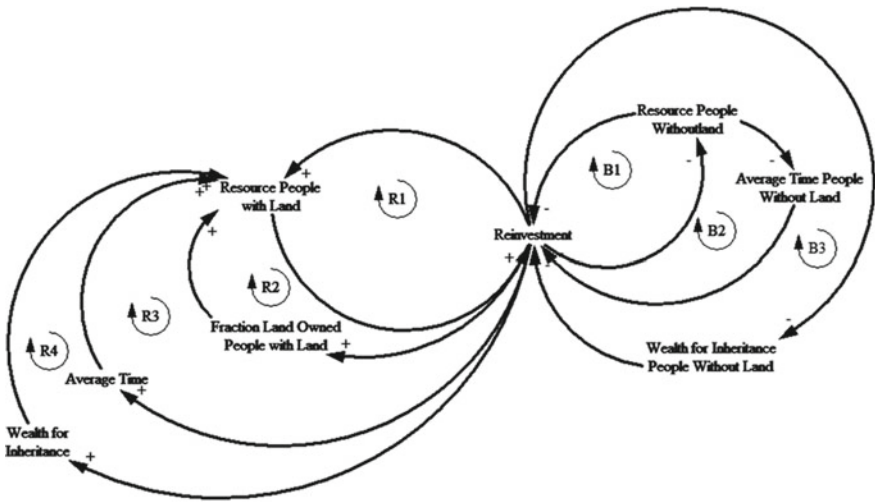

Fig. 12.2 Dynamic hypothesis inequality land

R2. "Fraction Land Owned by People with Land" represents the reinforcing feedback loop, where landowners have more investment resources, increasing their reinvestment and land ownership. However, significant disparities in land tenure perpetuate poverty and vulnerability, particularly among marginalized groups that lack resources and access to productive land.

R3. "Average Time" represents the balancing feedback loop, where cultural norms, expected behaviors, rights, and aspirations limit access to training and development opportunities for those who don't own land. This leads to a decrease in the possibility of generating wealth and reinvesting in land for those who do not own it.

R4. "Wealth for Inheritance" represents the reinforcing feedback loop, where a country's history can contribute to transmitting wealth from generation to generation, perpetuating land inequality. For example, unequal land distribution has been identified as the main obstacle to lasting peace and democracy in Colombia.

B1. "Resource People without Land" represents the balancing feedback loop, where individuals without access to land face significant inequality in access to resources and economic opportunities, perpetuating cycles of poverty and vulnerability.

While redistributive agrarian reforms have been successful at specific historical points, they require unique political and social conditions. In contrast, most agricultural reforms in Latin America have not effectively addressed land inequality due to short-term political aims and a lack of consideration of key socioeconomic factors affecting the intended beneficiaries.

Overall, the dynamic hypothesis provides a comprehensive understanding of the complex issue of land inequality, and offers potential solutions to address its root causes. By addressing these feedback loops through a systemic approach, we can develop innovative solutions that promote equitable land ownership and positive social, economic, and environmental outcomes.

While redistributive agrarian reforms have been successful at specific historical points, such as during revolutions or after wars, they require unique political and social conditions. However, in Latin America, where most agrarian reforms have taken place over the last century, they have not been effective in addressing land inequality due to short-term political aims and a lack of consideration for key socioeconomic factors affecting the intended beneficiaries. This contrasts with successful agrarian reforms in Mexico, Bolivia, Cuba, China, Vietnam, Japan, Taiwan, and Korea after World War II (Lipton, 2009).

The Green Revolution in Latin America was a period of agricultural transformation that began in the mid-twentieth century and continued until the 1970s. This revolution was marked by the introduction of new technologies and practices that boosted agricultural productivity, helping increase food production and reduce poverty in the region. The revolution aimed to address the growing population's needs, bringing about significant changes in farming techniques, including the use of high-yielding varieties, chemical fertilizers, and pesticides. However, it also has disadvantages such as the displacement of small traditional farmers and concerns over the environmental impact of intensive agriculture. Nevertheless, the Green Revolution has significantly impacted Latin America, and its influence can be seen today in the region's modern agricultural practices (Lorek, 2022).

However, the Green Revolution is not without its drawbacks. One of the biggest issues is the exacerbation of social and economic inequalities, particularly in land ownership. Large multinational corporations were often leading the way in terms of agricultural innovation, meaning that they were able to monopolize markets and displace small-scale farmers (Pingali, 2012).

Additionally, the Green Revolution, which has been credited with increased agricultural productivity and financial support, has also resulted in a reduction in crop diversity and biodiversity (Altieri, 2009; Gahukar, 1992; Reid, 1995; Singh, 2023). This reduction has led to a higher risk of crop failure and disease outbreaks, as well as limited opportunities for small-scale farmers to experiment with different crops and techniques (Singh, 2023). The Green Revolution was primarily focused on certain crops, such as rice and wheat, which led to a decline in the production of other minor crops, including millets (Gahukar, 1992; Singh, 2023). The Green Revolution has also been criticized for damaging the environment and causing a loss of traditional knowledge (Altieri, 2009). While the Green Revolution enhanced grain productivity, it favored wealthier farmers and left many poor farmers deeper in debt (Altieri, 2009). It is argued that the African Green Revolution should involve other crops and be adapted to other water and climate regimes (Ernest et al., 2010). The introduction of new dwarf wheat and rice varieties during the Green Revolution significantly enhanced grain productivity, but it also reduced crop diversity (Dai and Wang, 2015; Yu et al., 2007). Therefore, it is important to manage biodiversity in agricultural systems to ensure sustainable agricultural practices and reduce the risk of crop failure and disease outbreaks (Reid, 1995).

Cooperation among governments, communities, and individuals is crucial when addressing land inequality. In many parts of the world, land inequality is a major issue affecting access to resources and opportunities as well as social and economic stability. Some ways in which governments, communities, and individuals can work together to address land inequality include the following.

12.5.1 Developing Policies and Laws that Promote Land Reform

Governments have a crucial role to play in promoting sustainable land management practices and ensuring that land is a resource that benefits all people, regardless of ethnicity, gender, or socioeconomic status. One way that governments can achieve this is by passing laws that promote land redistribution and policies that protect the land rights of smallholder farmers and indigenous peoples. Additionally, governments can support community land management, which involves communities working together to manage land, resources, and natural areas in a sustainable way.

This can help to ensure that land is used in a way that benefits everyone, including future generations (Córdova et al., 2018; Rahman et al., 2017; Shiferaw et al., 2007).

Another important way that governments can promote sustainable land management is by promoting land tenure security. When people and communities have secure land rights, they are more likely to invest in their land, protect natural resources, and build livelihoods. Governments can also foster dialogue and collaboration between different stakeholders, including governments, communities, and individuals, to build trust, share knowledge, and collaborate on land management and land use decisions. (Aboagye, 2021; Chigbu, 2021; Huong, 2022; Jafary & Bradley, 2018; Paradza et al., 2020).

Investing in education and training is another important way that governments and communities can promote sustainable land management. By providing individuals and groups with the knowledge and skills they need to manage land sustainably and equitably, governments can help to build capacity and promote long-term sustainability. (Munthali, 2023).

Overall, working together, governments, communities, and individuals can create a more equitable and sustainable future for all. By promoting sustainable land management practices and ensuring that land is used in a way that benefits everyone, we can help to build a more just and sustainable world. (Aboagye, 2021; Huong, 2022; Chigbu, 2021; Córdova et al., 2018; Jafary & Bradley, 2018; Munthali, 2023; Paradza et al., 2020; Rahman et al., 2017; Shiferaw et al., 2007).

12.6 Conceptual Model Validation

This section describes the validation of dynamic hypotheses and causal diagram. The authors validated the diagrams against relevant literature and modeling discussions and assessed their structural validity using the guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010). The validation process is summarized in this section.

Qudrat-Ullah (2008) proposed that the behavioral validity of a simulation model can be evaluated by assessing its ability to reproduce the behavior of the system it represents. To determine the structural validity of a system dynamics-type simulation model, Qudrat-Ullah and Baek Seo (2010) proposed guidelines for evaluating the model's feedback structure, time delays, and parameter values.

Using these guidelines, the causal diagrams presented in this chapter were validated by assessing their ability to reproduce a system's behavior and structural characteristics, such as feedback loops and time delays. The causal diagrams for this study were valid and reliable.

The system boundaries in Fig. 12.3 are defined based on endogenous and exogenous variables. The endogenous variables considered for reinvestment are half-life, fraction of land owned by individuals, and inherited wealth. The exogenous variables included government policies, socioeconomic and cultural conditions, market trends, redistribution policies, access to credit and financing, conflicts and disputes

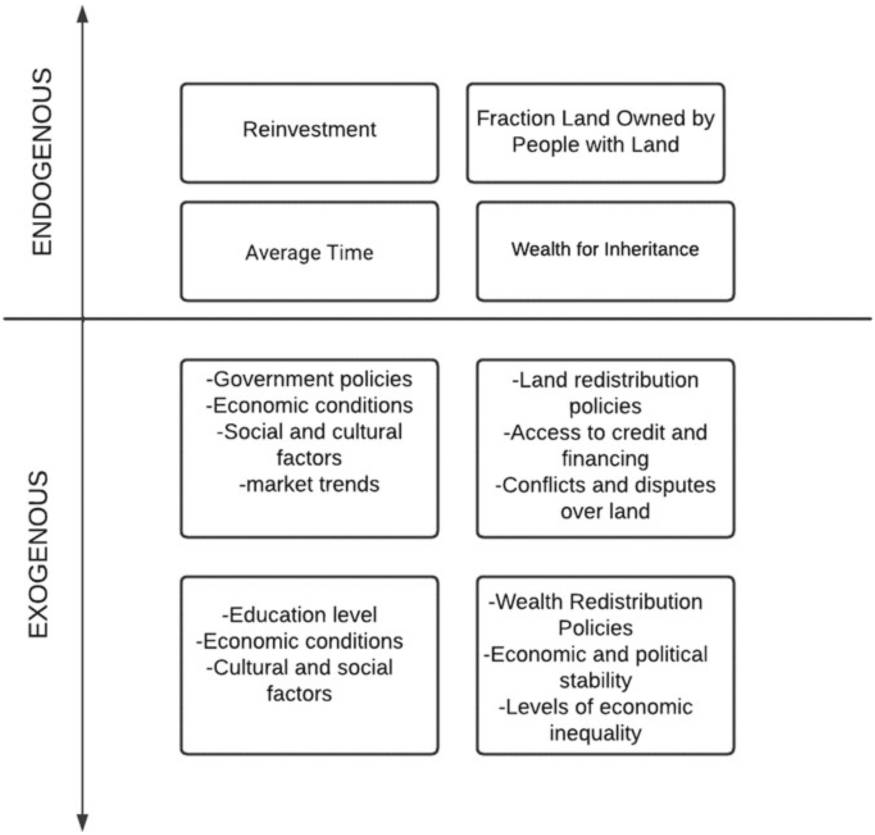

Fig. 12.3 Endogenous and exogenous variables for land reinvestment derived from this study

over land, educational levels, cultural factors, land redistribution policies, economic stability policies, and levels of inequality.

The endogenous and exogenous variables selected for this study are shown below on Fig. 12.3, with the most significant ones highlighted. These exogenous variables are critical for the existence and sustainability of the endogenous variables. It is important to note that endogenous variables such as half-life, fraction of land owned by individuals, and inherited wealth are entirely dependent on their associated exogenous variables. The exogenous variables include government policies, socioeconomic and cultural conditions, market trends, redistribution policies, access to credit and financing, conflicts and disputes over land, educational levels, cultural factors, land redistribution policies, economic stability policies, and levels of inequality. Without necessary support from these exogenous variables, endogenous variables cannot function effectively.

Table 12.1 summarizes the structures and concepts used to validate this chapter's causal loops and hypotheses. The table includes the authors, publication year, and titles of the works from which these structures and concepts were adopted.

The structures and concepts were drawn from various sources, including studies on intergenerational wealth transmission and inequality in small-scale societies (Mulder et al., 2009), land tenure and rural development (Food and Agriculture Organization of the United Nations, 2003), the "young farmer problem" in England (Hamilton et al., 2015), inheritance practices of agricultural land in Latin America (Dirven, 2002), land inequality in rural China (Chen et al., 2022), and the structural validity of a system dynamics-type simulation model (Qudrat-Ullah & Baek Seo, 2010).

By incorporating these structures and concepts, this study provides a comprehensive understanding of land inequality dynamics. The table demonstrates how various concepts were integrated into causal theories and how the structure of the land inequality system was developed. This approach enhances the validity and reliability of the chapter's causal loops and dynamic hypotheses.

The structures and concepts presented in Table 12.1 have been adopted from existing literature on land inequality. The reinforcing feedback loops of "Reinvestment" and "Fraction Land Owned by People with Land" highlight the relationship between resource acquisition and land ownership, which perpetuates inequality. The balancing feedback loops of "Average Time" and "Resource People without Land"

Table 12.1 Structures adopted from the existing work

Structures/concepts	Remarks
Mulder, M. B., Bowles, S., Hertz, T., Bell, A., Beise, J., Clark, G., … & Wiessner, P. (2009). Intergenerational wealth transmission and the dynamics of inequality in small-scale societies. science, 326(5953), 682–688	Causal structure was adopted
Food and Agriculture Organization of the United Nations. (2003). FAO STUDIES ON LAND TENURE. Land Tenure and Rural Development	Causal structure was adopted
Hamilton, W., Bosworth, G., & Ruto, E. (2015). Entrepreneurial younger farmers and the "young farmer problem" in England. Agriculture and Forestry, 61(4), 61–69	Causal structure was adopted
Dirven, M. (2002). Las prácticas de herencia de tierras agrícolas:¿ una razón de más para el éxodo de la juventud?. Cepal	Structural formulation was adopted
Chen, D., Hu, H., Song, C., & Lv, H. (2022). Land Inequality and Its Influencing Factors in Rural China in Modern Times: A Systematic Review. Land	Structural formulation was adopted
Umaña, W. P. (2014). Los significados de la revolución. Semántica, temporalidad y narrativa de la Revolución Verde. Historia Ambiental Latinoamericana y Caribeña (HALAC) revista de la Solcha, 3(2), 490–521	Structural formulation was adopted
Qudrat-Ullah, H., and BaekSeo S. (2010). 'How to do structural validity of a system dynamics type simulation model: The case of an energy policy model'. Energy Policy, 38(5): 2216–2224	Structural formulation was adopted

highlight the limitations and disparities faced by those without access to land, limiting their ability to generate wealth and reinvest in land.

The reinforcing feedback loop of “Wealth for Inheritance” demonstrates how a country’s history can contribute to the transmission of wealth from generation to generation, perpetuating land inequality. These structures and concepts were adapted from the works of Mulder et al. (2009), the Food and Agriculture Organization of the United Nations (2003), Hamilton et al. (2015), Dirven (2002), Umaña (2014), and Chen et al. (2022), and their structural formulations were adopted from Qudrat-Ullah and BaekSeo (2010). Integrating these structures and concepts into a systemic approach can provide insights into the underlying causes of land inequality and promote equitable land ownership.

The validation process for the causal diagrams and dynamic hypotheses presented in this chapter is summarized in Table 12.1 and Fig. 12.3. The authors validated the diagrams against relevant literature and modeling discussions and assessed their structural validity using guidelines proposed by Qudrat-Ullah (2008) and Qudrat-Ullah and Baek Seo (2010). Figure 12.3 illustrates the endogenous and exogenous variables selected for this study, which were derived from the literature review and used to validate causal diagrams and dynamic hypotheses. By incorporating various concepts from different sources, including intergenerational wealth transmission, land tenure, and rural development, and the structural validity of a system-dynamics-type simulation model, this study provides a comprehensive understanding of the dynamics of land inequality. The use of both Table 12.1 and Fig. 12.3 enhances the validity and reliability of the causal diagrams and dynamic hypotheses presented in this section.

12.7 Discussion

Land inequality is a complex and multifaceted issue that affects various aspects of society including economic growth and social justice. This study explores multiple factors that contribute to land inequality and how a systemic approach can help understand its root causes. One of the key findings of this study is that land inequality is perpetuated by several feedback loops including reinvestment rates, land tenure disparities, age, human capital, and wealth inheritance.

The reinforcing feedback loop of “Reinvestment” highlights the fact that individuals’ disposable reinvestment rates can increase investment and resource acquisition, leading to greater land ownership. However, this feedback loop can contribute to the concentration of land ownership among certain groups with access to more resources, thereby perpetuating land inequality. Similarly, the reinforcing feedback loop of “Fraction Land Owned by People with Land” shows that landowners have more investment resources, leading to greater reinvestment and land ownership. However, significant disparities in land tenure perpetuate poverty and vulnerability, particularly among marginalized groups that lack resources and access to productive land.

The balanced feedback loop of "Average Time" shows that cultural norms, expected behaviors, rights, and aspirations can limit access to training and development opportunities for those who do not own land. This leads to a decrease in the possibility of generating wealth and reinvesting in land for those who do not own it. The feedback loop of "Wealth for Inheritance" highlights that a country's history can contribute to transmitting wealth from generation to generation, perpetuating land inequality. The feedback loop of "Resource People without Land" shows that individuals without access to land face significant disparities in access to resources and economic opportunities, perpetuating cycles of poverty and vulnerability.

This study draws on several citations, including Matsuo and Ishizuka's (2004) work on keyword extraction and indexing, which supports the conclusion that access to land is a key factor in the fight against poverty worldwide. Esparcia et al.'s (2020) examination of think tanks and their use of digital communication to disseminate their activities supports the conclusion that policies and strategies should be designed to address the factors contributing to land inequality. Gisselbrecht et al.'s (2021) research on identifying trending topics in a streamed source can be used to manage the most pressing issues related to land inequality.

In conclusion, addressing land inequality requires a comprehensive approach that considers its contributing factors, including historical legacies, economic disparities, and social justice concerns. By adopting a systemic approach that involves cooperation between governments, communities, and individuals, we can promote sustainable land management practices and create a more equitable and sustainable future.

12.8 Conclusion

Land inequality is a significant issue that affects various aspects of society, ranging from food security to social justice. This chapter identified several dynamic hypotheses that contribute to land inequality, including wealth, reinvestment, age, and inheritance. Those with more economic resources are more likely to acquire and control land, thereby perpetuating land distribution inequality. Access to land is crucial for food security and the fight against poverty worldwide, and reinvestment is necessary to improve and maintain the quality of land. However, individuals who do not have access to land cannot reinvest, thereby perpetuating inequality.

This study identified several dynamic hypotheses for land inequality, which shed light on the different factors that contribute to this complex issue. The Reinvestment hypothesis (R1) indicates that individuals' disposable reinvestment rates can increase investment and resource acquisition regardless of land ownership status. However, privileged access to land ownership has contributed to the concentration of land ownership among certain groups, thereby perpetuating land inequality. The Fraction of Land Owned hypothesis (R2) suggests that land tenure disparities lead to poverty and vulnerability, particularly among marginalized groups that lack resources and access to productive land.

Age and Human Capital (R3) also influence land inequality. Younger populations tend to be more economically active, which leads to increased land ownership and resource reinvestment. However, access to training and development opportunities for the youth and old age can be limited, affecting their ability to generate wealth and reinvest in land. The Wealth Inheritance hypothesis (R4) indicates that historical factors such as the transmission of wealth from generation to generation contribute to land inequality. Agrarian reforms can address this issue, but their effectiveness depends on unique political and social conditions.

The Resource Access hypothesis (B1) highlights that individuals without access to land face significant inequality in access to resources and economic opportunities, perpetuating cycles of poverty and vulnerability. Age and Human Capital (B2) also affected the opportunities available to youth and old age. Access to training and development opportunities for those who do not own land is limited, which affects their ability to generate wealth and reinvest in land. The Wealth Inheritance Without Land hypothesis (B3) states that unequal land distribution perpetuates land inequality, affecting access to resources and opportunities.

Solutions to land tenure problems require systemic thinking and cooperation between governments, communities, and individuals. A more sustainable society can be created by addressing historical inequalities, promoting fair and equitable access to productive land for all people, and investing in education and training. Adopting a comprehensive approach that considers the different factors contributing to land inequality, including reinvestment rates, land tenure disparities, age, human capital, wealth inheritance, and resource access, is essential.

Furthermore, age influences inequality, with younger people having more time to accumulate resources and to reinvest in land. Inheritance can also perpetuate inequality, as those who inherit land have an advantage over those who do not. A country's history is also a significant cause of inequality in land tenure, with certain groups having privileged access to land ownership, maintenance of control, and access to land for generations.

To address land inequality, it is essential to develop policies and laws that promote land reform, foster dialogue and collaboration between stakeholders, and invest in education and training. This study reaffirms the importance of generational farming renewal and viability in the long-term, highlighting the need to provide young farmers with access to training and development opportunities to increase their economic activity and land ownership. By adopting a systemic approach involving cooperation between governments, communities, and individuals, we can promote sustainable land management practices and create a more equitable and sustainable future.

In conclusion, addressing land inequality is a complex issue that requires a comprehensive approach that considers the different contributing factors. A more sustainable society can be created by promoting fair and equitable access to productive land for all people, addressing historical inequalities, and investing in education and training.

12.8.1 Insights and Implications for Practice

This chapter seeks to provide a deeper look at the factors that contribute to inequality in the distribution of land tenure from the perspective of system dynamics. It aims to understand how the inheritance of our ancestors, available resources, the age of a population, and reinvestment have contributed to increasing inequality over the years. This approach allows researchers to model the behavior of different variables over time, such as the concentration of wealth, corruption, and the lack of adequate public policies for the management and distribution of land (Hernandez & McNamara, 2017).

For example, one can study how the concentration of land in the hands of a few owners can lead to decreased investment in land by less-privileged farmers, which in turn contributes to further concentration of land. It can also be useful for assessing the impact of different policies and strategies on land inequality. By modeling different scenarios, researchers can assess how different interventions may affect land distribution. This can be particularly useful for designing policies that consider the complex interactions between different variables in a system and have a positive impact on land distribution.

System dynamics also enable the identification of feedback dynamics that perpetuate land inequality. For example, the concentration of land in the hands of a small group of owners can generate greater inequality since these owners can use their economic and political power to influence government decisions and maintain their dominant position. It also allows us to recognize that land inequality is not caused by a single and simple actor or variable but requires a comprehensive and coordinated approach that involves different actors and levels of government (Hernandez & McNamara, 2017).

In conclusion, system thinking and dynamics can provide valuable insights into the study of land inequality. By modeling the behavior of different variables over time, researchers can better understand the causes and effects of inequality and assess the impact of different policies and strategies to address it effectively and sustainably (Hernandez & McNamara, 2017).

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Chapter 13
Biosecurity Adherence Using Cooperation Mechanisms: Leveraging System Thinking for Effective Strategic Organizational Biosecurity Decision Making

Cindy Daza-Ríos and Jorge-Andrick Parra-Valencia

Abstract This chapter seeks to generate knowledge to improve adherence to biosafety procedures by proposing a dynamic hypothesis that uses a model to explain the decision to cooperate or not through various mechanisms based on social dilemmas. The objective of this study is to generate conceptual and methodological frameworks that guide strategic decision making in organizations, as well as the definition of institutional policies that seek to improve the culture and communication among stakeholders seeking to reduce the negative environmental impacts and the effects on the quality of life of workers and other stakeholders that could be affected by microorganisms that represent a biological hazard that must be properly managed, also contributing to corporate sustainability. This research was framed within the development of a doctoral study in Bucaramanga, Colombia.

Keywords Biosecurity adherence · Cooperation · Biological risk factors · Stakeholders · Damage perception · Organizational culture · Safe behavior · System dynamics · Dynamic causal model · Infectious disease · And systemic thinking

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13.1 Introduction

Work activities in different sectors can generate adverse environmental effects and exposure to occupational risk factors. Biological risk factors are among the most critical factors affecting the environment and health of stakeholders, such as workers, customers, suppliers, and society. Biosafety refers to protective measures that seek to prevent the contamination of ecosystems and accidents or diseases caused by microorganisms, known as biological hazards. Biosafety management, or lack thereof, impacts the ecological, social, and economic dimensions (Heikkilä, 2011). Adequate biosafety management in organizational contexts should currently be a priority strategy considering the current trend towards sustainability and corporate responsibility, which seeks organizational decision-making considering internal and external stakeholders as good, socially responsible, and sustainable practices.

Different disciplines have studied biosecurity because of the different areas in which it can be applied, but recently academics from different areas have recognized biosecurity management as a social dilemma; that is, it requires the cooperation of many individuals to provide the public good or a shared resource, sometimes referred to as a "supply-side solution." It is important to note that the benefits of this public good are not exclusive. Biosafety management has been studied using the common resource approach; as a public good in this study, biosafety will have a common resource approach (Bagavathiannan, 2019).

Therefore, it is essential to adequately manage biosafety to prevent these negative impacts and promote the welfare of stakeholders and care for the environment. Biosecurity adherence is critical for reducing the risk of outbreaks, epidemics, or pandemics in all economic sectors. To promote biosecurity adherence successfully, fostering stakeholder cooperation and promoting strategies such as dialogue, education, and joint projects are essential. These strategies help ensure that all stakeholders know their responsibilities and consider culture, incentives, and individual differences.

In social dilemmas, all individuals are better off if they decide to cooperate. According to the literature, social dilemmas can be faced by the assignment of property rights, control by an external agent, and cooperation as self-regulation; constructs have been designed to evaluate the effectiveness of cooperation mechanisms in social dilemmas (Parra, 2010). This study proposes a preliminary dynamic hypothesis to explain compliance with biosafety procedures, which can be promoted by establishing effective communication with stakeholders and setting clear expectations and objectives. All stakeholders should receive comprehensive education and training programs encouraging dialogue to ensure that individual differences are respected and protected. Stringent penalties should be enforced for violations, and feedback should be provided to ensure continued adherence. With these measures, stakeholder cooperation can be achieved more quickly.

Depending on the specific context and application, biosecurity can be classified as a public good or common resource. Generally, a public good is non-excludable and non-rivalrous in consumption, meaning that individuals cannot be excluded from using it and that one person's use does not diminish its availability to others. In the case of biosecurity, specific measures, such as disease surveillance, quarantine, and vaccination, may be considered public goods, as they benefit society as a whole and cannot be restricted to only those who pay for them.

On the other hand, a common resource is a type of good rival in consumption, meaning that individuals' use of the resource reduces its availability to others. In a biosecurity context, resources such as clean water, arable land, and genetic diversity can be considered common resources as they are subject to depletion and overuse if not appropriately managed. It's important to note that biosecurity involves a complex mix of public goods, common resources, and private goods. The classification of specific measures or resources may depend on the circumstances and the stakeholders involved. Generally, public and private investments, regulations, and incentives are required to promote effective biosecurity management.

Free-riding can be assumed in biosecurity when individuals or groups benefit from collective efforts and investments in biosecurity without contributing to them. This can occur when some individuals or organizations fail to take appropriate actions to prevent or control biosecurity threats, such as not vaccinating their livestock or not implementing appropriate biosecurity measures in their operations, while still benefiting from the efforts of others who take such actions. In a social dilemma framework, free-riding can be seen as a form of defection. Some individuals defect from cooperative efforts to achieve mutual benefits and pursue self-interest. This can create a collective action problem in which the presence of free riders undermines the benefits of cooperation.

To address the issue of free-riding in biosecurity, it may be necessary to design incentives and disincentives that encourage individuals and organizations to contribute to the collective effort. This can involve a combination of regulations, education and outreach, financial incentives, and social norms that promote responsible behavior and discourage free-riding. System dynamics modeling can be a helpful tool for analyzing the effects of different interventions on the behavior of individuals and groups in the context of biosecurity management.

System dynamics Modeling is an analytical approach to understanding complex systems. This effectively improves cooperation through mechanisms designed to account for the interdependency between various components. By accounting for the relationships between variables, stakeholders can better understand the implications of their decisions and their impacts on the overall system. System dynamics Modeling can lead to increased cooperation by providing a deeper understanding of the underlying systems and allowing stakeholders to see the implications of their decisions. In addition, it can help to identify potential instabilities and inefficiencies in the system and devise new strategies for improvement. These elements improve stakeholder cooperation and provide a more effective organizational system.

13.2 History of Biosecurity Adherence

A. Which factors have historically motivated adherence to biosecurity regulations?

Since the beginning of human civilization, biosecurity regulations have become a necessary part of life. Until recently, cultural norms and values such as religious beliefs and social taboos were important in biosafety standards. In many agrarian societies, activities such as hunting and farming are restricted due to religious prohibitions and to protect the plants and animals integral to the population's subsistence. These prohibitions formed the basis of early biosecurity regulations, demonstrating the importance of cultural norms in motivating people to adhere to biosecurity regulations.

In the organizational area, there has been an evolution in the study of strategies to prevent accidents and occupational events, focusing on technical aspects and human factors (human failures). There has been a discussion of sociotechnical systems. Today, we speak of organizational safety culture as the practices workers implement in their companies.

B. How has the level of adherence to biosecurity regulations changed over time?

Historically, adherence to biosecurity regulations has largely been dictated by cultural norms. In many societies, religious beliefs and social taboos form the foundation of biosecurity rules and motivate people to adhere to them. However, as societies modernized and moved away from traditional cultural norms, the importance of biosecurity regulations often diminished, thus decreasing adherence.

As humanity continues to become more diverse and globalized, different approaches to biosecurity regulations have been adopted, resulting in a more nuanced view of their importance and a higher level of adherence in general. For instance, in countries where biosecurity regulations are seen as critical to protecting public health, adherence levels tend to be higher than in countries where biosecurity regulations are seen as more of an inconvenience than a necessity. Consequently, the level of adherence to biosecurity regulations has changed over time, depending mainly on the cultural values and attitudes of the population. Biohazards can cause public health problems (Enemark, 2017). Therefore, it is important to define the guidelines that promote implementing a safety culture in different contexts.

C. What are examples of successful biosecurity initiatives based on adherence to regulations?

For biosafety procedures to be implemented, using different tools that promote biosafety is necessary. It is impossible to comply with biosafety standards without adherence to these procedures. Therefore, in recent years, organizations have begun to talk about safety culture as a strategy to promote these safe behaviors in workers and avoid occupational accidents and diseases while contributing to labor welfare and quality of life in employees while increasing the productivity and sustainability of organizations. Suppose that the organization's safety culture needs to be considered in the strategies and guidelines designed by the company. In this case, it is likely that the results will not be sustained over time (Garavito et al., 2023, Fernández et al., 2005). To promote this preventive culture in organizations, one of the methodologies used in recent years is behavior-based safety, a methodology that seeks to reduce substandard acts; these two of the most used elements in the implementation are observation and feedback (Pariona-Palomino & Matos-Ormeño, 2021).

13.3 Social Dilemmas and Cooperation

Social dilemmas are situations where individuals, acting in their own self-interests, produce a worse outcome for everyone involved. The tragedy of the commons, as described by Hardin (1968), is a well-known example of a social dilemma. In this scenario, a group of individuals shares limited resources, such as fishing ponds, and each person may be tempted to overfish, even though they know that this will eventually deplete the resources and leave everyone worse off. Social dilemmas share two key features (Dawes, 1980):

Individual rationality: Each individual has a clear incentive to act with self-interest.

Collective irrationality: The outcome of everyone acting in their self-interest is worse for everyone involved.

Resolving social dilemmas can be challenging, given the conflict between individual and collective interests. However, some strategies can promote cooperation and prevent worse outcomes. One strategy is communication, which enables people to coordinate their actions and avoid negative outcomes. Trust is another important factor because individuals who trust each other may be more willing to cooperate. Institutions such as governments and businesses can promote cooperation and prevent social dilemmas (Ostrom, 1990).

In conclusion, social dilemmas are a complex and challenging problem; however, they are also an important area of research. By better understanding social dilemmas, we can develop better strategies to promote cooperation and prevent adverse outcomes.

What types of social dilemmas are associated with biosecurity adherence?

Social dilemmas are a significant concern regarding biosecurity adherence as they can lead to decreased adherence and increased risk. A social dilemma occurs when individuals face a moral dilemma and must choose between two conflicting strategies to achieve an end goal. This may be in the form of an individual's decision to not adhere to biosecurity regulations to achieve a more significant personal gain or a collective decision to not adhere to biosecurity regulations due to a perceived "free-rider" effect. Social dilemmas can also arise from inequitable distribution of resources and unequal power dynamics, thus leading to an increased risk of nonadherence in biosecurity. As a result, it is essential to recognize potential social dilemmas associated with biosecurity adherence and to take proactive steps to ensure that any moral dilemmas faced by individuals or groups are resolved in the best interests of all stakeholders, as biosafety has been studied as a public good and a shared resource because of its characteristics. However, in the model proposed in this research, biosafety is approached based on its characteristics as a common resource.

On the other hand, researchers have reported that there are not many studies on individual decision-making in biosafety; these decisions of individuals have a long-term influence on organizational intervention strategies to promote adherence to biosafety procedures; psychological, cognitive, and social factors have been investigated in biosafety-related behaviors; the most studied factors have been beliefs, knowledge, attitudes, motivations, and norms (Mankad, 2016). Finally, it has also been reported that disclosing information associated with disease prevalence improves adherence compared with disclosing information associated with implemented management measures (Merrill, 2019). Therefore, defining the relevant information that should be known to individuals should be a priority factor when defining strategies that seek to promote decision-making that contributes to adherence to biosafety procedures.

Cooperation Mechanisms to cope with Social Dilemmas

Designing effective cooperation mechanisms is essential for promoting cooperation and preventing negative outcomes in social dilemmas. One such mechanism is communication, which facilitates individual coordination and promotes cooperation (Dawes, 1980). Another important element is trust, which can enhance cooperation by reducing the risk of exploitation (Ostrom, 1990). Additionally, institutions such as governments and businesses can promote cooperation by establishing rules and incentives encouraging individuals to act in collective interests (Hardin, 1968). Effective cooperation mechanisms should also consider the diversity of individuals and their preferences and the context in which the social dilemma occurs (Ostrom, 1990). By considering these elements in the design of cooperation mechanisms, we can develop effective strategies to promote cooperation and prevent negative outcomes from social dilemmas.

How can cooperation among people promote biosecurity adherence?

Cooperation among people is essential to promote biosecurity adherence, as it effectively reduces the risk of non-adherence. One way to achieve this is through collaboration between different stakeholder groups, which can help ensure everyone understands their responsibilities and is accountable for their actions. Cooperation can also increase awareness of biosecurity regulations and promote dialogue and communication among stakeholders. Through cooperation, stakeholders can work together to develop mutually beneficial solutions to any potential problem, thus reducing the risk of nonadherence to biosecurity regulations. Furthermore, cooperation provides a platform for discussing new ideas and techniques that can be used to improve biosecurity adherence, thereby contributing to an overall safer environment for all stakeholders. This could improve biosafety adherence, a problem in which it has been mentioned that not much information is available and is required (Jirkof & Schmutz, 2019).

What work has been conducted to promote biosafety through social dilemmas?

Biosafety has not been widely studied under the conceptual framework of cooperation and social dilemmas, which is an opportunity to generate a theoretical framework and constructs to explain the behavior of workers with respect to adherence to biosafety and thus be able to design strategies for improvement in the organization. Researchers have reported the use of cooperation for biosafety management, specifically for controlling pests known as weeds. Choosing between collective and individual interests during pest management has been seen as a social dilemma by applying the eight principles designed by Elinor Ostrom in future studies (Bagavathiannan, 2019).

Researchers have mentioned the need to generate more knowledge on the subject and study biosafety's characteristics as a public good and common resource. Hence, this study seeks to provide knowledge to improve the conceptualization of biosafety in social dilemmas.

13.4 Biosafety and System Dynamics

Combining system dynamics modeling and biosecurity can increase cooperation toward managing emerging infectious diseases. Bespoke modeling of threats can inform risk management responses, leading to more profitable and positive margins for all value chain actors while reducing the number of outbreaks. (MacLeod & Spence, 2020; Ouma et al., 2018). Biosecurity is critical in controlling the spread of infectious diseases, and human behavioral change, in response to increased awareness of disease risks, is essential to modeling animal disease dynamics (Songserm et al., 2006; Tan et al., 2021). Utilizing system dynamics models to assess the impact of interventions can further enhance the efficacy of biosecurity measures (Ouma et al., 2018). Meteorological data can also be applied in biosecurity to predict organism distribution and assess the probability of events (Hemming & Macneill, 2020).

However, efficacy of biosecurity practices depends on human behavior and risk attitude (Bucini et al., 2019). Multiple factors affect biosecurity compliance, including social cues that affect cooperation with biosecurity practices (Trinity et al., 2020). Finally, the public goods nature of biosecurity benefits could create collaboration among stakeholders (French et al., 2007).

In conclusion, policymakers should institutionalize collaboration and employ a multi-disciplinary approach to ensure their biosecurity measures are effective. There is a need for integrated surveillance, interdisciplinary integration of techniques, and partnerships with multiple stakeholders to mitigate global biosecurity risks (Dewulf et al., 2018; French et al., 2007). Biosecurity measures should be implemented to assess the impact of interventions effectively, and human behavioral factors should be considered when modeling animal disease dynamics (Bucini et al., 2019) (Citaciones se incluyen al final).

System dynamics and causal models are modeling approaches used to understand how complex systems work and how they can be improved. System dynamics focuses on how different system components interact over time, while causal models focus on identifying causal relationships between different variables in a system.

According to Sterman (2019), “system dynamics is a modeling methodology that focuses on the interaction between different components of a system over time.” System dynamics models use flowcharts and mathematical equations to represent these interactions and how they affect the system’s behavior. On the other hand, causal models focus on identifying causal relationships between different variables in a system. According to Pearl (2018), “causal models are tools for understanding how variables are causally related to each other and how these relationships can be used to predict the effect of interventions in the system.”

System dynamics models are used to understand complex systems’ behavior and assess the impact of different policies and strategies on system behavior over time. While causal models are used to understand how different factors can influence a specific outcome.

An organization functions as an open system that interacts with its environment. On the other hand, adherence to biosafety is a complex problem that must be viewed holistically because there are different organizational factors, such as culture, and personal factors, such as knowledge, attitudes, and beliefs, that influence people when making decisions about their behavior. Therefore, using systems thinking to understand how the components interact in decision-making associated with safe behavior will enable the design of successful institutional strategies and policies that promote cooperation and adherence to biosafety procedures.

The impact of organizational and human factors on decision-making, as well as the factors themselves, can change over time; therefore, tools such as system dynamics that allow modeling problems of dynamic complexity could be fundamental for the design of organizational strategies that are relevant and coherent to the business context and needs. Thus, implementing biosafety procedures will contribute to organizational productivity and sustainability, quality of life, and satisfaction of workers and reduce negative environmental impacts. For this reason, this tool, which allows modeling and simulation of complex dynamic problems, is beneficial in trying to explain the causes and relationships between the different variables that influence adherence to biosecurity procedures, as well as to simulate different scenarios to offer the best possible solution.

As a result of the research progress in the formulation of the doctoral thesis on biosafety adherence based on cooperation and by means of system dynamics, a dynamic hypothesis on a model of biosafety adherence is proposed, which can be seen in Fig. 13.1.

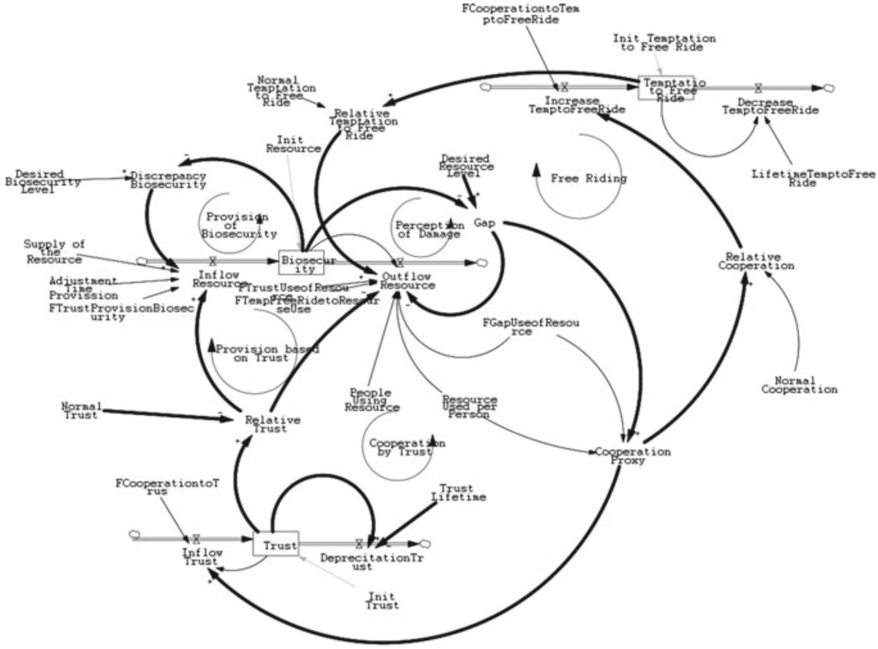

Fig. 13.1 Proposed biosafety adherence model

13.5 Research Questions

Promoting cooperation among stakeholders in biosecurity adherence is essential to reducing the risk of non-adherence and considering factors such as traditionally predominant cultural norms and the need for incentives to promote greater adherence and individual differences in risk tolerance.

The doctoral research project, of which this book chapter is a part, will seek to generate knowledge on the personal and organizational factors that influence bio-safe behavioral decision-making and on the most essential characteristics for the design of successful institutional strategies.

How do personal and organizational factors influence bio-safe behavioral decision-making?

However, we need help finding previous work in the literature on what information is necessary to cooperate in Biosecurity Adherence situations, and we hope to generate useful knowledge in this area by answering these questions.

13.6 Conceptual Model

The research chapter presented here proposes a hypothesis to understand the complex dynamics of biosecurity and the factors that promote or hinder cooperation among stakeholders. This hypothesis suggests that feedback loops created by cycles of temptation to defect, trust, resource provision, and the perception of harm play a critical role in promoting cooperation in biosecurity.

The dynamic hypothesis emphasizes the importance of trust and the perception of biological safety in promoting cooperation among stakeholders. This suggests that trust-building mechanisms, such as effective communication and stakeholder engagement, can facilitate cooperation and promote the perception of biological safety. Similarly, providing sufficient resources and support can enhance trust and promote cooperation between stakeholders.

However, the hypothesis also acknowledges the challenges of achieving effective biosecurity, such as free-riding, lack of trust, and perception of damage. To address these challenges, the hypothesis proposes a comprehensive understanding of the underlying dynamics and feedback loops that shape a system's behavior and outcomes.

Overall, the dynamic hypothesis presented in this research chapter provides a framework for understanding the complex dynamics of biosecurity and offers insights into the development of effective strategies to enhance biosecurity and promote cooperation among stakeholders.

In the proposed biosafety model, biosafety is considered a common resource, and three mechanisms of cooperation are presented: perception of harm, the temptation to defect, and cooperation through trust. Finally, service provision was also considered.

A diagram of the dynamic hypothesis identifies several feedback cycles around biosecurity. In this context, biosecurity is considered a resource that enables us to define the provision of biosecurity and the reduction in the level of biosecurity that could lead to the temptation to abandon it. Depending on cooperation, we have a cycle of cooperation based on trust, which allows us to define the appropriation and deterioration of biosecurity and the provision of biosecurity. Similarly, cooperation is based on the perception of harm. This approach integrates the mechanisms of temptation to abandon, cooperation based on the perception of harm, and cooperation based on trust that affects both the appropriation and provision of biosecurity. In this way, we offer an enriched perspective on how cooperative management could lead to better biosecurity management.

This chapter presents a dynamic hypothesis that suggests the importance of trust and the perception of biological safety in promoting cooperation in biosecurity (Mankad & Curnock, 2018). Feedback loops generated by the cycles of temptation to defect, trust, resource provision, and perception of harm play a critical role in this process (Mankad & Curnock, 2018). As cooperation increases, trust also increases, leading to decreased appropriation of the shared resource. Conversely, a decrease in cooperation results in a decrease in trust, which increases the temptation to defect and the appropriation of shared resource (Mankad & Curnock, 2018).

Achieving effective biosecurity faces challenges such as free riding, lack of trust, and perception of damage (Onwude, 2023a, 2023b; Shapiro, 2022a, 2022b). Research shows that increasing awareness of the potential damage caused by the spread of diseases can lead to increased engagement in biosecurity actions (Payne et al., 2022). Moreover, trust in the expertise and knowledge of stakeholders is essential for achieving effective biosecurity (Renault et al., 2017; Seppelt et al., 2018a, 2018b).

Effective biosecurity measures are critical in preventing disease outbreaks and their economic impacts, and their implementation can be affected by the psychosocial factors of stakeholders (Fountain, 2023; Renault et al., 2021a, 2021b). However, some studies express concerns about the biosecurity management process and the need for more trust in authorities (Mankad & Curnock, 2018).

13.7 On the Modeling of Biosecure Behavior Based on Cooperation

13.7.1 The Size of the Group

The group size is an important factor in determining the likelihood of cooperation. In small groups, it is easier to monitor the behavior of others and to enforce cooperation. This is because it is more difficult to keep track of the actions of a large number of people. It is also more difficult to punish individuals who defect from cooperation in large groups.

For example, a study by Ostrom and Walker (1998) found that cooperation was more likely to occur in small groups of farmers managing a common grazing area. The researchers found that the farmers were more likely to cooperate when they could easily monitor each other's behavior and had a strong sense of community.

13.7.2 The Level of Information Sharing

The level of information sharing is also an important factor in determining the likelihood of cooperation. Information sharing can help individuals to understand the consequences of their actions and to make more informed decisions about whether or not to cooperate. In groups with a high level of information sharing, individuals are more likely to understand the benefits of cooperation and the costs of defection. This can lead to more cooperation.

For example, a study by Ostrom and Walker (2002) found that cooperation was more likely to occur in groups of water users sharing a limited water supply. The researchers found that the water users were more likely to cooperate when they had access to information about the water supply and when they could trust each other to share the water fairly.

13.7.3 The Presence of Punishment Mechanisms

The presence of punishment mechanisms can promote cooperation. Punishment mechanisms can deter individuals from defecting from cooperation. In groups with punishment mechanisms in place, individuals are less likely to defect from cooperation because they know they will be punished. This can lead to more cooperation.

For example, a study by Ostrom and Walker (2002) found that cooperation was more likely to occur in groups of fishermen sharing a limited fishing ground. The researchers found that the fishermen were more likely to cooperate when they had a system of fines in place for those who violated the rules of the fishery.

In the proposed dynamic hypothesis, when the supply of the resource and trust increases, the resource input also increases. Likewise, perceptions of harm increase, cooperation, and trust increase, and when the desire for a biosafety level increases, the biosafety discrepancy also increases. if the temptation to defect increases, the resource output also increases, and if the desire for the resource level increases, the resource output decreases.

13.7.4 Conclusion About the Proposed Biosafety Adherence Model

In conclusion, the dynamic hypothesis proposed in this paper highlights the importance of trust and the perception of biological safety in promoting cooperation in biosecurity. Addressing the challenges of free riding, lack of trust, and perception of damage can be achieved through stakeholder engagement, education, and communication. Building trust and increasing awareness can lead to a perception of the importance of biosecurity, which can motivate stakeholders to cooperate and engage in biosecurity actions. Effective biosecurity measures are critical in preventing disease outbreaks and their economic impacts, and their implementation can be influenced by the psychosocial factors of stakeholders (Fountain, 2023; Renault et al., 2021a, 2021b).

The likelihood of cooperation is affected by the size of the group, the level of information sharing, and the presence of punishment mechanisms. By understanding these factors, policymakers and other stakeholders can play a role in promoting cooperation in biosecurity. In addition to the factors discussed in this chapter, other factors can affect the likelihood of cooperation, such as the group's culture, the history of cooperation in the group, and the individual motivations of the group members. By understanding these factors, policymakers and other stakeholders can create environments more conducive to cooperation.

13.8 Conceptual Model Validation

System dynamics models are causal models. The key to the modeling process is identifying how the structure and decision policies help generate observable behavior patterns in a system. Therefore, identifying the appropriate structure is the first step to establishing the validity of a model, and then behavioral validity must be performed. This validation process is iterative (Qudrat-Ullah & BaekSeo, 2010).

Identifying endogenous and exogenous variables resulting from this research is presented below, highlighting the most noteworthy ones. These exogenous factors are vital in the presence and durability of endogenous variables. It is crucial to emphasize that endogenous variables' functionality and essential support depend entirely on their associated exogenous variables.

Figure 13.2 presents the structures and concepts adopted from the existing literature as empirical validations of the dynamic hypothesis presented in this chapter. This chapter highlights the importance of trust and perception of biological safety in promoting cooperation in biosecurity (Mankad & Curnock, 2018). The hypothesis suggests that feedback loops generated by cycles of temptation to defect, trust, resource provision, and perception of harm play a critical role in this process (Mankad & Curnock, 2018). The structures and concepts adopted from the literature include causal structures, structural formulations, and empirical data from studies on biosecurity in pig herds (Postma et al., 2016), broiler production (Dewulf et al., 2018), and antimicrobial use in agriculture and food sectors in Tanzania (Mdegela et al., 2021). These studies shed light on the challenges of achieving effective biosecurity, such as free riding, lack of trust, perception of damage (Onwude, 2023a, 2023b; Shapiro, 2022a, 2022b), and the importance of increasing awareness and trust in stakeholders' expertise and knowledge to promote cooperation (Renault et al., 2017; Seppelt et al., 2018a, 2018b). However, some studies have expressed concerns about the biosecurity management process and little trust in authorities (Mankad & Curnock, 2018), highlighting the need for further research and improvement in biosecurity governance (Fountain, 2023; Fountain, 2023).

Table 13.1 provides an overview of the structures and concepts adopted from existing studies related to the research problem discussed in this paper. These structures and concepts have been studied through various approaches, and are empirical validations of the dynamic hypothesis presented in this chapter, as shown in Fig. 13.2. The dynamic hypothesis suggests that feedback loops generated by cycles of temptation to defect, trust, resource provision, and the perception of harm play a critical role in promoting cooperation in biosecurity.

The literature adopted in Table 13.1 includes causal structures, structural formulations, and empirical data from studies on biosecurity in pig herds (Postma et al., 2016), broiler production (Dewulf et al., 2018), and antimicrobial use in agriculture and food sectors in Tanzania (Mdegela et al., 2021). These studies shed light on the challenges of achieving effective biosecurity, such as free-riding, lack of trust, and perception of damage, and highlight the importance of increasing awareness and trust in stakeholders' expertise and knowledge to promote cooperation. However, some

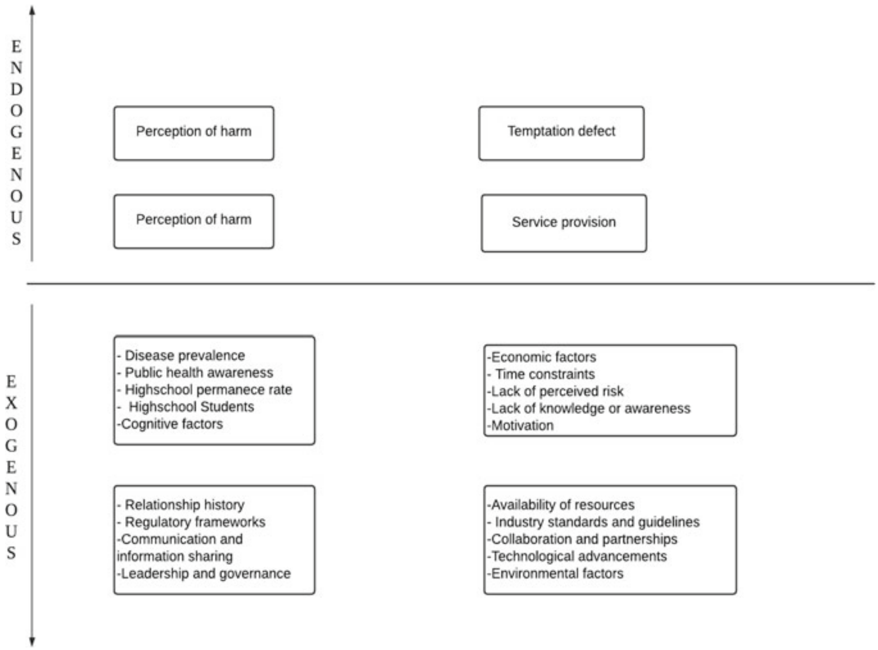

Fig. 13.2 Endogenous and exogenous variables

Table 13.1 The structures and concepts adopted from the existing work

Structures/ concepts	Remarks
Postma et al. (2016)	Causal structure was adopted
Mdegela et al. (2021)	Causal structure was adopted
Dewulf et al. (2018)	Structural formulation was adopted
Parra (2010)	The construct is used to evaluate the effectiveness The construct is used to assess the effectiveness of cooperation mechanisms in large-scale exhaustible resource social dilemmas, which integrates three cooperation mechanisms: trust-based, perceived harm and norm-based norm-based

The following are relevant works that have studied the causal structure of the research problem mentioned in this paper through different approaches.

studies have expressed concerns about the biosecurity management process and little trust in authorities, highlighting the need for further research and improvements in biosecurity governance.

In summary, Table 13.1 enriches the understanding of the structures and concepts related to the research problem and demonstrates how they have been studied using various approaches, providing empirical evidence for the dynamic hypothesis presented in this chapter.

13.9 Discussion

Several research studies highlight the importance of biosecurity measures, although they do not directly address the dynamic hypothesis and its feedback loops around biosecurity. Postma et al. (2016) found that disease prevention through biosecurity measures in agricultural research is crucial for improving health status. Similarly, Mdegela et al. (2021) noted poor biosecurity practices in some agricultural sectors. Furthermore, Dewulf et al. (2018) highlighted the importance of reasonable biosecurity procedures to ensure healthy production in the agricultural sector.

In conclusion, these research results highlight the importance of properly implementing biosecurity measures to prevent diseases in animal production, with this sub-sector of the agricultural sector being one of the sectors with the most published information associated with these issues. However, they do not explicitly discuss the dynamic hypothesis and its feedback loops around biosecurity.

13.10 Conclusion

In conclusion, System Dynamics modeling effectively improves cooperation among stakeholders by investigating the interdependency between components. This approach can identify new strategies and inefficiencies in a system, leading to improved collaboration across all parties to achieve the most effective outcomes. For further research, additional analyses could be conducted on specific components of the system to understand better how changes in these elements could affect the overall system. Additionally, alternative approaches to System Dynamics Modeling should be explored to determine whether more efficient mechanisms for improving cooperation can be developed.

This research proposes a preliminary dynamic hypothesis that seeks to contribute to biosafety management by improving adherence to procedures and promoting biosafety behaviors to enjoy an environment free of contamination and workers whose health is not affected by biological risk factors. This research was part of the first year of a doctoral study in Bucaramanga, Colombia. In the future, it will be possible to conduct theoretical and experimental research to test the proposed model, design new and more complete models, and formulate strategies to intervene and improve biosafety adherence based on cooperation with a systems thinking approach.

13.10.1 Insights and Implications for Practice

Decision-making in biosecurity behavior has been studied at organizations' operational, tactical, and strategic levels (Trinity, 2019). Still, different authors agree on the need to generate knowledge on this issue. Traditionally, strategies that seek to promote biosafé behaviors in organizations have been approached individually without trying to consider and understand the relationship between the different factors that influence decision-making, which is perhaps why the results of their implementation are not as expected, and low compliance rates are obtained.

This study proposes that social dilemmas are a conceptual framework that contributes to structuring policies and guidelines that promote biosecure behaviors, articulating different theories and approaches that have sought to implement biosecure practices in organizations. Specifically, we propose a model for managing biosecurity as a common resource that we hope to put into practice and test in the future in the doctoral thesis from which this research was founded.

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Part VI
Sustainability Science and Systems Thinking

Chapter 14
The Sustainable Management of Plastic Contents Recycling in Bangladesh: A System Dynamics Approach

Mohammad Shamsuddoha, Mohammad Abul Kashem, and Hassan Qudrat-Ullah

Abstract The increasing use of plastics has led to environmental concerns and sustainability issues, prompting scholars to study the feasibility of plastic content recycling. Though plastic contents are harmful, removing and reusing or recycling them to save the environment and society is inevitable. The uncertainty of its economic viability, followed by the need to find the best, most affordable solution and the expertise to handle the situation, makes it volatile in Bangladesh. The initiatives are not affluent, even infelicitous, without enough government or non-profit sector backing. Thus, this research develops a causal loop diagram using a System Dynamics (SD) method to assess the current state of plastic recycling and sustainability challenges. In addition, the study explains efficient techniques for gathering, sorting, and valuing recyclables in order to build a sustainable environment for a densely populated country. SD approach used in this study enables the identification of feedback loops through drawing causal loop diagrams to identify relevant variables and solutions for the plastic recycling industry. This study proposes summary recommendations for improving plastic recycling, including creating a robust infrastructure, promoting education and awareness programs, and developing policies that benefit from adopting sustainable practices. The paper concludes that an SD model, reverse and circular economy can help convert plastic waste into valuable resources to achieve sustainable development goals.

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Keywords Sustainability · Sustainability · Recycling · Plastic · System dynamic · Causal loop diagram

14.1 Introduction

Plastic, a widespread use synthetic material for its durability, versatility, and low cost, comes at a significant cost to the environment and society (Geyer, 2020). A substantial portion of this plastic waste is composed of plastic particles or micro-plastics, originating from various sources, including plastic bags, bottles, and other single-use plastics, as well as from the disintegration of more oversized plastic items (Dey et al., 2021). Moreover, the buildup of plastic garbage in the environment also has a number of detrimental repercussions, including a threat to animals, health effects, and even aesthetic effects (Wang et al., 2021). Arguably, the hassles against clogging storm drains, flooding, and the cleanup and disposal of plastic waste are expensive, and taxpayers and businesses bear these costs. Even though existing literature has found microplastics in tap water, bottled water, and even in the air we breathe, raising concerns about the potential health effects of long-term exposure to these particles (Kontrick, 2018), even persisted for centuries (Shamsuddin et al., 2017). Various marine animals, including fish and birds, ingest these particles, leading to health issues and even death. For instance, plastic production, transportation, and disposal contribute to greenhouse gas emissions (Shen et al., 2020). As such, plastic production releases significant amounts of carbon dioxide and other harmful chemicals, contributing to climate change.

Research from the International Union for Conservation of Nature (IUCN) in 2021 states that plastic trash is an issue that is becoming more and more of a worry globally, with an estimated 14 million tons entering the oceans each year. Garbage has increased from 178 to 646 tonnes daily in Bangladesh (Nadiruzzaman et al., 2022). However, the amount of recycled plastic varies depending on the kind of plastic and the recycling technique employed. Environmental advocacy group Greenpeace studies show that only 5% of the 51 million tonnes of plastic garbage generated in the United States in 2021 was recycled (Rossi & Morone, 2023). But every year, the average person consumes 156 plastic bottles. In America, 60 million plastic water bottles are discarded daily and only 12% of the 35 billion empty water bottles discarded in the US each year get recycled (Rossi & Morone, 2023). As for solutions, plastic particle recycling transforms plastic waste into new plastic products or raw materials for manufacturing. The process relates to collecting plastic waste, sorting it based on the type of plastic, cleaning it, melting it down, and reforming it into new plastic products or raw materials (Evode et al., 2021). Out of the several methods of plastic particle recycling, mechanical recycling pertains to grinding or shredding plastic waste into tiny particles, which are then melted down and molded into new products (Yang et al., 2012). Chemical recycling breaks down plastic waste into chemical components to create new plastic products (Vollmer et al., 2020). Thermal recycling employs heat to break down plastic waste into its essential components to be used as fuel or raw materials (Singh et al. 2017). Out of these measures, the plastic recycling businesses are still more concerned about economic viability and environmental compatibility.

Therefore, one of the most urgent environmental problems facing our civilization is the problem of garbage management and disposal. Implementing efficient trash reduction, reuse, and recycling solutions is essential to safeguarding the environment and conserving resources since waste generation rises daily (Kurniawan et al., 2023). According to the literature, the best way to lessen plastic waste's negative consequences is to use it less, whether by recycling (Kiessling et al., 2023), adopting reusable items, or avoiding single-use plastics (Rossi & Morone, 2023). Alternative materials to plastic are another option for materials made from natural sources, such as bio-plastics (Dey et al. 2021). The absence of facilities for collecting and sorting plastic garbage is one of Bangladesh's biggest problems. They failed to make a structured process of plastic contents collections followed by routing them for other value addition for saving the environment and making extra economic and social benefits. Many areas have limited or no facilities for collecting and sorting plastic waste, making recycling difficult. In some cases, the cost of recycling plastic may be higher than the cost of building new plastic, making it difficult for recycling companies to compete. In this situation, the country needs to develop a structure first based on its limitations and scarcity of resources, followed by deploying appropriate methods to utilize the waste resources and find sustainable solutions.

14.2 Literature Review

14.2.1 Negative Impacts of Plastic Particles on the Environment

The harmful consequences of plastic pollution on the environment are complicated and numerous, frequently affecting environmental pollution, harm to animals, hazards to human health, harm to ecosystems, and financial expenses. It is crucial to keep this in mind. The summarized negative impacts (in Table 14.1) are reviewed as follows:

14.2.2 World Scenario of Plastic Particle Recycling

Plastic trash has become a severe problem in the United States due to the millions of tons of plastic garbage dumped in landfills, streams, and oceans yearly. Because 90% of the recovered material is sold inside the state, their operations have residual pollution rates of less than 8%, which promotes regional development, as per the report of WCAX, USA. Materials Recovery Facility (MRF) is seeking methods to

Table 14.1 Negative Impacts of Plastic Particles in the Environment

Negative impact	Explanation
Marine pollution (Kiessling et al., 2023)	Plasticparticles end up in the oceans and other bodies of water, harming marine life and disrupting ecosystems where fish and other marine animals may mistake plastic particles for food, leading to ingestion and potentially death
Soil contamination (Evode et al., 2021)	Plasticparticles usually take hundreds of years to break down, impacting the growth of plants and other organisms in the soil and contaminating the groundwater
Air pollution (Darimont, 2023)	When plasticparticles are burnt, it release toxic fumes and particles into the air, contributing to air pollution and potentially harming human health
Climate change(Shen et al., 2020)	Climate changeand greenhouse gas emissions are made worse by the manufacture and disposal of plastic. Additional factors contributing to carbon emissions and other greenhouse gases include the extraction and transportation of raw materials, the production of plastic goods, and the disposal of plastic trash
Wildlife endangerment (Tiwari et al., 2023)	Plasticparticles entangle wildlife, such as birds and small mammals, leading to injury or death, particularly common with plastic bags and other larger pieces of plastic debris
Human health risks (Wang et al., 2021)	Plasticparticles have been found in food and drinking water, potentially exposing humans to harmful chemicals contributing to respiratory and other health issues when inhaled or ingested
Economic costs (Darimont, 2023)	The costs associated with cleaning up plasticdebris from beaches and other areas and lost revenue from tourism and other industries that rely on clean environments have high economic costs
Migration Impairment (Wang et al., 2021)	Some wildlife species, such as sea turtles, use magnetic fields to navigate during migration. Plasticparticles in the water disrupt these magnetic fields, causing disorientation and impairing migration
Habitat Destruction (Shamsuddin et al., 2017)	The accumulation of plasticdebris in natural habitats, such as oceans, rivers, and forests, alters the ecosystem and destroys the natural habitat of many species
Reduced property values (Singh et al., 2017)	Areas with high levels of plasticpollution may reduce property values, as people may be less likely to want to live or work in areas with environmental damage
Loss of business reputation (Niyommaneerat et al., 2023)	Companies associated with plasticpollution may face negative public perception and damage to their brand reputation, potentially leading to lost sales and revenue
Increased waste management costs (Kurniawan et al., 2023)	Plasticparticles contaminate waste streams and make recycling more difficult and expensive. This might lead to higher waste management costs for municipalities and businesses
Fines and regulatory costs (Yang et al., 2012)	Governments may impose fines or regulations on businesses that contribute to plasticpollution, which leads to additional costs and financial penalties

boost its game and invest in new equipment and technology to increase productivity (Li et al., 2023). Businesses that use robotic arms and artificial intelligence to sort things effectively, like AMP Robotics, are thriving (Johannessen, 2023). Still, there are more and more opportunities for investment. International companies, notably Nine Dragons, one of China's largest paper manufacturers, are investing thousands of millions of dollars in recycling facilities in the US (Darimont, 2023). Again, chemical recycling as plastic waste in the UK breaks down the plastic particles at a molecular level, producing high-quality raw materials used to make new plastic products (Tiwari et al., 2023) and imposing a plastic bag tax (Sharp et al. 2023). Extending producer responsibility (EPR), schemes have also been implemented in the UK (Mayanti and Helo, 2023), which mandate that manufacturers of plastic goods bear responsibility for product disposal, involving the associated expenses of product collection and recycling at the brink of its useful life. The EPR programs are anticipated to increase plastic product recycling rates in the UK and decrease the quantity of plastic trash dumped in landfills.

Singapore has implemented a waste-to-energy incineration program to manage waste by burning it to generate energy. The ash generated from this process is then used as a construction material (Greef et al., 2023). While this process may not be the most sustainable option, it is an effective way of managing waste in Singapore. However, Japan is also known for its advanced waste management system and various initiatives to promote plastic particle recycling and effective waste management. The government has implemented various waste management initiatives in Japan to encourage recycling and reduce plastic waste (Nobusawa, 2023). One of these initiatives is the 3Rs (Reduce, Reuse, Recycle) campaign, which promotes waste reduction, recycling, and the reuse of products (Nobusawa, 2023). Another initiative is the Plastic Waste Management Strategy, which aims to reduce Japan's plastic waste by 25% by 2030 (Loy et al., 2023).

In Bangladesh, only 37.2% of the 646 tonnes of plastic garbage collected in Dhaka each day are recycled; a circular economic model may or may not be a practical strategy for managing plastic waste in Bangladesh (Tayeb, 2022). The rest is discarded in various places, including landfills, aquatic bodies, parks, roads, and seashores. This garbage has a negative impact on the nation, the entire planet, and its people. It also hurts the ecosystem. The government of Bangladesh has created a National Action Plan for Sustainable Plastic Management based on the 3R method of Reduce, Reuse, and Recycling to address plastic pollution in a planned manner (Tayeb, 2022). This objective is to decrease plastic waste through developing a circular economic model (Tiwari et al., 2023) where recycle 50% of plastics by 2025, phase out 90% of single-use plastic by 2026, and reduce the production of plastic trash by 30% by 2030 compared to the baseline of 2020–21 (Kiessling et al. 2023). Some initiatives are already working toward plastic waste management in Bangladesh. For example, the government has banned single-use plastic bags, and various NGOs are working on plastic waste management programs. However, there is still a need for more extensive and effective waste management and recycling programs. Now, it is essential to have a comprehensive approach that involves education, awareness, and infrastructure development to ensure effective waste management recycling in Bangladesh.

14.3 Research Gap

The implications of plastic waste on the environment are being actively discussed and researched worldwide. This is particularly crucial in Bangladesh, where managing plastic waste is a major obstacle. Unfortunately, research on efficiently managing and recycling plastic waste for the nation is inadequate. This research will explore various avenues, including the ways ahead steps like identifying the sources and types of plastic waste, recycling technologies, and stakeholder engagement such as policymakers, waste collectors, recyclers, and consumers. However, plastic waste management and recycling initiatives must be economically viable to be sustainable. On the other hand, there is a need for a policy framework that supports and benefits plastic waste management and recycling initiatives in Bangladesh. Such studies may offer useful information for creating environmentally and economically advantageous strategies for local governance and recycling plastic trash.

14.4 Methodology

The burning question for Bangladesh plastic recycling is a doubt on economic profitability followed by the appropriate cheapest but effective method and know-how to deal with the whole thing. It is evident from the Western and developed countries that plastic particles must be eliminated even if it will be a negative profit project. Bangladesh is a densely populated country with insufficient government or not-for-profit support to do the same as Western countries. In this scenario, this paper introduces a System Dynamics approach to model a similar plastic recycling supply chain model and find effectiveness and efficiency. System dynamics is an interdisciplinary approach that involves business and social sciences in modeling complex system behavior over time (Forrester 1987; Cosenz & Noto, 2016). Instead of concentrating on specific components, this approach examines a system's behavior as a whole (Mele et al., 2010). Using system dynamics, one can explore how changes in the structure and operations of a system impact its performance (Adane et al., 2019). Although this method applies to any complex system, it is beneficial in analyzing complex systems such as farming operations (Kalaugher, et al., 2013). Similar techniques in the complex poultry supply chain are used to achieve sustainable outcomes (Shamsuddoha, 2015, 2022; Shamsuddoha and Woodside 2022; Shamsuddoha et al., 2022) and sustainable frameworks (Shamsuddoha et al., 2023). Likewise, plastic recycling involves several interrelated factors that must be balanced to achieve the desired outcomes.

14.4.1 Structural Validity

By reviewing the literature and recommendations from the experts, the connections between cause and effect have been identified. Theoretical ideas from the literature have been used to figure out these relationships, along with particular parameters and coefficients derived through empirical estimates using secondary data sources and earlier investigations. The ideology of this model was keen to structural validation from the earlier research of Barlas (1989) and Senge and Forrester (1980) with the guided knowledge from the Qudrat-Ullah (2008). The causal loop diagram for the model of plastic waste creation and mitigation is shown in Figs. 14.1 and 14.2. The causal linkages in the graphic are shown by arrows that lead from the cause variable to the effect variable. Positive signs (+) and negative signs (-) indicate that a rise in the cause variable causes an increase in the impact variable, respectively. These causal interactions produce positive or negative feedback loops, depending on whether there are negative links inside the loops. Positive feedback loops boost the impact and cause it to increase exponentially, whereas negative feedback loops counterbalance the total effect. Positive feedback loops occur when there is an even number of negative links in the loop and vice versa.

System boundaries, feedback loops, stocks and flows, time delays, uncertainty, and stakeholder perspectives might consider for essential validation criteria, depending on the advice of the experts (Qudrat-Ullah, 2005; Qudrat-Ullah & Seong, 2010). Because of the philosophy and scope of this research, this study did not measure stock and flow diagrams in the model; instead, it illustrates the system's behavior and comprehends how the elements interact over time and how the system reacts to

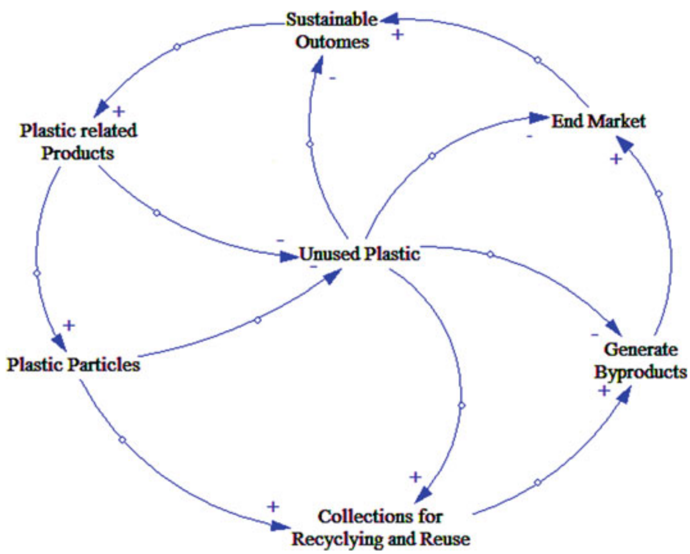

Fig. 14.1 Simple causal diagram

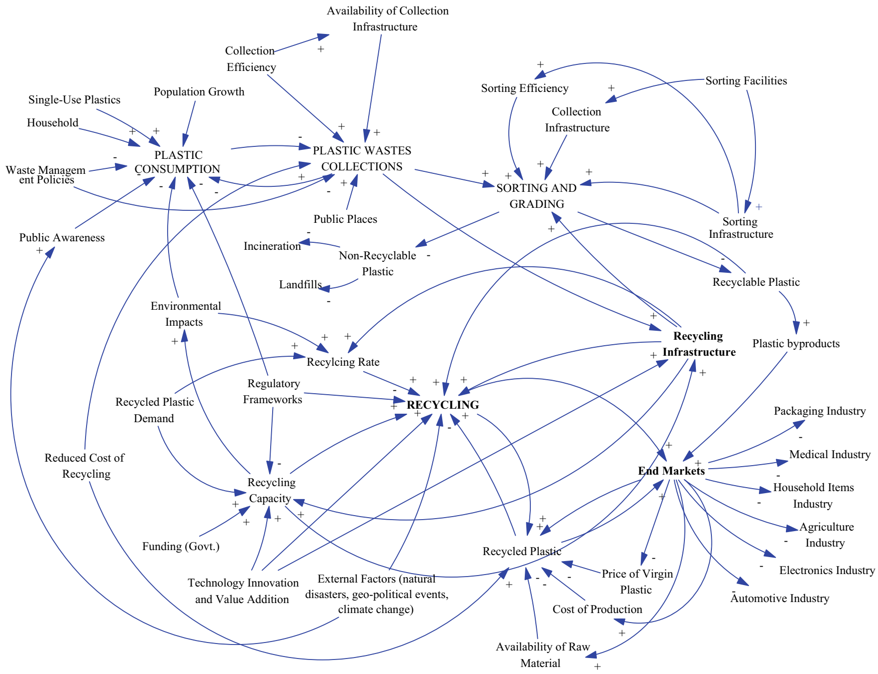

Fig. 14.2 Causal loop model of plastic waste recycling

various situations, events, and interventions. Likewise, the causal loop diagram shows the interrelationships and interactions between the components involved, such as consumption patterns, waste collection, sorting and grading, recycling infrastructure availability, demand for recycled plastic products, and end market.

And these steps were done with careful validation, paying attention to the recycling system's boundaries and the inputs and outputs that weigh in on the final market's plastic consumption. Each recycling-related action was supported by a loop that considered the opinions of various system stakeholders, including consumers, manufacturers, and waste management firms. However, this study considered relevant aspects that may be useful to include for further research utilizing the same paradigm. All subsequent documentation has been crafted with the "right behavior for the right reasons" concept introduced by Barlas (1989) as a guiding principle. Following Qudrat-Ullah and Seong (2010), the structural validity of this model is established through a thorough evaluation of the causal loop diagram, ensuring its consistency, completeness, and realism. This paper also emphasizes the importance of accurately representing the problem and identifying the causal relationships among the elements within the conceptual model. The complete model is verified by identifying recurrent patterns of causal interactions inside the system (feedback loops), such as reinforcing loops and balancing loops, and by determining cause-and-effect correlations among variables (causal linkages). With the help of suitable references, this model also ensures that the causal links appropriately depict the system's dynamics and capture the key variables and feedback loops that affect plastic recycling. By considering these variables, the structural integrity of a plastic recycling system dynamics model can be ensured, enabling accurate prediction of outcomes across different recycling scenarios and offering valuable insights for policy-making. Ultimately, incorporating these factors can serve as a safeguard to maintain the validity of the model.

14.4.2 Causal Loop Diagram, Modeling and Discussion

This research develops a causal loop model for visualizing and understanding complex systems of the plastic waste recycling system. This model overviews the interactions between various factors influencing plastic waste recycling and identifies potential leverage points for improving the system. Initially, the key variables that affected the system for plastic waste recycling were the amount of plastic waste generated depending on the plastic consumption pattern (Evode et al., 2021), the plastic waste collections (Kosior & Crescenzi, 2020), sorting and grading (Tiwari et al., 2023), and recycling with the possible linkage with the collection infrastructure, the availability of recycling infrastructure (Vollmer et al., 2020), the demand for recycled plastic products (Ackerman and Levin, 2023), and the end markets (Loy et al., 2023). The entire causal loop diagram is idealized based on similar studies of Dhanshyam and Srivastava (2021), Kala and Bolia (2022) and Giannis et al. (2017). Based on the information, this study draws a simple causal model for plastic recycling (Fig. 14.1) and extends with various associated variables (Fig. 14.2). These two model shows the feedback loops that control the system behavior to map out the relationships between these variables. The next step is to get the waste recycling process stakeholders' approval on a causal loop diagram to quantify the model using the stock and flow diagram approach. Such quantification can find sustainable effectiveness in light of economic, social and environmental benefits.

14.4.2.1 Plastic Consumption

Plastic consumption alludes to the use of plastic products irrespective to single-use plastics and product design subject to their durability and lifespan. This consumption also influences the amount of plastic waste generated by households and industries with due concern on population growth, public awareness and other sources. It is crucial to have an efficient and cost-effective system in place to collect plastic waste from various sources and sort it for recycling which in turn impacts the efficiency of this process for the overall success of plastic recycling.

14.4.2.2 Collection of Plastic Wastes

Collecting plastic waste from various sources includes households, industries, and public places. The effectiveness of this process is governed by factors such as the availability of collection infrastructure, waste management policies, and public awareness. However, the collection infrastructure involves physical structures, processes, collection centers, waste management facilities, transportation systems, and personnel required to collect plastic waste, including waste bins, waste-carrying vehicles, sorting facilities, and waste management personnel. The interrelationships between plastic waste consumption or generation items with the collection are complex and dynamic. For instance, the amount of plastic waste generated will affect the number of collection bins and collection vehicles needed. Also, the efficiency of the sorting process will determine the amount of recyclable and non-recyclable plastic waste generated.

14.4.2.3 Sorting and Grading Technology

After plastic waste is collected, it needs to be sorted and graded. Sorting involves separating different types of plastic materials based on their composition, while grading determines the quality of the plastic material. The sorting and grading process is essential for efficient recycling since different types of plastic require different recycling processes. Additionally, the quality of the plastic material affects its market value. Again, this process involves sorting and grading plastic waste into different types based on their composition, size, and color. Here, manual sorting is done by workers who separate the plastic waste into different categories based on visual inspection and manual sorting. In contrast, automated sorting is done by machines that use sensors and artificial intelligence to sort plastic waste into different categories. The recyclable plastic will be repurposed into new goods, while non-recyclable plastic waste either be incinerated or discarded in landfills. However, sorting infrastructure, a vital factor of sorting and grading, covers the physical structures, processes, and personnel required for sorting and processing collected plastic waste (Ackerman & Levin, 2023). In addition, sorting infrastructure includes conveyor belts, sorting machines, shredders, and other processing equipment. For instance, improvements in the collection and sorting technology excel in a greater quantity and quality of plastic waste, which leads to increased efficiency and effectiveness of shredding, cleaning, washing, and extrusion/molding technologies (Vollmer et al., 2020). Similarly, extrusion/molding technology advancements drive innovation and research into more efficient and effective collection and sorting methods. So, a holistic approach considering all these items is necessary to create a successful system dynamics model for plastic recycling.

14.4.2.4 Recycling

The recycling process is related to the available and adequate infrastructure, regulatory framework, recycling capacity and demand for recycled plastics. On the other hand, the recycling infrastructure is required to recycle plastic waste, such as recycling plants, equipment, and personnel, where the effectiveness of the recycling infrastructure is influenced by factors such as funding, technology, and regulatory frameworks. For instance, an increase in recycling capacity could lead to higher collection rates (Kurniawan et al., 2023), but if demand for recycled plastic does not keep up, there could be oversupply and downward pressure on prices (Rossi and Morone, 2023). On the other hand, increased demand for recycled plastic could lead to higher prices and more significant investment in recycling infrastructure, which could increase recycling capacity and collection rates (Singh et al., 2017). Again, recycling capacity is influenced by factors such as the efficiency of the recycling process, the availability of raw materials, and the demand for recycled plastic. Conversely, consumer preferences, market demand, and government policies influence the need or demand for recycled plastic products. The rise in plastic waste production resulted in a decline in the efficiency of the recycling system (Shen et al., 2020), leading to a decrease in recycling capabilities and an escalation of environmental consequences. It is feasible to pinpoint the primary causes of plastic waste production and create plans for enhancing recycling and waste management of plastic by modeling these interrelationships. The existence of end markets for recovered plastic goods is necessary for the recycling of plastic waste to be successful. End markets are the industries that purchase and use recycled plastic products.

14.4.2.5 End Markets

End markets would model the demand for recycled plastic products, such as packaging, construction materials, and consumer goods based on market size, product specifications, and pricing. It covers the different industries or sectors that consume the recycled plastic products produced by the recycling process. For example, the packaging industry is one of the most significant end markets for recycled plastic products to have a variety of packaging materials such as bags, containers, bottles, and films. The markets are multifaceted and cover wider usage, such as the construction materials used recycled materials for pipes, flooring, roofing tiles, and insulation materials; the automotive industry for dashboards, bumpers, and door panels; and the electronics industry for computer housings, mobile phone cases, and other electronic components. The other instances were available for the textile, medical, household items, and agriculture industries.

Once more, the capacity of plastic recycling, the rate of collection infrastructure, and the demand for recycled plastic products are all influenced by the end markets, which consist of manufacturers, retailers, and consumers (Nadiruzzaman et al., 2022). It also covers the price of virgin and non-recycled plastic materials in the market, influencing the demand for recycled plastic products by affecting the price competitiveness of recycled materials. Again, other items like environmental regulations and policies promote plastic waste reduction and recycling by affecting collection rates, recycling capacity, and demand for recycled plastic. Likewise, investment in recycling infrastructure and demand for recycled products are propelled by environmental regulations (Kosior & Crescenzi, 2020). However, if the regulations are excessively strict or inadequately enforced, they may also generate entry barriers and restrict capacity expansion. Ultimately, the end markets for the plastic recycling system dynamics model must consider all these interrelated items to provide a comprehensive understanding of the plastic recycling industry and inform policy decisions supporting its growth and sustainability. The recycling process efficiency is greatly improved by technological innovation (Kurniawan et al., 2023). New technologies are intended to increase the quantity of plastic that can be recycled, lower the cost of recycling, and enhance the quality of recycled plastic. All the above factors and subcategories should be considered when developing a comprehensive system dynamics model for plastic recycling. Such a model would allow future researchers to explore the interactions between these items and identify interventions that could reduce plastic waste generation and increase recycling rates.

14.4.3 Summary Causal Loop Interactions

Plastic consumption brings up the use of plastic products, and its impact on plastic waste generation depends on factors like population growth and public awareness. Efficient collection systems involving infrastructure, policies, and public participation, are crucial for successful plastic recycling. Sorting and grading technology separates plastic waste based on composition and quality, enabling appropriate recycling processes. Recycling infrastructure, capacity, and demand influence the effectiveness of recycling. End markets determine the demand for recycled plastic products, spanning industries like packaging, construction, automotive, electronics, textiles, etc. The interplay between end markets, regulations, and investment affects the recycling system. Technological innovation enhances recycling efficiency. To create a comprehensive system dynamics model for plastic recycling, relevant factors and their interactions must be considered to align with the policy decisions for sustainability and growth. Therefore, the primary cause of waste generation, including plastic waste, is primarily attributed to the significant rise in plastic consumption, specifically Plastic Particles. As the increase of Plastic Related Products grows from the advent of Sustainable Outcomes, there is an increased quantity of Plastic Particles, which reduces the Unused Plastic.

Similarly, the amount of plastic particles increases the Collection for Recycling and Reuse, ultimately leading to the generation of byproducts. Again, unused plastic reduces the Generation of Byproducts abut leads the supply into the End Market. The End Market is where the Used Plastic eventually ends up, and this End Market will help to improve Sustainable Outcomes.

14.5 Plastic Recycling Impacts, Measurement and Possibilities

14.5.1 Possible Measures Against the Negative Impact of Plastic Particles

These are only a few actions that may be performed to lessen the harm that plastic particles cause to the environment. A combination of these measures and others may be necessary to effectively address the issue of plastic pollution and its harmful effects (Table 14.2).

14.5.2 Waste Management Possibilities

The potential approach is to benefit recycling by offering financial rewards to individuals and businesses that recycle plastic waste (Kosior & Mitchell, 2020) to collect and sort their plastic waste, leading to increased recycling rates. Additionally, the government could consider implementing a plastic waste tax or levy on plastic packaging businesses, providing a financial incentive to reduce plastic waste (Loy et al., 2023). The other possibilities were:

- Separating garbage into distinct categories, such as recyclables, biological waste, toxic waste, etc., is a key component of effective waste management for separating waste at the source (Kurniawan et al., 2023).
- Recycling or turning waste materials like paper, plastics, metals, and glass into new goods helps preserve earth's resources, cuts down on garbage sent to landfills, and uses less energy (Yang et al. 2012).
- Upcycling for transforming waste materials into products of higher value by repurposing or modifying the materials to create new products to reduce waste and create new economic opportunities (Dey et al., 2021).
- Composting is a method of converting natural waste, such as food scraps and yard trash, into a nutrient-rich soil amendment that may be used in gardens and farms as well as to minimize the amount of garbage that is dumped in landfills (Sandeep et al., 2023).
- Waste-to-energy technologies convert waste into renewable energy sources like electricity or heat by incinerating, gasifying, or pyrolyzing it, decreasing the amount of trash dumped in landfills (Lee et al., 2023).
- Donating unwanted items such as clothing, furniture, and electronics reduces waste and provides resources to those in need, even by charities and non-profit organizations (Ntapanta, 2023).
- E-waste recycling for recycling electronic waste such as computers, smartphones, and televisions minimizes the number of hazardous materials sent to landfills and conserves natural resources (Palanisamy & Subburaj, 2023).

Table 14.2 Possible measures against the negative impact of plastic particles

Measure	Description	Example
Reduce (Shen et al. 2020)	Reducing plasticproducts' use prevents plastic particles' release into the environment	Encouraging the use of reusable bags as opposed to plasticbags for one-time usage
Recycle (Kosior & Mitchell, 2020)	Recyclingplastic waste reduces the amount of plastic in landfills or oceans, reducing the chances of plastic particles entering the environment	Separating plasticwaste from other wastes and recycling them through proper channels
Ban (Thomas, 2023)	Plasticparticles are kept from entering the environment by outlawing specific plastic products, such as microbeads and single-use plastics	Prohibiting the manufacturing and use of plasticmicrobeads in cosmetics
Biodegrade (Shamsuddin et al. 2017)	Promoting the use of biodegradable plasticshelps prevent the environment from becoming overrun by plastic garbage	Using biodegradable plasticbags made from cornstarch or other natural materials
Clean-up (Evode et al,. 2021)	By removing plastictrash from the environment, harmful effects on wildlife and public health and the discharge of plastic particles are lessened	Conducting beach cleanups to remove plasticwaste from shorelines and oceans
Education(Evode et al., 2021)	The discharge of plasticparticles into the environment may be stopped by educating people about the harmful effects of plastic pollution and the best ways to limit plastic waste	Providing educationand awareness programs in schools and communities about reducing plastic use and proper waste disposal
Innovation (Dey et al., 2021)	Innovative solutions that prevent the discharge of plasticparticles into the environment and minimize plastic trash might have a big impact	Developing biodegradable plasticalternatives, such as plastics made from plant-based materials or fungi

- Zero waste initiatives aim to minimize waste by advocating for sustainable practices, promoting recycling, and reducing consumption to limit the amount of waste disposed of in landfills. They also encourage adopting sustainable production and consumption practices (Ahmed et al., 2023).

Waste management is crucial for protecting the environment and conserving resources. Also, removing and reusing or recycling waste materials help lower the garbage dumped in landfills, protect natural resources, and promote sustainable consumption and production practices (Yang et al., 2012). Implementing effective waste management strategies such as segregation, recycling, upcycling, composting, waste-to-energy, donations, e-waste recycling, and zero-waste initiatives might achieve these goals and create a more sustainable future.

14.5.3 Possible Ideas to Collect Plastic and Its Substances

In order to tackle this problem, different methods are available to gather plastic waste. One method is a manual collection, which involves physically picking up plastic waste by hand (Conlon, 2023). Although this approach can be time-consuming and require a lot of physical labor, it may still be effective in regions with no other alternatives. It will be performed by volunteers, local communities, or waste management personnel efficiently by organizing regular cleanup events. For example, community groups or non-profit organizations may hold regular beach cleanups or litter pickup days in public spaces (Castaldi et al., 2021). Such incidents are typically communicated to the public via social media, local news channels, and posters. The automated collection involves using machines to collect plastic waste more efficiently and faster than manual collection and is used in areas with high levels of plastic waste (Li et al., 2023). Automated waste collections are achieved using trash compactors or garbage trucks fitted with sensors to identify and collect plastic waste (Hayat, 2023). Another innovative approach uses drones with cameras and sensors to identify and collect plastic waste in hard-to-reach areas such as oceans, rivers, or mountainous regions (Wigmore & Molotch, 2023). Using a specialized claw or vacuum, the drone can scan and collect plastic waste from a particular location.

Various innovative approaches to collecting plastic waste, such as plastic-eating bacteria, are being developed and tested (Ali et al., 2023). Scientists are working on developing bacteria that break down plastic waste into harmless substances (Ahmed, 2023). These bacteria could be used in landfills or wastewater treatment plants to help break down plastic waste. In addition, plastic-catching boats are fitted with nets and trawls that scoop up plastic waste from the ocean's surface (Spencer et al., 2023). After gathering the plastic waste, it must be transported to land for recycling or disposal. Again, plastic waste banks accept plastic waste from individuals and businesses (Prabawati et al., 2023). The waste is then sorted, cleaned, and recycled into new products. Incentives such as monetary rewards or discounts are offered to encourage people to bring their plastic waste to the bank. Also, reverse logistics (RL) theory can be used to collect and process unused and harmful plastic contents (Valenzuela et al., 2021). For instance, reverse vending machines accept plastic waste and give rewards such as discounts or vouchers in return (Ackerman & Levin, 2023). Colombia has implemented reverse logistics enables the model to find out recycling contents and use them appropriately to find economic viability (Halabi et al., 2013). This approach incentives people to recycle their plastic waste rather than dispose of it improperly. Plastic waste is a growing problem worldwide, with millions of tons of plastic ending up in landfills, oceans, and waterways yearly. However, the other mixed ways to collect plastic waste might be workable through community cleanup events through volunteers, beach cleanup machines, waste-to-energy conversion, and plastic waste collection drives.

14.5.4 Ways of Collecting Plastic Waste Using Circular Economy and Reverse Logistics

Implement a plastic waste collection program for households, businesses, and public spaces by the government, private companies, or non-profit organizations.

- Use reverse logistics to transport waste for collection, transportation, and disposal of wastes to transport plastic waste from the collection points to recycling centers.
- Sort plastic waste based on the types of plastic and its potentiality for recycling.
- Recycle plastic waste to produce new products by mechanical recycling, chemical recycling, and pyrolysis.
- Use recycled plastic to produce new products such as furniture, building materials, and consumer goods, reducing the need for virgin plastic and promoting a circular economy.
- Promote awareness of the plastic waste collection program and awareness campaigns to educate the public on the importance of recycling and reducing plastic waste through social media, billboards, and public announcements.
- Partner with stakeholders such as waste management companies, recycling companies, and local communities regarding resources and expertise.

14.5.5 Possible Initiatives for Bangladesh in Plastic Wastage Recycling

Bangladesh, one of the world's most populous nations, has been battling the issue of plastic garbage for many years. The use of single-use plastic has become a major environmental challenge in Bangladesh. Most of this plastic waste is generated in the capital city of Dhaka, where plastic consumption is the highest (The Daily Star, 2021). Nevertheless, plastic waste in Bangladesh is not appropriately managed, leading to widespread environmental pollution. Plastic waste is often dumped in landfills, rivers, and oceans, leading to significant ecological damage. In order to decrease the usage of single-use plastic and encourage recycling, the government must develop efficient rules and regulations. Implementing a fee on plastic bags might lower usage and bring in money for trash management. The public and commercial sectors must invest in infrastructure to handle plastic garbage. It would be possible to lessen the amount of plastic debris in the environment by establishing recycling plants and waste management facilities. Mass people must be aware of the harmful effects of plastic trash. The government and civil society might launch public awareness campaigns and encourage eco-friendly alternatives. The private sector must invest in research and innovation to develop eco-friendly, sustainable methods to reduce, recycle, and reuse plastic particles to save society.

14.5.6 Suggestive Ways Toward Sustainable Plastic Recycling

Generally, maintaining sustainable plastic contents recycling's decisiveness for minimizing the environmental impact of plastic waste accounted for implementing effective recycling systems, raising awareness and educating the public, improving collection and sorting infrastructure, encouraging extended producer responsibility (EPR) and fostering collaboration. More specifically, the entire recycling process is guided by concentrated efforts, for instance, labeling separate bins for different types of plastic materials in public places, workplaces, and residential areas; and conducting public awareness campaigns to inform people about the value of recycling and effective plastic waste management. The concept can potentially be expanded to encompass the identification, cleaning, and accurate sorting of recyclable plastics. It also encourages establishing dedicated recycling centers and facilities equipped with advanced sorting technologies for better separating plastic materials, making recycling more effective and efficient. With the help of this recycling system, producers should be held accountable for the complete life cycle of their goods, including disposal and recycling. Manufacturers' responsibility drives them to utilize more recyclable materials and develop more accessible recycled products. Ultimately, a joint effort and collaboration from the government bodies, businesses, non-profit organizations, and the public to promote sustainable plastic recycling along with encouraging partnerships and collaborative initiatives to tackle plastic waste management challenges, share best practices, and develop innovative solutions.

14.6 Theoretical and Managerial Implications

Recent years have seen a substantial increase in awareness of the problem of plastic trash and its environmental consequences, which has prompted the development of several mitigation solutions. System dynamic research on plastic content recycling and sustainability offers several theoretical and administrative implications in this context. Due to its contribution, the system dynamics approach used in this study helps identify the critical variables influencing the sustainability of plastic recycling and the understanding of the intricate relationships and feedback loops among various variables, both of which can be used to create efficient environmental policies and strategies. However, this study stimulated the behavior of multidimensional factors like consumption, collections, sorting, and grading under various scenarios with a view to a dynamic understanding of the system and its behavior over time, which may be useful for suitable outcomes of various policy interventions.

The suggestions for raising plastic recycling rates, decreasing plastic waste, or encouraging the use of sustainable alternatives to conventional plastics, as well as the advice for policymakers and industry leaders, will be effective with the proper considerations. The development of more efficient and sustainable methods for managing plastic trash will be considerably aided by this review on plastic content recycling and sustainability utilizing a System Dynamic approach. Regarding the contribution, the thorough analysis of the existing literature on sustainability and plastic recycling and identifying the major difficulties and opportunities in these fields provide clear perspectives on plastic recycling and a comprehensive analysis of these processes' social, economic, and environmental effects. In the context of plastic recycling and sustainability, it might be difficult to fully represent the complexity of the system, which can result in inaccurate predictions from the model. There could occasionally be some unique aspects that are not considered that could impact the system dynamics of this plastic recycling process as a whole. Additionally, this causal loop model could not capture the entire range of uncertainties that might affect the system due to assumptions and constraints of the studied literature, which could result in incomplete or inaccurate conclusions. The potential of emerging technologies like bioplastics or chemical recycling might be a considerable issue for future research and the effects of shifting consumer behavior on plastic recycling and sustainability.

14.7 Conclusion

Due to the considerable environmental damage done by plastic contents, the research on recycling has attracted increased attention in recent years. The study develops a causal loop model to understand the complicated plastic waste recycling system better. Plastic consumption, garbage collection, sorting and grading, recycling infrastructure, demand for recycled plastic products, and end markets are key elements for influencing the recycling system. The relevant factors were thoroughly examined through existing literature to comprehend their interdependence and how changes in one variable can affect the performance of others. The study emphasizes the importance of government regulations, stakeholder participation, and market demand for recycled plastic in plastic recycling systems. Policies and laws stimulating plastic consumption reduction, promoting trash segregation at the source, and supporting recycling infrastructure development are crucial to ensuring the system's efficacy. Stakeholder participation is also essential for raising awareness and encouraging behavior change, whereas market demand might impact recycling costs and system feasibility. The study also highlights the relevance of sorting and grading equipment in classifying plastic waste for recycling efficiently and cost-effectively. Sorting and grading technology can potentially increase the quality and quantity of plastic trash accessible for recycling, which is critical for meeting the demand for recovered plastic products. In the future, this study needs to convert the stock and flow diagram model to prove the model outcomes for sustainable plastic recycling quantifiably. Thus, this study provides unique insights to policymakers, industry stakeholders, and researchers interested in supporting sustainable solutions for plastic waste management.

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Chapter 15
The Potential Impact of ESG Spending on Public Perception of the Canadian Oil Sands

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Abstract The "Oil Sands in Alberta", Canada, are facing transformational change due to national and global pressure for greenhouse gas abatement. For Oil Sands ("the industry") to survive, it must achieve a 'new normal', where the business of supplying energy is conducted within a framework of increased regulation of its environmental, social, and regulatory governance (ESG) framework. For the 'new normal', post-transition state to become a stable basis for business operations, the perception of the industry must be neutral at a minimum and ideally positive. The quantitative metrics of perception reflect the many complex dimensions of ESG: the current levels of CO_2 emissions, performance toward Net Zero, and regulatory compliance. Since the approach that a single perception metric is not possible, we propose four metrics that collectively have the greatest influence on Oil Sand's industry decisions regarding ESG investments and spending—First Nations, the Environmental Lobby, Investors, and the General Public. The factors driving each perception metric are both exogenous and endogenous and linked, creating behaviours amenable for study using system dynamics. This study comprehends the potential of reinvesting profits from Oils Sands into Environmental, Social, and Governance (ESG) to improve its public

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perception with the effort to lead to net-zero emissions and the industry's survival. First, a System Dynamics (SD) model to portray oil production using mining and in-situ drilling features is built. Next, the calibrated model analyzes the emissions produced in the process, the use of land and water, and the impact on wildlife and fish in the surrounding area. Finally, these effects are simulated for the well-being of First Nations people in Northern Alberta by showcasing the potential of investment in emissions abatement technology and through social services and infrastructure to determine if this investment might influence environmentalists' and First Nations' perceptions. As a result, for economic aspects, the model reveals past/future prices and profits of the Oil Sands. In addition, the model examines collected royalties and taxes that can support government programs by the province or the country and the jobs created and the workers' productivity. The major findings evaluate perception as a complex and synergistic combination of values we describe as well-being: "economic well-being, social well-being, and environmental well-being", as well as specific sub-values related to emissions, wildlife, fish, land, and water. Of particular importance is the impact of public perception on investor perceptions. Investors are central to the well-being of the industry. To our understanding, this is the first validated SD model of the Oil Sand industry visualizing perceptions. The current model excludes the influence of "supply and demand" relationships on the future potential of the Oil Sands industry. Determining other controllable influencers, such as Albertan and Canadian government policies, must also be considered in future work. The SD model could inform the practical ESG policy approaches for adoption by the policymakers, practitioners, and researchers on the achievement of Oil Sands in Canada, thereby convincing First Nation people and the country at large. It can also be adapted for countries where Oil Sands are investigated. The study recommends that the industry make a concerted effort to reach "net-zero emissions by 2050" to reverse declining perception of the industry by many of its stakeholders. Thus, this quantitative model of stakeholder perceptions fills a crucial methodological gap in studying Oil Sands.

Keywords Oil sands · Public perception · System dynamics (SD) model · Environmental social and governance (ESG) · First nations · Northern Alberta · Environmental standards · Conventional oil · Canada · Stakeholders · Fossil fuel reserves · Surface mining · GHG emissions

15.1 Introduction

Oil Sands (OS) consist of oil, sand, water and clay (Oil Sands, n.d.), with the defining characteristic being that the oil is in an extremely viscous form called bitumen. Bitumen deposits are considered unconventional crude oil, contrasting with lower viscosity deposits known as conventional crude oil. Alberta's OS constitutes the third largest oil reserves globally (after Venezuela and Saudi Arabia), at about 160 billion barrels of proven reserves (Oil Sands, n.d.; Falebita & Koul, 2015; Statista, 2022)

(Table 15.1). It is strategically important to Canada as it provides significant employment, and oil exports significantly contribute to Canada's trade balance (Statista, 2022). Geographically spread (see Fig. 15.1), the positive features of Canada's OS are that the country is politically stable, has very high environmental standards and, unlike conventional oil, this resource has no geological risk (there is no uncertainty about the reserve's presence and exploitability); thus making Canada a reliable supplier.

However, the OS industry faces significant challenges addressed in this chapter. First, this capital-intensive industry requires stable revenues to acquire capital funding. Second, the oil recovery processes are energy intensive, producing relatively high greenhouse gas emissions. Third, significant national and international public opinion advocates for the OS industry's closure (Leahy, 2019; Virla et al., 2021).

Like the oil industry, environmental factors generate opposition to the OS from many activists and Environmental, Social, and Governance (ESG) conscious investors (Palacios, 2021; Poveda, 2015; Poveda & Lipsett, 2013). The relatively remote location from major refining centres requires pipelines for shipping; however, various opposition sources have slowed pipeline development (Janzwood, 2020). Alternatives, like shipping by rail, are costly. A further complicating factor is the very high viscosity of bitumen, necessitating further upgrading or dilution to make it suitable for shipping.

This research explores the complicated balancing act between investing in environmental mitigation and providing a return to capital providers. In this chapter, we look at the viability of the OS industry from the perspective of the impact of ESG investment starting from a System Dynamics model from a previous OS study (Falebita et al., 2022). System Dynamics was chosen as a modelling approach because it can be used to study the behaviour over time of a complex system showing the historical trends and making projections based on the system's structure into the near-term future with confidence (Forrester, 1961; Forrester & Senge, 1980; Coyle, 1996; Martinez-Moyano & Richardson, 2013).

Table 15.1 Global oil reserves in selected countries 1990–2020

(In billion barrels)

Country	1990	2000	2010	2020
Venezuela	60.1	76.8	296.5	303.8
Saudi Arabia	260.3	262.8	264.5	297.5
Canada	181.5	181.5	175.2	168.1
Iran	92.8	99.5	151.2	157.8
Iraq	100.0	112.5	115.0	145.0
Russia		69.0	89.7	107.8

Source Statista (2022)

Fig. 15.1 Map of Canadian Oil Sands region (*Source* Image by Norman Einstein, 2006)

The public perception of the "economic and environmental impacts of the OS" is of particular importance. We divide the public into the general public and three influential lobby groups (Investors, Environmentalists, and First Nations). We assume the federal and provincial governments' perception of the OS are reflected in the guidelines for oil production projections provided in (Vaillancourt et al., 2014; Canada Energy Regulator, 2021a, 2021b). Finally, we examine the impact of Environmental, Social, and Governance (ESG) investments on these four parts of the public perception. We believe that improving the public perception of the industry will positively impact its long-term viability.

Section 15.2 provides a literature review on the OS industry, ESG investments, and previous SD-based examinations of the energy industries. We demonstrate that this study fills a necessary gap in the extant literature. Section 15.3 describes the SD model we used to examine oil production, the OS's environmental, social, and economic impacts, and how the tradeoffs between re-investment of retained earnings into the core business or ESG factors affect public perception. We call this re-investment approach the Strategic Focus of the industry. In Sect. 15.4, we discuss the application of the SD model. In particular, we demonstrate how the model was calibrated and validated, describe the input parameters we use in the model, and show graphical results. Section 15.5 presents the implications of the model results and how the model can be used to develop policies to improve the industry's long-term viability. Finally, Sect. 15.6 concludes with recommendations concerning how this approach can provide practical insights for better decision-making.

15.2 Literature Review

15.2.1 Oil Sands

Oil Sands are fossil fuels that significantly contribute to global energy resources. Additionally, they are responsible for significant contributions to greenhouse gases (GHG) given the high energy required for production. The Canadian OS are predominant among Canada's fossil fuel reserves, accounting for roughly 81% of Canadian crude oil production. Canadian OS production is currently forecast to peak between 2032 (Evolving Policies) and 2038 (Current Policies) before a decline is witnessed (Canada Energy Regulator, 2021a, 2021b).

In 2019, Canadian production represented about 5% of global production according to the Canada Energy Regulator (2021a, 2021b). OS could be extracted by surface mining to depths of 75 m and below or via in-situ (drilling) techniques for depths greater than 75 m. However, such in-situ methods are energy intensive to lower the bitumen viscosity, resulting in large GHG emissions (Ashrafi et al., 2021). Notably, about 80% of oil sand reserves in Alberta occur at depths greater than 75 m (Bergero et al., 2022; Falebita et al., 2022). The study of Ashrafi et al. (2021) identifies and details innovative decarbonization technologies available for in-situ extraction that could significantly cut GHG emissions by 8% and reduce energy requirements. Further, while examining different technology deployment scenarios for decarbonization, Bergero et al. (2022) emphasize the place of low-carbon extraction technologies in Canadian OS development.

15.2.2 Environmental, Social and Governance

Environmental, Social and Governance (ESG) was introduced about twenty years ago and has evolved into a yardstick for social responsibility preferred by managers across the globe (Fig. 15.2). Unfortunately, it also represents one of the biggest controversies in finance (Brown, 2023).

ESG started as an approach for rating companies based on their ability to respond to environmental, social and corporate governance risks, which led to its name.

Fig. 15.2 Structure of the ESG. *Source* Brown (2023)

Nevertheless, there are controversies and criticisms of ESG. Such as the proprietary nature of the ESG methodologies used by companies, making it difficult to evaluate, and the fact that ESG investments are limited in addressing major social and environmental challenges. The global effects of climate change due to increases in GHG emissions have heightened the interests and resolve of stakeholders in the energy industry to continue to clamor for increased corporate social responsibility, particularly ESG reporting among energy companies (Blair, 2021). The Alberta OS is responsible for approximately 9.3% of the total GHG emissions of Canada. Also, as per (Virla et al., 2021) the OS is notable to be "as one of the most carbon-intensive types of crude oil production". They envision three stakeholder perspectives as risks for sustainability in the Canadian energy transition. Also, they propose integrative local narrative strategies as fundamental for attaining climate targets.

Furthermore, the perspective of Bergero et al. (2022) lends credence to increased ESG investments as a strategy for developing decarbonization technologies. In another study by EU researchers of "risk blindness," the idea is that local (Alberta) stakeholders are ignoring science and resisting international climate policies by supporting ongoing Oil Sands production. It is also important to note that such studies do not align with other international research, such as by the International Energy Association (n.d.), stating that oil is required for the energy transition for the foreseeable future (Virla et al., 2021).

15.2.3 Public Perception

Several studies and hands-on experience with risk show the significance of risk perceptions for people's behaviour. For example, Williams et al. (2015) constructed various social networks on climate change where users communicated through the "microblogging platform Twitter." Authors classified 'user attitudes' to climate change grounded on message content and observed public perception to strongly influence actions to deal with the complex issue of climate change. However, the public engagement inferences differed on this vital global challenge. In another study, Siegrist and Árvai (2020) studied the factors that shape people's risk perceptions over forty years. They propose grouping risk perceptions according to "the characteristics of hazards, attributes of risk perceivers, and application of heuristics to inform risk judgments". Several topical studies undertaken to understand public perception inter-related to the domain of study are as follows:

- Carbon capture utilization and its storage (CCUS), bridges technology to sustainable energy production. However, its deployment depends on technological development and social fabric (public perception). As such, Selma et al. (2014) analyzed public perception in understanding factors important for CCUS approval as a project, as opposed to the satisfactoriness of CCUS at the societal level.
- Clarke et al. (2016) studied public opinion through a telephonic survey investigating how geographic proximity interrelates with political ideology to impact issue support. They addressed the "**public perception** of unconventional oil and natural gas development via hydraulic fracturing" in this context. Their findings revealed, "that as respondents' geographic distance from areas experiencing significant development increases, political ideology becomes more strongly associated with issue support." In addition, as this divide widens (supporting construal level theory), people refer to multiple consequences, including "political ideology."
- Garreaud et al. (2017) attempted to identify the complex vegetation changes of the central Chile megadrought (MD) vis-à-vis its historical records. Some attributes included precipitation deficit, groundwater levels, vegetation productivity, irrigated croplands, forest plantations, and government measures to reduce the effect of the drought. The public perception—mainly the knowledge of the MD disposition and "the biophysical influences" guided the preparedness to handle the future climate scenario.
- The carbon pricing captured from numerous empirical studies, Maestre-Andrés et al. (2019) relate public perceptions with the acceptability of the policy instrument and recognize "carbon pricing instruments as 'fair' to increase policy acceptability". Also, with a preference to use revenues for 'environmental projects' rather than warrant fairer policy outcomes, the authors recommend combining revenue redistribution to "support vulnerable groups and environmental projects like renewable energy to increase policy acceptability."
- Wang and Lo (2021), in their review surrounding the incumbent fossil fuel energy paradigm, classify public perception as one of the just transition themes along

with labour orientation, a framework for "justice, a socio-technical transition, and a governance strategy". Also, this 'just-transition' theme could benefit from expanding the geographical reach and attending to the power dynamics.

15.2.4 System Dynamics

System Dynamics is often used to examine complex systems where their many parts work together to achieve a specific goal (Coyle, 1996; Forrester, 1961). One of the unique aspects of the System Dynamics approach is the focus on systems that change over time. It is based on cause-and-effect relationships modelled using concepts from calculus and physics, particularly highly interconnected systems of first-order differential equations solved using numerical methods. This interconnectedness is used to demonstrate the importance of a feedback perspective. For example, the connections between the parts of the system are identified as reinforcing or balancing feedback loops. This approach leads to highly non-linear behaviour over time. A well-calibrated System Dynamics model can replicate historical patterns and project future behaviour in the long term if the system's structure does not change (Barlas, 1996). Simulation experiments can then be carried out to examine the impact of system changes that might result from various policies. System Dynamics is a top-down modelling approach in which the modeller is an omniscient observer.

There have not been too many academic publications that have constructed calibrated SD Models for the Oil Sands domain. For example, an SD Model (Elshorbagy et al., 2007) built a simulation environment that accurately simulates the various hydrological processes using STELLA Software through visual computations to assess "short- and long-term" performances for the mining industry in Canada. In addition, Keshta and Elshorbagy (2011) developed a calibrated SD watershed model to evaluate the hydrological performance and design for "reconstructed soil covers". They used a meteorological dataset (1979–2006). Also, the validated SD model of soil water simulates the forest dynamics for multiple soil profiles. The simulated results provided an effective remedy to increase reclamation and forest productivity (Huang et al., 2013).

The current model is the first validated SD model established for the Oil Sand industry visualizing perceptions. The current model excludes the influence of "supply and demand" relationships about the future potential of the Oil Sands industry. Determining other controllable influencers, such as Albertan and Canadian government policies, must also be considered in future work. The SD model could inform policy approaches for adoption by the policymakers, practitioners, and researchers on the achievement of Oil Sands in Canada, thereby convincing First Nation people and the country at large. Thus, this quantitative model of stakeholder perceptions shall be able to fill a crucial methodological gap in studying Oil Sands.

15.3 Methodology

15.3.1 Model Description

The large SD model is split into a collection of sub-models for convenience. Each sub-model represents a component of the overall research question being studied, which we have defined as "What is the impact of ESG spending on the public perception of the Canadian Oil Sands?". The simulation settings of the model are set to cover the period 2012 to 2050. Also, the terminology with units and initial values is in Appendix.

Since the model is focused on a single research question, it does not purport to be a model of the entire OS industry. In our case, we have selected only those elements of the industry at an appropriate level of detail to address the research question. These elements, grouped into sub-models, are described below.

(a) The ***Oil Production sub-model*** consists of three model views—Oil Production (Fig. 15.3), Productivity, and Workforce. Oil production is the logical start to describe this System Dynamics model. There are two methods of extracting bitumen from the OS: mining and in-situ (described as drilling). Both of these methods are highly capital-intensive. As OS production is very complex, for this sub-model, we consider an abstract and highly aggregated approach based on workforce size and workforce productivity, which are combined to match the mining and in-situ oil production with the 2012 to 2050 OS production forecasts from the Canada Energy Regulator (2021a, 2021b).

Also, OS production is classified according to royalty rate type as being either a Gross Royalty project or a Net Royalty project according to the project costs

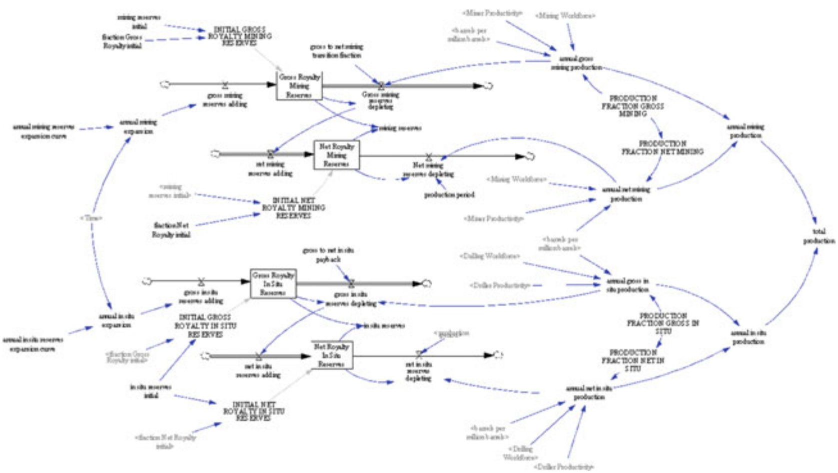

Fig. 15.3 The oil production sub-model

incurred in bringing that production online. A lower gross royalty rate is applied to gross revenues until those revenues exceed an agreed payout threshold, with the payout threshold based on allowable project costs. After reaching the payout threshold, a higher net royalty rate is applied to net revenues. As the royalty type and duration depend on several factors specific to each project, a highly aggregated set of equations is used to determine the production volumes for each royalty type. These four variables—annual gross mining production, annual gross in-situ production, annual net mining production, and annual net in-situ production, are then input to the *Economics sub-model* for the calculation of gross and net revenue.

(b) The ***Economics Benefits sub-model*** is contained in the Economics model view (Fig. 15.4). The cash flow model is a simple comparison of the amount of price per barrel of oil compared to the break-even price for mining and in-situ production. Historical trends in the price of a barrel of oil are used for 2005 to 2022, and the future price of oil is assumed to be the 2022 value. The break-even price is the price which will compensate for the costs of oil production. When the price of oil is above the break-even point, the oil producers will make a profit; when it is below the break-even point, they will suffer a loss. However, we assume all the oil produced will be sold at the current price. Price and break-even price are then used with gross and net production volumes to determine a single value for the industry's gross revenue and net revenue per year, applying deductions and rate calculations as appropriate to determine each.

Economic benefits combine royalties paid to the province and federal government from the production process and various taxes paid by industry (Alberta Oil Sands Royalties, n.d.). In particular, we examine corporate taxes, carbon taxes, and income taxes from the workforce. We measure an abstract concept of the changes in economic "well-being" as the ratio of the economic benefits in the current year compared to the economic benefits obtained in 2012. This economic well-being will influence the perception of the industry by the general public and investors. We will use this concept of "well-being" throughout the model to measure the progress made in the ESG factors over time.

(c) The ***Strategic Focus sub-model*** exhibits the OS industry transitioning from a traditional focus on production cost to one incorporating ESG imperatives. The most prominent ESG imperative is carbon emissions reduction. Still, there are many others: land and water contamination, fish and wildlife contamination, social infrastructure, and First Nations concerns are also included. Some of these imperatives, such as carbon emissions abatement, are regulatory and therefore have mandatory compliance. The cost of meeting regulatory imperatives can be measured directly. Other imperatives are societal and are measured in terms of stakeholder perceptions of the OS industry. While stakeholder perceptions do not have the force of law, these stakeholders significantly influence government policy, which can enact more stringent regulations. This causal link gives stakeholder perceptions a near-regulatory influence on the OS industry strategic focus. The cost of meeting social imperatives is indirect and measured in terms of improving perceptions.

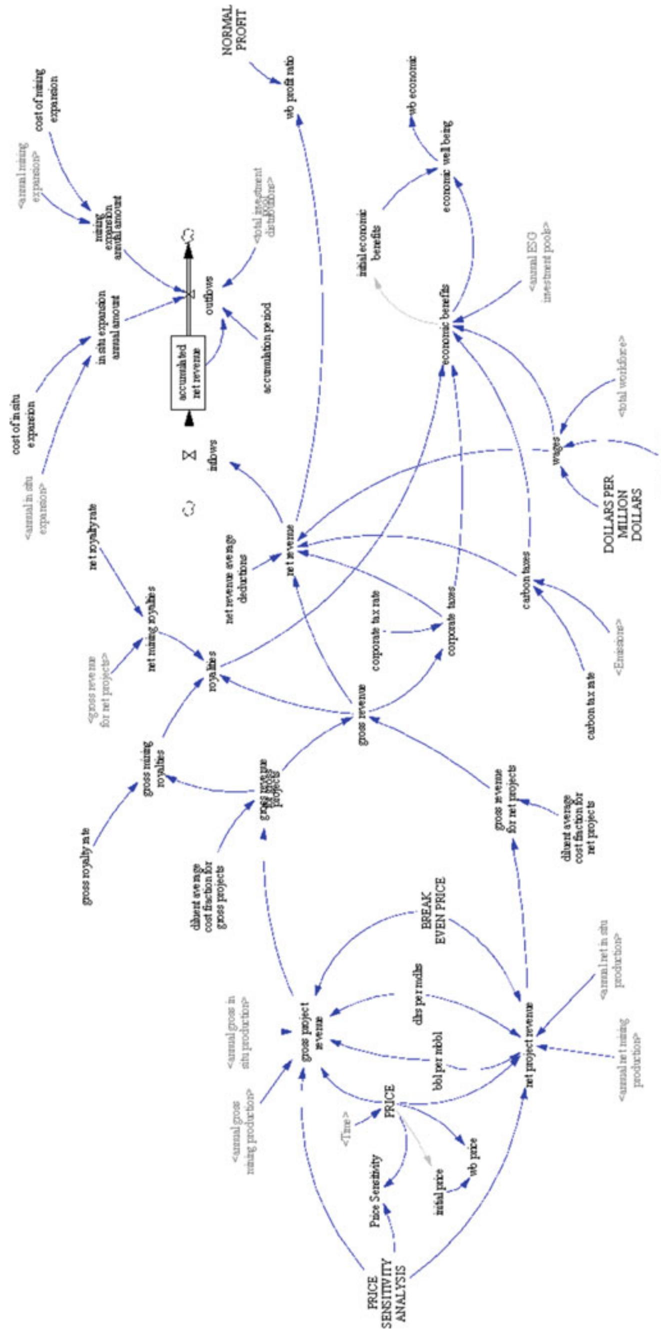

Fig. 15.4 The economic benefits sub-model

Regardless of the perception category—regulatory or social—the money to fund ESG investment must come from OS operational revenues. Demand uncertainty makes long-term operating revenue forecasts unreliable, greatly complicating long-term strategy development (Canada Energy Regulator, 2021a, 2021b). Hansen et al. (2021) show that relative to 2020 production figures, combined in-situ and mining production forecasts to 2040 could either grow by 75% in the reference case or fall by 25% in the low oil price scenario. Such a wide variation in production forecasts, and therefore revenue forecasts, would typically suggest a conservative business strategy with a traditional cost focus for investments. Also, an inward, production cost–focused investment strategy would reduce ESG spending and thereby severely limit the industry's ability to address ESG imperatives. Recalling the causal link described above (see Fig. 15.5), reduced ESG investment also risks operational revenues because of more stringent and costly regulations. Thus, it is clear that a balanced investment strategy is required.

By constructing a system dynamics model that links the two investment requirements, we can analyze the investment impacts and identify scenarios that balance corporate stability and ESG imperatives. While the model can simulate a wide range of scenarios, we have chosen three: (a) Low ESG investment with full corporate/operational focus, (b) High ESG focus that maximizes ESG spending from available investment funds, and (c) Balanced ESG focus, which is the hybrid scenario that balances both. While Low ESG is essentially a classic low-cost producer scenario, the High ESG is a differentiated price scenario where high levels of ESG spending support charging a high price premium, and the Balanced ESG attempts to balance the lowest production cost with a medium price premium. Thus, the emerging strategy for the OS industry is a balancing act between attaining ESG leadership status and maintaining industry profitability at sustainable levels. For this study, we refer to this allocation process as Strategic Focus, where allocation is split between two investment pools—Core Business Investment Pool (core pool) and ESG Investment Pool (ESG pool).

In the ***Strategic Focus sub-model***, the core pool assigns funds to two capital expenditure pools—operations projects and expansion projects. The model does not identify particular projects. Similarly, the Strategic Focus sub-model allocates ESG pool funds, in this case, to three sub-pools—Social Benefits, Environmental Benefits (which include emission abatement), and energy transition. The *Social Benefits and Environmental Benefits sub-models* further allocate the funds to initiatives within those categories; energy transition funds are added to the expansion projects funds and applied in the *Oil Production sub-model*.

Much of the industry's ESG leadership focus is on CO_2 abatement. OS abatement investments are coordinated by an industry joint venture partnership, the Pathways Alliance (n.d.), and are focused mainly on a joint-use CCUS infrastructure. While abatement is an important core business investment focus, we have included it in the ESG investment pool for this study. As such, the

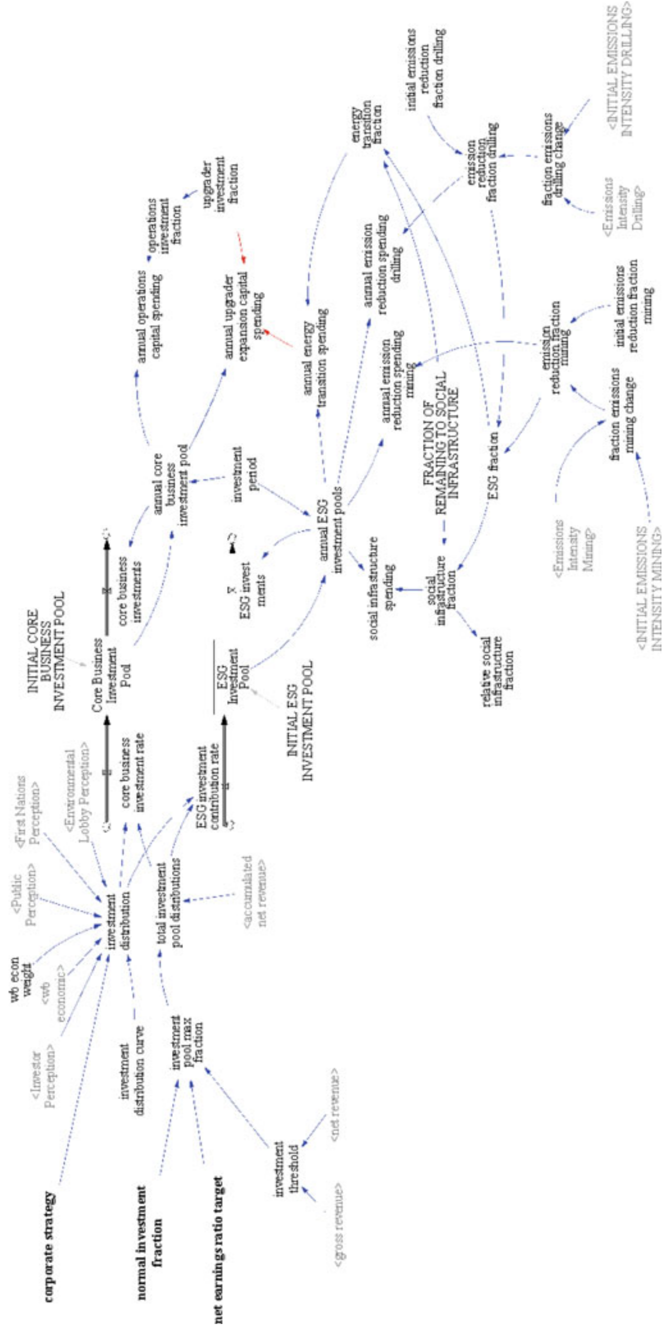

Fig. 15.5 The strategic focus sub-model

core business investment pool, which consists of all other capital and operations improvements, does not include CCUS or additional emission abatement capital.

(d) In the ***Social Benefits sub-models*** (Fig. 15.6), we focus on the social benefits and costs to the First Nations people affected by the OS industry. There are three primary aspects of social impacts from the Oil Industry: the ability of the First Nations people to satisfy their traditional lifestyle while benefiting from modern conveniences such as modern infrastructure and social services. Social well-being will influence the perception of the oil industry by the First Nations, the general public, and investors. We recognize that First Nations' perception significantly affects the industry's viability.

(e) The ***Environmental Benefits sub-models*** (Fig. 15.7) calculate OS production impacts on five aspects of the environment: land, water, wildlife, fish, and emissions. The well-being indicators from this sub-model become inputs to the Perceptions sub-model. For example, land availability is based on estimates of the land used for mining and in-situ extraction. Also, we model land reclamation when portions are no longer mined or drilled on. Although operations use a significant amount of water, almost 80% is recycled, so net new water use never exceeds the allowable limit. Since it doesn't exceed the limit, there is no impact on fish life expectancy, but accumulated fish and the related well-being—fish (wb-fish) variable decline linearly. This might be true due to birth, deaths, and fishing flows, but OS operations are not causing the decline in wb-fish. The same is true for land—no OS impact from land on wildlife expectancy, but wildlife is declining.

Water compares actual water use for mining and in-situ production operations, deducts the recycled water use, and compares the net benefit of makeup water to the allowable Surface Water Quality Management Framework limits established by Alberta Energy Regulator (2022). If net usage exceeds the permissible limit, OS operation's impact on fish life expectancy is calculated as the fraction of the allowable limit that exceeds the normal fish expected life.

The wildlife model examines the impact of land availability on the population. The effect of land availability and wildlife population on First Nations hunting is significant. Wildlife well-being influences the First Nations' perception of the OS industry. The model that examines fish illustrates the effect of water use on the fish population. And similar to wildlife, fishing by First Nations people will be impacted, affecting the First Nations' perception of the oil industry.

As megatonnes/year, emissions are calculated separately for mining and in-situ operations based on production volumes, industry values for emissions intensity, and the annual emission abatement spending for each product type. The emissions rates for each product type are aggregated into a single yearly emissions rate for the industry; this value is a key input to the Perceptions sub-model. The Emissions are particularly important to the perception of the industry by environmentalists, First Nations, and the public. We expect that environmentalists may never have a favourable view of the OS; however, if the OS can reach

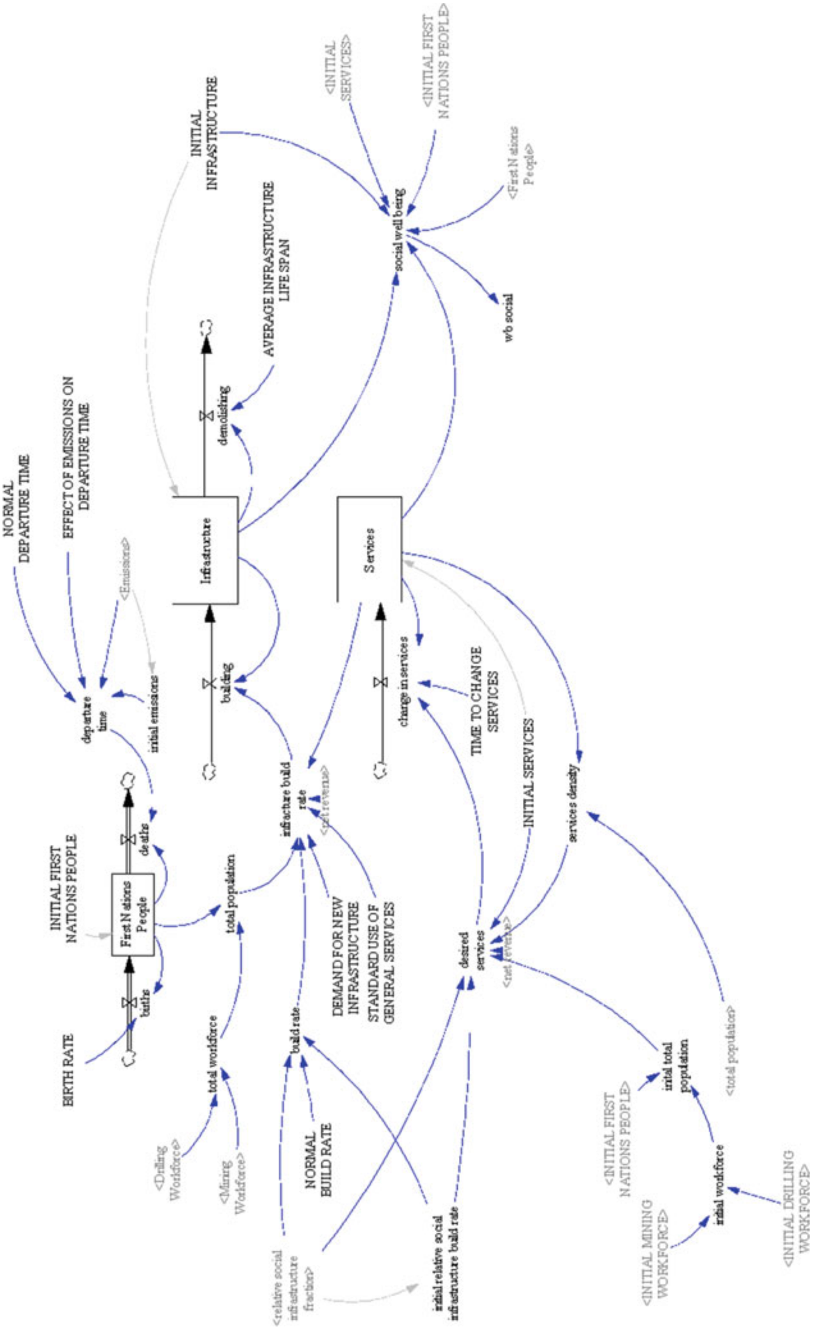

Fig. 15.6 The social benefits sub-model

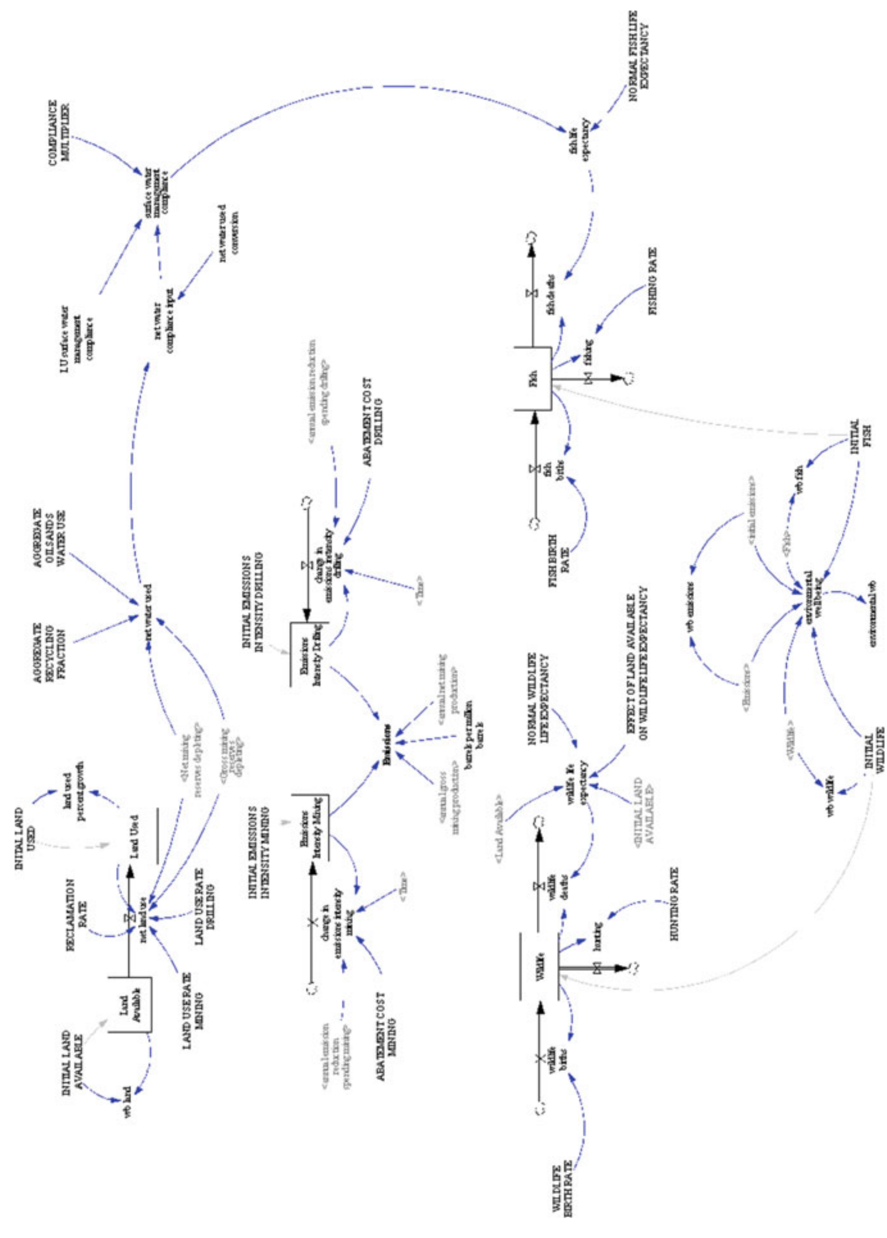

Fig. 15.7 The environmental sub-model

net-zero emissions with abatement technology by 2050, the environmentalists' perception may improve from where it is at present. First Nations and public perceptions are modelled as being more flexible and improving as abatement investments show strong emissions reductions.

(f) The ***Perception Model:*** Changing perception can be slow and difficult. We modelled four highly interrelated public perception aspects: the general public and three influential lobby groups: environmentalists, First Nations, and investors (see Fig. 15.8). We modelled the synergies between these four groups where improved perception by one group will positively influence the perception of the other groups.

General public perception is influenced by oil prices and economic well-being created by the industry and the emissions produced by the industry. The type and magnitude of social benefits to the First Nations people influences general public perception. Complex synergies are associated with the perception of the OS by environmentalists and investors. The perception of the environmental lobby is assumed to be influenced by the changing emissions levels and the well-being of fish and wildlife but independent of the perceptions of the other groups. The OS industry's investments in their social well-being influence the First Nations' perception. Still, their primary focus is the impact on the culture and way of life, particularly the well-being of the land, wildlife, and fish. The perception is also independent of the other groups. The economic well-being and the synergies with the other groups influence the investors' perception.

A delayed reaction is modelled to capture the difficulty of changing perceptions over time. The delay is assumed to be the longest for the environmental lobby, suggesting that the perception of the environmental lobby is the hardest to change. The wait for First Nations is less than the environmental lobby offering the First Nations are more open to changing their perception. The delay in the general public is even less, meaning the general public may be easier to influence. Finally, the delay in investor perception is relatively short, suggesting investors react quickly to changes in the industry.

15.4 Model Validation

Forrester and Senge (1980) state that it is impossible to validate a System Dynamics model completely and provide a list of tests designed to build confidence in a model. Also, Barlas (1996) provides similar tests to validate a model. Keeping in view that a System Dynamics model cannot be completely validated (as per Forrester & Senge, 1980), this model described in Sect. 15.3.1 (Figs. 15.3, 15.4, 15.5, 15.6, 15.7 and 15.8) was built with the aid of peer-reviewed articles, regulator data, and experts familiar with the Oil Sands industry, and their expertise was helpful for the structural testing of the model. Data for Oil Sands royalties was retrieved from the Alberta Oil Sands Royalty Data (n.d.) webpage at the Alberta Government Open Data website, with aggregate data validated at the in-situ and mining level.

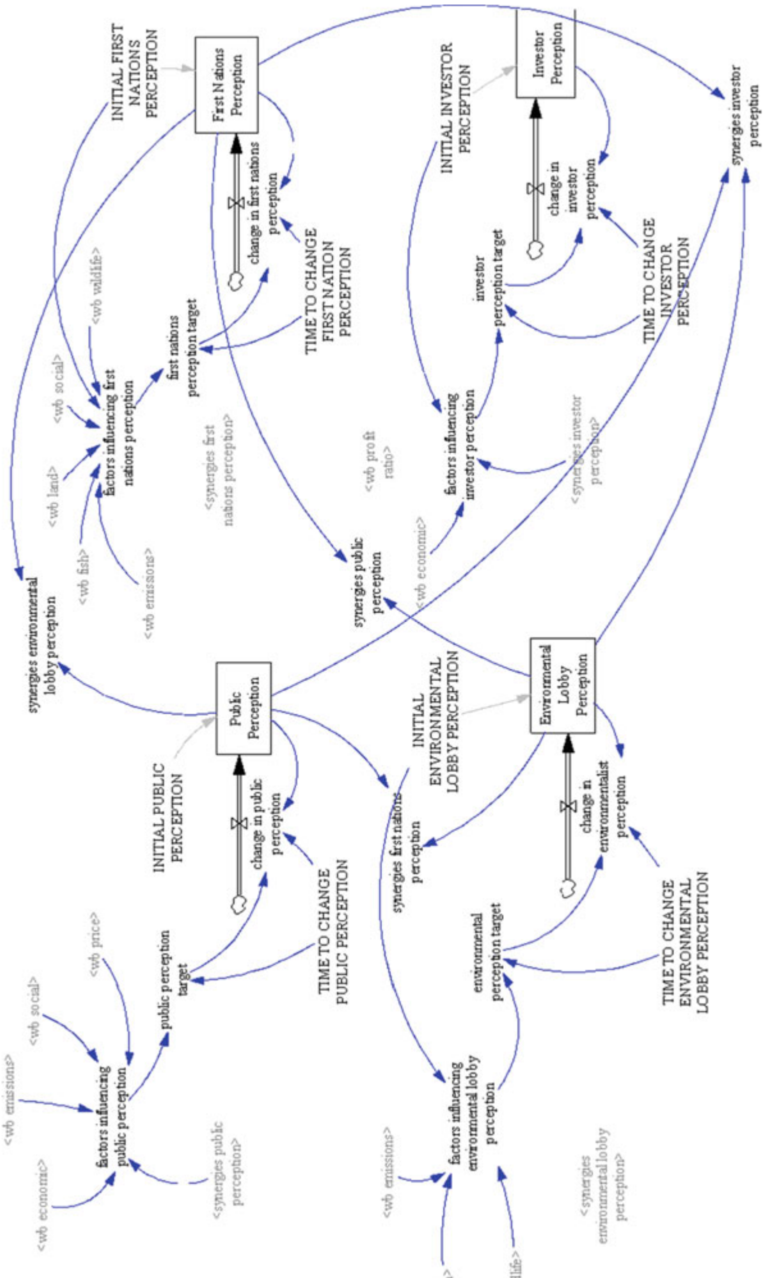

Fig. 15.8 The complex nature of public perception

Furthermore, we conducted a behavioural pattern validation of the oil sand production portion of the model. We used the historical data and projected values for mining and in-situ oil production provided by Canada Energy Regulator (2021a, 2021b). Lastly, historical data and the model results were matched by varying the workforce and productivity values for mining and in-situ oil production, and the results are in Figs. 15.9 and 15.10.

We also linked our model to the best available historical data on oil prices. We used the most recent oil price for projections without preconceived assumptions about future oil prices. Many sub-models represent future policy options for the Oil Sands industry leadership to consider. We can only validate these sub-models if we examine the assumptions built into them, which were carried out under structural testing.

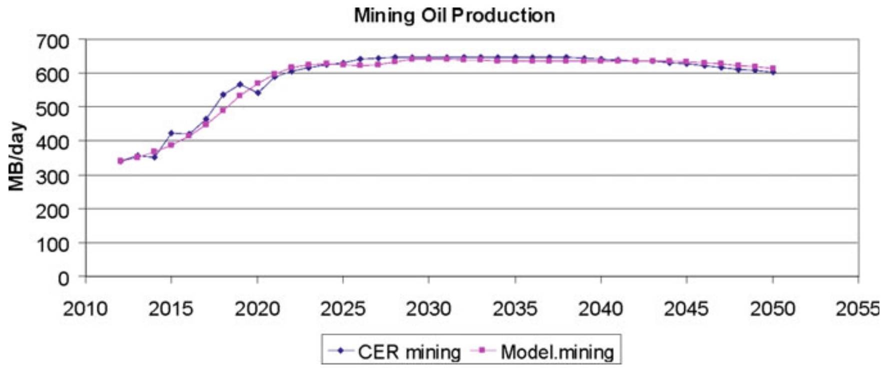

Fig. 15.9 Historical and projected values for mining

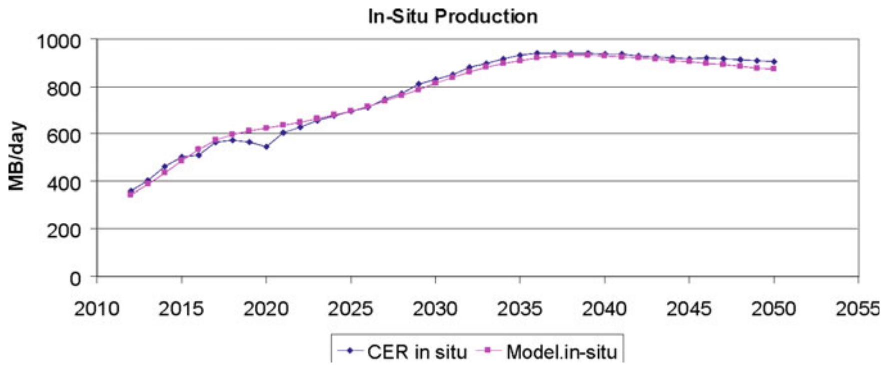

Fig. 15.10 Historical and projected in-situ oil production

15.5 Results

We examined three settings for the Strategic Focus: low ESG spending, balanced ESG spending, and high ESG spending. Low ESG spending implies that most of the industry's profits are reinvested in their core business. Figures 15.11 and 15.12 show the relative investment in the core business and ESG for the three strategic focus options. We can see that the core business investment pool is projected to increase continuously, whereas the ESG investment pool is projected to decline. This reflects the relative progress of the OS industry in achieving its carbon reduction and social and environmental well-being targets, which in turn is reflected in the overall perception measures. The base case for ESG spending shows steady progress toward those targets, especially achieving "net-zero emissions by 2050". This leads to upward trends in three of the four perception indicators after 2030, environmental lobby perception being the exception. With improved perception indicators, the investment balance shifts back toward corporate investment. This is necessary since long-term crude oil demand forecasts show a decline after 2040, and hence the need to invest in technologies that can lower the cost of production to keep the industry sustainable at lower production volumes while still being able to make ESG investments at a level that doesn't cause backsliding on abatement and overall ESG performance.

Figure 15.13 shows the projected CO_2 emissions from the OS. With high ESG spending, net-zero emissions will be almost reached by 2050. With balanced ESG spending, CO_2 emissions will also nearly reach net zero by 2050. The low ESG spending option shows a considerable decline in CO_2 emissions but is far from net zero by 2050.

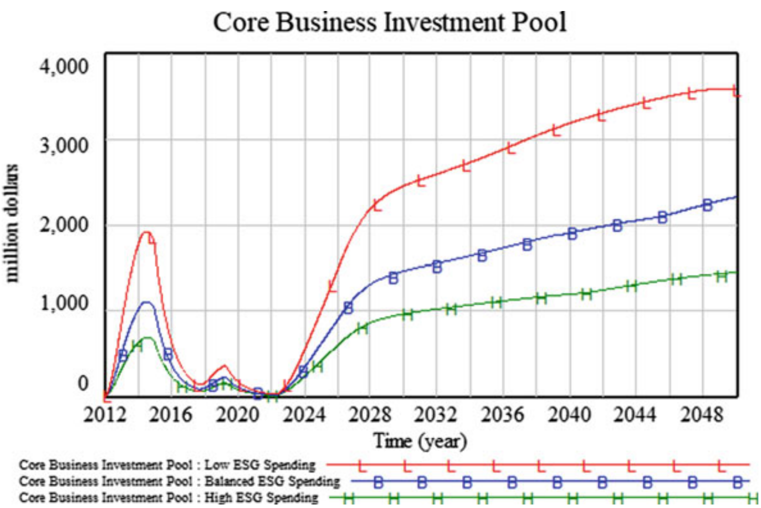

Fig. 15.11 Core business investment pool for the three strategic focus options

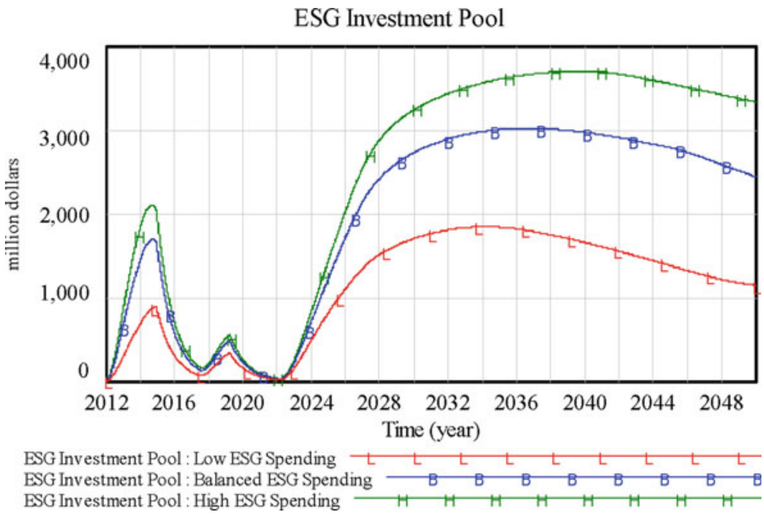

Fig. 15.12 ESG investment pool for the three strategic focus options

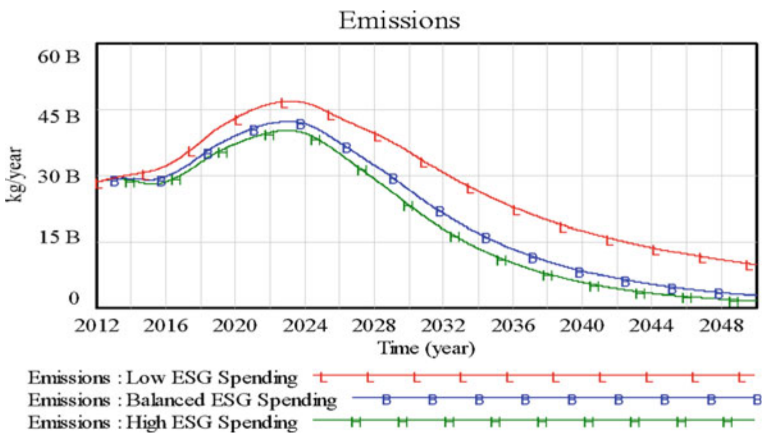

Fig. 15.13 CO_2 emissions for the three strategic focus options

Figure 15.14 shows the change in public perception over the period. Here the perception measure can take on any value between − 1 (negative perception) and 1 (positive perception), with a value of 0 representing a neutral perception. We estimated that the initial public perception in 2012 was 0.3, but the perception was declining and was slightly negative in 2022. Therefore, we projected a small improvement in public perception in the mid-2020s; however, a further decline was projected for the late 2020s. Around 2030, public perception was projected to increase, created by a delayed reaction to the reductions in emissions that were projected to begin around 2025. However, the public perception is only expected to rise to the 2012

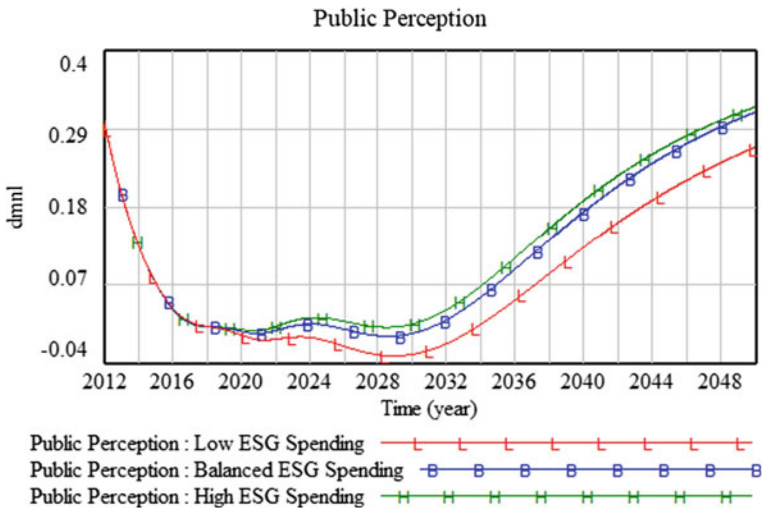

Fig. 15.14 General public perception of the OS for the three strategic focus options

level by 2050. Also, notice little difference between the public perception values for the balanced and high ESG spending options.

Investor perception was assumed to be 0.1 in 2012 but, like public perception, was declining (see Fig. 15.15). There were fluctuations in the perception between 2015 and 2025. We find a relatively rapid improvement in investor perception until 2028 and more gradual progress in investor perception after that. We notice the balanced and high ESG spending strategic focus will lead to indifference among investors by 2050.

First Nations' perception was assumed to be − 0.1 in 2012. It was found to hold reasonably steady until 2020, when it started to decline (see Fig. 15.16). It was projected to reach its low point in 2030 and then begin to increase. After 2040, the First Nations' perception is projected to become positive. Notice there is relatively little difference between the results for the balanced and the high ESG spending options.

The perception of the environmental lobby has the same pattern as the First Nations' perception. However, it is somewhat more negative (see Fig. 15.17). We assumed the perception in 2012 was − 0.5. In all three cases, the perception remains steady until 2020. Then the perception begins to decline to reach its lowest values after 2035. Then there is a gradual increase in the perception back to the 2012 level by 2050 for the balanced and high ESG spending options, while the low ESG spending option has not recovered. Notice the balanced and high ESG spending options lead to quite similar results.

Figures 15.18 and 15.19 compare perceptions of ESG investment spending (Fig. 15.18) and annual OS emissions (Fig. 15.19). Both graphs were run using the balanced ESG parameters.

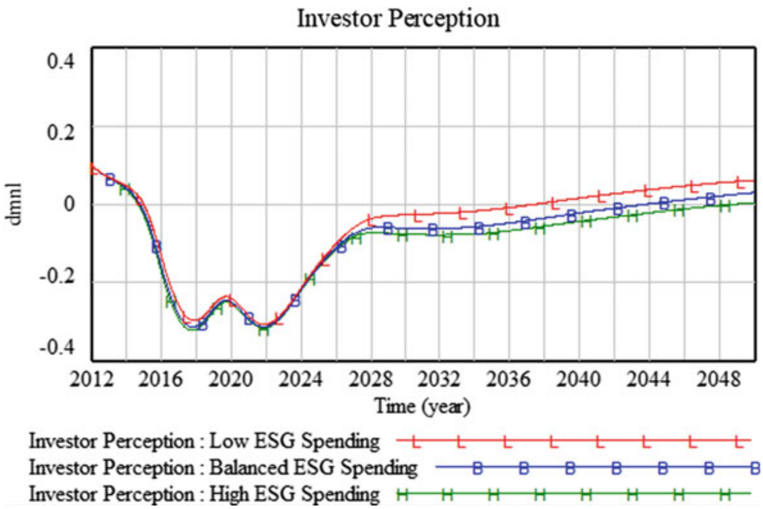

Fig. 15.15 Investors' perception of the OS for the three strategic focus options

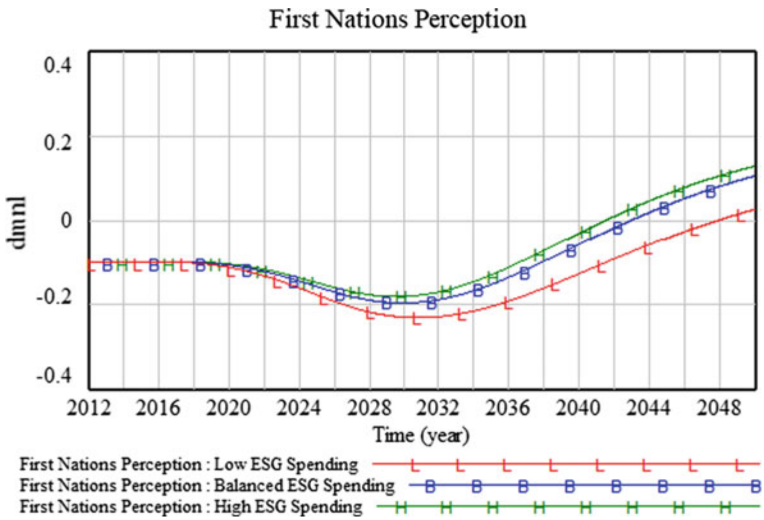

Fig. 15.16 First nations perception of the OS for the three strategic focus options

In Fig. 15.18, the large oscillations in the ESG investment curve (purple, dashed line) reflect the impact of the oil price volatility on OS investment spending due to the model constraint that investment spending does not occur in years where net revenue falls below the investment cut-off threshold, as happened in 2015–2016 and 2019–2021. As expected, Investor Perception (yellow line) tracks ESG investment spending until 2030 but continues upward while ESG investment spending trends are

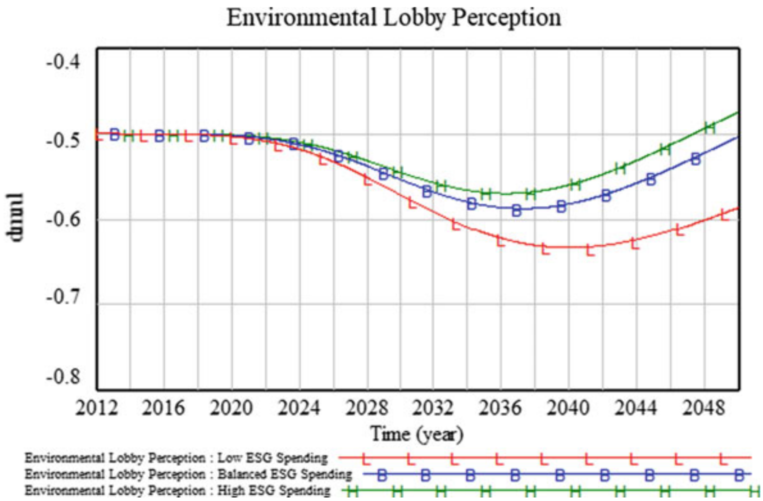

Fig. 15.17 Environmental lobby perception of the OS for the three strategic focus options

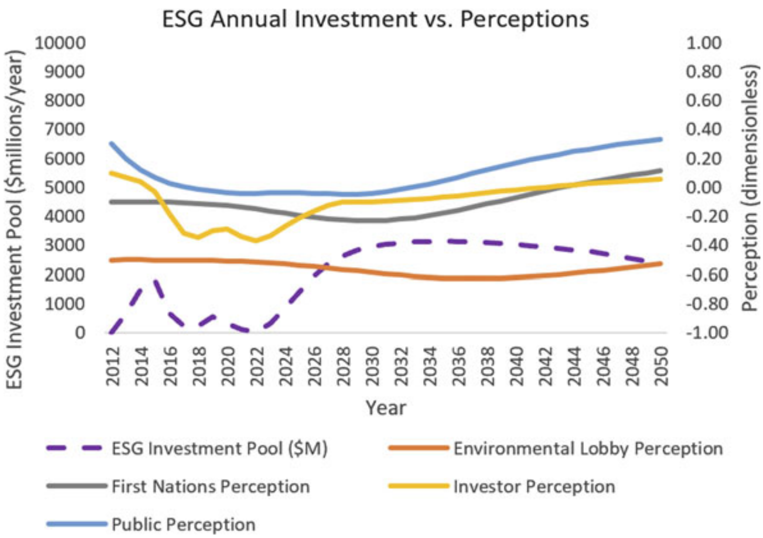

Fig. 15.18 ESG investments versus all perceptions

down. The same upward trend after 2030 is also observed in First Nations and Public Perception. Therefore, no discernible change in Environmental Lobby Perception can be attributed to ESG investment.

Comparing perceptions to emissions abatement performance, as in Fig. 15.19, shows the perception indices for First Nations, investors and the public dipping while annual emissions are rising and then improving once there has been substantial

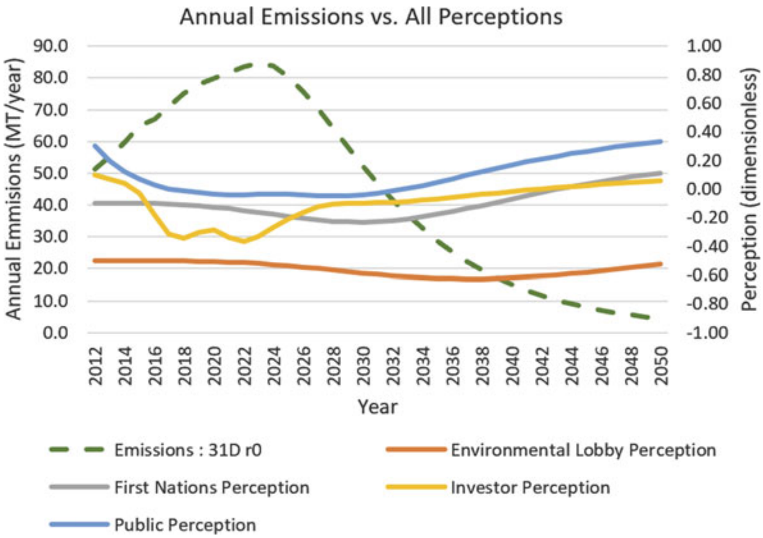

Fig. 15.19 Annual OS emissions versus all perceptions

improvement in emissions reduction. Again, the perception indicator for the environmental lobby remains strongly negative and essentially unchanged regardless of emissions performance, with perhaps a slight improvement near 2050 as emissions approach the net zero goal.

In Fig. 15.20, we again compare two key ESG-related variables—ESG annual investments and carbon taxes—to OS industry gross and net revenues using the balanced ESG scenario parameters.

As seen in Fig. 15.18, gross and net revenue (grey and green lines, left (secondary) axis) oscillated before 2022 due to oil market instability before recovering and remaining relatively flat through 2050. ESG investments (red line, right (primary) axis), calculated as a percentage of net revenue, follow the same pattern. As expected, carbon taxes (blue line, right (primary) axis) has the same pattern as emission abatement in Fig. 15.19. This chart indicates that market fundamentals, not ESG spending, will strongly influence OS revenues.

These results suggest that a balanced approach to ESG spending leads to a satisfactory return on investment and emissions reductions. Our scenario tests indicate that the OS may reach nearly net-zero emissions with either balanced or high ESG spending. In contrast, it will not be able to get to net-zero emissions in the low ESG spending situation.

In terms of perception, the changes for the general public, investors, and First Nations with a balanced or a high ESG strategic focus was similar. There were substantial differences in the perception of the environmental lobby for these two options, with high ESG spending leading to a substantially higher perception. However, in both cases, the perception was projected to remain negative until 2050.

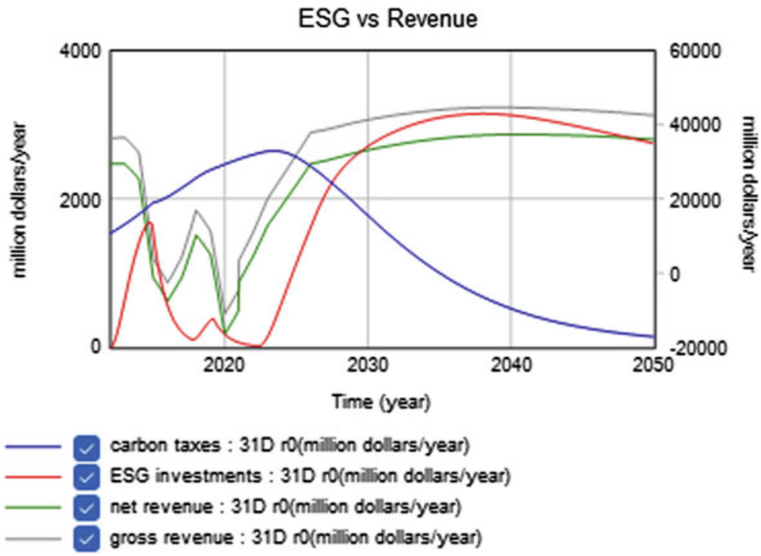

Fig. 15.20 ESG variables (investments and carbon taxes) versus gross and net revenue

15.6 Discussion

The model analysis shows the OS industry can pursue a range of scenarios where significant ESG investment, especially in emission abatement (reduction), addresses stakeholder ESG concerns, as measured by public perception while remaining financially stable, as measured by net revenues. Judiciously balancing investments in internal process improvement (to reduce emissions and increase worker efficiency) and spending on environmental and social progress within the areas of impact demonstrates that it is possible to extend the life of the OS sector to at least 2050. Overall, this spending needs to balance providing a return to investors and improving public perception of the industry. Part of the funding for environmental and social initiatives comes from royalties and corporate and carbon taxes, which enhance public support (Alberta Oil Sands royalties, n.d.). The model assumes a stable regulatory framework to sustain OS investments for environmental and social initiatives and forecast employment levels and capital and operational spending.

While the findings show net-zero-emissions would not be achieved by 2050 in any of the above scenarios, it is worth noting that those findings assumed an industry corporate investment threshold of 15% of net revenues per year. That threshold resulted in peak ESG annual investment of \$3.1 billion/year in 2038 and emissions of 5 MT/year in 2050 in the ESG balanced scenario. The threshold increase would also see the social fraction of the ESG investment pool increase from \$1.0 billion/year to \$1.6 billion/year for the 15% and 25% levels, respectively. In turn, this would further improve public and First Nations' perception, although likely at the expense of investor perception.

Significant uncertainties could affect model results. These include future oil price trends, which are influenced by alternate sources of supply, and price shocks such as those seen previously. Further, there is uncertainty in investor behaviour and the extent to which this may be affected by negative perceptions of the industry by the environmental and First Nations lobbies and the general public of the OS industry. At the same time, there is ongoing research and development into OS abatement (Janzen et al., 2020). There is also significant uncertainty in the industry's ability to develop abatement measures (Virla et al., 2021) to reduce emissions to obtain the projected values in the model results.

15.7 Conclusions

Oil Sands are strategic resources, particularly in Canada. Though the Oil Sands industry in Canada is perceived to be in its sunset, ESG investments could significantly change this scenario. Hence, by leveraging the feedback modelling capability of system dynamics, this study demonstrates the potential of ESG investments to revamp the industry.

This study examined the impact of ESG investments on the public perception of Canadian Oil Sands and was achieved through a system dynamics model that explores the interactions between ESG investments and returns on investments for investors. This stemmed from the belief that an improved public perception of the Oil Sands industry would positively impact the viability of the sector in the long term. This study shows significant and increasing investments in the core business against ESG activities, such that ESG investments are expected to decline. However, high and balanced ESG investments could lead to near-net-zero CO_2 emissions by 2050.

On the contrary, low ESG investments could lead to a decline, but not enough to attain net-zero CO_2 emissions by 2050. Regarding public perception, a decrease is observed and expected to persist till the late 2020s. Nevertheless, a rise is expected around 2030; by 2050, it should reach the initial value of 2012. Likewise, for investor perception, the decline persists until rapid and gradual improvements from 2028 till 2050. It is worth mentioning that both balanced and high ESG spending do not yield noticeable differences in both public and investor perception. Similar patterns were observed for the perception of the environmental lobby and the First Nations, where the values were unchanged until 2020. After that comes a decline until 2035, followed by a gradual increase until 2050 for both the balanced and high ESG options, this is not so for the low ESG spending option.

The study surmises a need for a balanced approach for ESG investments (balanced-high) to attain satisfactory returns on investments and reduce emissions. While for perceptions (general public, investors and First Nations), balanced and high ESG investments yield similar results. However, there are significant variances in environmental lobby perception for balanced and high ESG investments, where high ESG investments lead to a substantial increase in perception. From the above, there is the possibility of extending the life of the Oil Sands industry in Canada till at least 2050 through a careful balance of investments in processes and social improvements, as well as return on investments and positive public perception. However, this would be unattainable without a supportive regulatory framework from the government.

15.7.1 Limitations and Future Work

This study's limitations include favourable assumptions about future oil prices and abatement technologies. Here the dimensions of significant uncertainties, including future oil prices, alternative sources of oil supply, investor behaviour, and the ability of the industry to develop measures for reducing emissions, could be explored. Further, the study might more fully explore the impact of providing financial returns to investors and the resulting implications for expansion decisions. For example, in the case of increasing the corporate investment threshold to 25%, ESG investment will peak at $5 billion/year in 2035 and emissions under 1 MT/year in 2050, with minimal impact on revenue.

15.7.2 Insights and Implications for Practice

In practice, this study offers tangible insights and implications, which could redefine the complex task of policymaking, capturing and influencing public perceptions. It also illustrates the need for and the means to balance ESG and core business investments. In addition, this study brings to the fore the value of a systems view in complex environmental issues, such as managing the Oil Sands industry in Canada.

Declarations
Author Contributions: All authors contributed equally.

Conflicts of Interest: NIL.

Software Used: https://vensim.com/

Calibrated System Dynamics Model: https://github.com/ivanwtaylor/Oil-Sands

Data for validation: Significant parts of the model were validated using the data accessed from the Statistical Handbook published by CAPP (Canadian Association of Petroleum Producers www.capp.ca) and Canada Energy Regulator (2021a, 2021b). All sources of data are listed under the References section.

Appendix

Terminology (initial values and units)

Name	Value	Units
Abatement cost drilling	0.0333	kg/(barrels * million dollars)
Abatement cost mining	0.0333	kg/barrels/million dollars
Accumulation period	1	Year
Aggregate oilsands water use	10.5	dmnl
Aggregate recycling fraction	0.75	Fraction
Average infrastructure life span	50	Years
Average wage	120,000	Dollars/person/year
Average wage inflation	1.025	dmnl
Birth rate	0.02	People/(year*person)
Breakeven price	50	Dollars/barrels
Carbon tax rate	0.3	Dollars/kg
Compliance multiplier	1,000,000	dmnl
Corporate tax rate	0.08	Fraction
Cost of in-situ expansion	10	Dollars/barrels
Cost of mining expansion	20	Dollars/barrels
Diluent average cost fraction for gross projects	0.315	dmnl
Diluent average cost fraction for net projects	0.268	dmnl
Fish birth rate	0.39	Fish/fish/year
Fishing rate	0.2	Fish/fish/year
Fraction gross royalty initial	0.73	dmnl
Fraction net royalty initial	0.27	dmnl
Fraction of remaining to social infrastructure	44,929	dmnl
Gross royalty rate	0.0378	Fraction
Gross to net in-situ payback	44,936	1/year
Gross to net mining transition fraction	44,951	1/year
Hunting rate	0.2	Wildlife/wildlife/year
In-situ reserves initial	245,562	Million barrels
Initial land used	901	km^2
Initial drilling workforce	9000	People
Initial emissions intensity drilling	75.5202	kg/barrels
Initial emissions intensity mining	91.0125	kg/barrels
Initial emissions reduction fraction drilling	0.8	dmnl
Initial emissions reduction fraction mining	0.12	dmnl
Initial environmental lobby perception	− 0.5	dmnl

(continued)

(continued)

Name	Value	Units
Initial first nations people	10,000	People
Initial first nations perception	− 0.1	dmnl
Initial fish	100	Fish
Initial infrastructure	100	Buildings
Initial investor perception	0.1	dmnl
Initial land available	4800	km^2
Initial mining workforce	8500	People
Initial miner productivity	36,798	Barrels/(year * person)
Initial public perception	0.3	dmnl
Initial services	1000	Service units
Initial Wildlife	100	Wildlife
Inventory market value	120	Dollars/barrel
Investment period	1	1/year
Land use rate drilling	4.93E−05	km^2/million barrels
Land use rate mining	0.00381558	km^2/million barrels
Net earnings ratio target	0.18	dmnl
Net revenue average deductions	329	Million dollars/year
Net royalty rate	0.297	dmnl
Net water used conversion	0.000197	dmnl
Normal build rate	0.1	Buildings/buildings/year
Normal departure time	72	Years
Normal fish life expectancy	5	Years
Normal investment fraction	0.15	dmnl [0,1,0.01]
Normal profit	30,000	Million dollars/year
Normal wildlife life expectancy	10	Years
Mining reserves initial	68,928	Million barrels
Price sensitivity analysis	0.2	dmnl
Price shock	0.5	dmnl
Production fraction gross in-situ	0.51	dmnl 1/42.7
Production fraction gross mining	0.51	dmnl
Production period	1	1/year
Reclamation rate	0.11	1/year
Standard use of general services	100	People/service units
Time to change environmental lobby perception	10	Year
Time to change first nation perception	5	Year
Time to change investor perception	1	Year
Time to change public perception	3	Year

(continued)

(continued)

Name	Value	Units
Time to change services	10	Years
Upgrade period	1	1/year
Upgrader investment fraction	0.6	dmnl
wb econ weight	0.5	dmnl [0,1,0.1]
Wildlife birth rate	0.295	Wildlife/wildlife/year
Year of price shock	2022	Year

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Part VII
Dealing with the Complexity of Healthcare Systems

Chapter 16
Understanding the Dynamics of the Logistics of N95 Mask with Systems Thinking

Hassan Qudrat-Ullah

Abstract A supply chain refers to a system of activities and structures that an organization uses to transform the inputs into outputs for the customer. The process starts with the production and ends with the delivery to the final user, and all the steps in between are connected and coordinated to achieve the desired output. The supply chain involves the inventory and movement of materials for the production process, as well as the management policies that regulate the different flows. Supply chain management is the smooth and efficient management of the flow of goods and services from their source to their destination through various channels. In this report, we will examine the production and distribution of N95 masks in Canada. An N95 mask is a protective device that health professionals wear during surgical procedures. It helps to trap the bacteria in liquid droplets from the user's mouth and nose to prevent transmission to others. Activities such as coughing, sneezing, breathing, and speaking can release bacteria that may infect a person undergoing surgery. We will explore how different raw materials are assembled into finished products in the production line, and how they are transported through various modes of transportation to the users in Canada.

Keywords COVID · N95 · Masks · Canada · Supply chain · Production processes · Distribution processes · Inventory management · System dynamics · Systems thinking · Healthcare · Health professional · Personal protective equipment (PPE) · Model testing and validation

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16.1 Introduction

The COVID-19 pandemic has posed unprecedented challenges for the global health system and society at large. As the virus spreads rapidly across the world, infecting millions of people and causing hundreds of thousands of deaths, the need for effective prevention and treatment measures becomes more urgent than ever. One of the key strategies to contain the pandemic and protect the health and safety of the population is to ensure the availability and proper use of personal protective equipment (PPE). The COVID-19 pandemic has highlighted the importance of (PPE) for health professionals and other frontline workers (Health Canada, 2021).

PPE refers to any device or garment that is worn by an individual to reduce the risk of exposure to hazardous substances or environments. PPE can include gloves, gowns, goggles, face shields, respirators, masks, and other items that are designed to protect the wearer from physical, chemical, biological, or radiological hazards. PPE plays a vital role in preventing the transmission of infectious diseases, especially in healthcare settings where workers are in close contact with patients and bodily fluids. PPE can also benefit other sectors and groups that are exposed to high-risk situations, such as emergency responders, law enforcement officers, essential workers, and vulnerable populations (Health Canada, 2021).

Among the various types of PPE, N95 masks are considered to be the most effective in filtering out airborne particles and preventing the spread of the virus. N95 masks are a type of respirator that can filter out at least 95% of very small particles (0.3 μm) that may contain bacteria or viruses. N95 masks are commonly used and worn by health professionals during operation procedures or other medical interventions that may generate aerosols or droplets from the user's mouth and nose. These activities include coughing, sneezing, breathing, speaking, intubation, suctioning, bronchoscopy, and nebulization. By wearing N95 masks, health professionals can reduce the risk of infecting themselves or others with potentially harmful pathogens (PHAC, 2021).

However, the demand for N95 masks has far exceeded the supply, creating a global shortage and a challenge for supply chain management (Bennett & O'Neill-Stephens, 2021). Supply chain refers to a set of structures and procedures that are undertaken by an organization to convert the inputs into outputs for the customer. Starting from the production and ending with the delivery to the end user, all the activities involved in this process are a series of links that support and complement each other to get the final output delivered to the customer. The supply chain includes the stock and flow structures for the procurement of inputs to be applied to the process, as well as the managerial policies authorizing the various flows. Supply chain management is managing the flow of goods and services smoothly from its origin which is processed through various channels and finally to the end user (CDCP, 2021).

The supply chain of N95 masks involves several steps and actors, such as raw material suppliers, manufacturers, distributors, retailers, healthcare facilities, and consumers. Each step and actor faces challenges and opportunities in ensuring the availability and quality of N95 masks. Some of the common challenges include:

- Limited production capacity: The production of N95 masks requires specialized equipment and materials that are not widely available or easily scalable. The production process also involves strict quality standards and regulations that need to be met and verified before releasing the products to the market.
- High demand and hoarding: The demand for N95 masks has surged dramatically due to the pandemic, exceeding the normal consumption levels by several orders of magnitude. This has led to panic buying and hoarding by consumers, retailers, governments, and other entities that want to secure their supplies of N95 masks. This behavior has resulted in artificial shortages and price gouging in some markets.
- Distribution bottlenecks: The distribution of N95 masks involves multiple modes of transportation (air, sea, land) and intermediaries (wholesalers, distributors) that need to coordinate and cooperate to deliver the products to their final destinations. However, the distribution network faces several constraints and disruptions due to factors such as border closures, travel restrictions, logistical delays, tariffs, sanctions, and theft.
- Allocation dilemmas: The allocation of N95 masks involves making decisions about who should receive the limited supplies of N95 masks and how much they should receive. These decisions are influenced by ethical, political, economic, and social considerations that may vary across different regions, countries, and contexts. The allocation dilemmas also raise questions about the fairness, transparency, and accountability of the decision-making process and its outcomes.

The issue that we aim to address in this chapter is the surge in demand for N95 masks due to the ongoing pandemic that has affected the world. Specifically, we intend to analyze the production and distribution of N95 masks in Canada, one of the countries that faced difficulties in securing adequate supplies of PPE during the pandemic. We will examine the various stages of the supply chain, from the procurement of raw materials to the delivery of finished products to the end users. We will also identify the key challenges and opportunities for improving the efficiency and resilience of the supply chain. By doing so, we hope to provide insights and recommendations for enhancing the availability and accessibility of N95 masks in Canada and beyond.

16.2 Theoretical Review

This chapter will focus on the key variable of production rate that will vary over time and the uncertain demand in the context of the pandemic. We will also examine the policy changes that the Food and Drug Administration (FDA) implemented for N95 masks. The FDA regulates N95 masks as class II medical devices under 21 CFR 878.40.40 and reviews and clears them before they enter the market. The FDA has been working with N95 mask manufacturers to understand and address the supply chain issues related to the COVID-19 outbreak and prevent any shortage of these products (FDA, 2021). The FDA also advises that N95 respirators are critical supplies that should be reserved for healthcare workers and other medical first responders, as recommended by current Centers for Disease Control and Prevention (CDC) guidance is not used by the general public to protect themselves from COVID-19 (FDA, 2021). The FDA is in the process of revising its policy on the reuse of N95 masks and is expected to order a return to standard procedures (International Business Times, 2021). Those are critical supplies that must continue to be reserved for healthcare workers and other medical first responders, as recommended by current CDC guidance.

We will review the current FDA policies and guidance on the reuse of N95 masks and the criteria for issuing emergency use authorizations (EUAs) for these masks. We will also examine the challenges and risks associated with the reuse of N95 masks, such as the potential loss of filtration efficiency, fit, and integrity, and the possible exposure to contaminants and pathogens. We will also discuss the best practices and recommendations for the safe and effective reuse of N95 masks, such as the use of decontamination methods, fit testing, inspection, and storage. We will also explore alternative options for respiratory protection, such as face shields, surgical masks, barrier face coverings, and powered air-purifying respirators (PAPRs). We will also address the issues of counterfeit and substandard N95 masks that have entered the supply chain and pose a threat to the health and safety of healthcare workers and the public. We will provide some tips and resources for identifying and reporting these fraudulent products to the FDA. We hope that our report can provide some useful information and guidance for healthcare workers and facilities on the reuse of N95 masks and other respiratory protection devices during the COVID-19 pandemic.

An N95 respirator is a device that covers the nose and mouth and provides a very close fit and high efficiency in filtering airborne particles. The name "N95" means that the respirator can block at least 95% of very small (0.3 μm) particles when tested carefully. If worn correctly, the N95 respirator can offer more protection than a face mask. However, even a well-fitted N95 respirator does not eliminate the risk of getting sick or dying (CDC, 2021). An N95 respirator is a type of filtering facepiece respirator that is commonly used by healthcare workers during surgical procedures or other medical interventions that may produce aerosols or droplets from the user's mouth and nose. These activities can release bacteria or viruses that may cause infections in other people. The N95 respirator helps to capture the bacteria or viruses in the droplets and prevent them from spreading.

An N95 respirator is a respiratory protective device designed to achieve a very close facial fit and very efficient filtration of airborne particles. Note that the edges of the respirator are designed to form a seal around the nose and mouth. The N95 Respirators are commonly used in healthcare settings and are a subset of N95 Filtering Facepiece Respirators (FFRs), often referred to as N95s (CDC, 2021). Here are the key terms:

N This is a Respirator Rating Letter Class. It stands for "Non-Oil" meaning that if no oil-based particulates are present, then you can use the mask in the work environment. Other mask ratings are R (resistant to oil for 8 h) and P (oilproof).

95 Masks ending in a 95, have a 95 percent efficiency. Masks ending in a 99 have a 99 percent efficiency. Masks ending in 100 are 99.97 percent efficient and that is the same as a HEPA quality filter.

3 μm The masks filter out contaminants like dust, mists, and fumes. The minimum size of 0.3 μm of particulates and large droplets won't pass through the barrier, according to the Centers for Disease Control and Prevention (CDC).

Material The filtration material on the mask is an electrostatic non-woven polypropylene fiber.

Valve Some disposable N95 masks come with an optional exhalation valve. "The presence of an exhalation valve reduces exhalation resistance, which makes it easier to breathe (exhale,)" according to the CDC (2021).

An N95 respirator is a device that covers the nose and mouth and provides a very close fit and high efficiency in filtering airborne particles. The name "N95" means that the respirator can block at least 95% of very small (0.3 μm) particles when tested carefully. If worn correctly, the N95 respirator can offer more protection than a face mask. However, even a well-fitted N95 respirator does not eliminate the risk of getting sick or dying (CDC, 2021). An N95 respirator is a type of filtering facepiece respirator that is commonly used by healthcare workers during surgical procedures or other medical interventions that may produce aerosols or droplets from the user's mouth and nose. These activities can release bacteria or viruses that may cause infections in other people. The N95 respirator helps to capture the bacteria or viruses in the droplets and prevent them from spreading. The N95 respirators are made of non-woven fabric with good bacterial filtration and air permeability. The material used is polypropylene, a synthetic plastic fiber made from fossil fuels like oil. Polypropylene is also used to make surgical masks, but N95 respirators have a higher density of fibers and are more tightly fused. Polypropylene fibers are produced by melt blowing, which involves extruding the melted plastic onto a conveyor and forming a web of fibers that are cooled and bonded together. The web of fibers has a cotton-like texture and is often given an electrostatic charge to enhance its filtering efficiency. The web of fibers forms the inner filtration layer of the N95 respirator that filters out hazardous particles (Health Desk, 2021; Good Housekeeping, 2021). The N95 respirator also has other components, such as aluminum, polyurethane, steel, rubber, and polyisoprene, to make the straps, nose bridge, valve, and seal.

N95 masks are tested for their filtration efficiency and other performance characteristics before they enter the market. The tests include the following (CBC, 2021; Canada, 2021):

- Bacteria filtration efficiency (BFE): This test measures how well the mask can filter out bacteria from the air. The test uses an aerosol of staphylococcus aureus bacteria that is sprayed on the mask at 28.3 L per minute. The mask should be able to catch at least 95% of the bacteria.

- Particle filtration efficiency: This test measures how well the mask can filter out particles from the air. The test uses an aerosol of polystyrene microspheres that are 0.3 μm in size. The mask should be able to filter out at least 95% of the particles.
- Breathing resistance: This test measures how easy or hard it is to breathe through the mask. The test uses a flow of air that is shot at the mask, then measures the difference in air pressure on both sides of the mask. The mask should have a low breathing resistance that does not compromise its filtration efficiency or fit.
- Splash resistance: This test measures how well the mask can resist liquid penetration and contamination. The test uses simulated blood that is splashed on the mask with forces similar to human blood pressure. The mask should prevent the liquid from passing through and reaching the wearer's face.
- Flammability: This test measures how resistant the mask is to catching fire and burning. The test uses a flame that is applied to the mask for a few seconds. The mask should not ignite or burn rapidly.

However, the supply of N95 masks has not been able to keep up with the demand, leading to shortages and rationing in many healthcare facilities across the country. According to a survey conducted by the American Nurses Association in July 2020, 68% of nurses reported that their employers were still requiring or encouraging them to reuse disposable N95 masks (ANA, 2020). The shortage of N95 masks has been attributed to several factors, such as the lack of domestic production capacity, the disruption of global supply chains, the hoarding and price gouging by some distributors and retailers, and the inadequate stockpiling and distribution by the federal government (WSJ, 2020). The shortage of N95 masks has posed serious risks to the health and safety of healthcare workers and their patients, as well as the general public. N95 masks are designed to filter out at least 95% of airborne particles, including viruses and bacteria, and provide better protection than surgical or cloth masks. Several studies have shown that healthcare workers who wear N95 masks have a lower risk of contracting COVID-19 than those who wear other types of masks (JAMA, 2020).

16.3 The Development of the Conceptual Model

The COVID-19 pandemic has created an unprecedented demand for N95 masks worldwide. We aim to examine the production and distribution of these masks and identify the challenges and limitations in their supply chain. We also hope to propose policy solutions to enhance the availability of these vital supplies for healthcare workers and the public, to reduce the transmission of COVID-19 and curb the pandemic. We will use systems thinking approach to model the production and distribution of N95 masks during the COVID-19 pandemic. We will use data from various sources to estimate the initial values and parameters of our model. We will calibrate our model by comparing the simulated results with the observed data. We will validate our model by conducting sensitivity analysis and testing different scenarios. We will use our model to examine the causes and consequences of the shortage of N95 masks and to evaluate the impacts of different policy solutions, such as increasing the domestic production capacity, diversifying the global supply chain, reducing the export restrictions and tariffs, and promoting the reuse and recycling of N95 masks. We will also discuss the limitations and assumptions of our model and suggest some directions for future improvement and research. We hope that our model can provide some insights and recommendations for N95 mask management and decision making during the pandemic and beyond (Figs. 16.1, 16.2 and 16.3).

To improve the supply of N95 masks, we can start by increasing the production capacity to meet the high demand. However, the demand is so overwhelming during a pandemic that it exceeds the supply by far. One source reported that the usage of these masks went up by 1700% (Diamond, 2020). In this paper, we will explore some strategies to increase the availability of N95 masks in a pandemic situation. Our initial assumption is that it is impossible to respond quickly enough to the need and that other types of PPE are needed to slow down the transmission of covid-19. We also need to prepare better for future pandemics. Figure 16.4 presents our conceptual model aka a Dynamic Hypothesis. It has three major feedback loops, R1, R2, and B1 which are responsible for the fundamental dynamics of N95's production and distribution and distribution system.

Dynamics of B1: The availability of raw materials affects the production level. The more raw materials are in stock or transit, the higher the inventory level for raw materials. This creates a feedback loop that balances the production and the inventory, as shown in Fig. 16.1.

However, the availability of raw materials also depends on the supply chain and the market conditions. The supply chain involves the suppliers, the transportation, and the delivery of raw materials. The market conditions involve the demand, the price, and the competition for raw materials. These factors can affect the availability of raw materials in positive or negative ways. For example, if the demand for raw materials increases, the price may increase as well, which can reduce the availability of raw materials. On the other hand, if the supply chain is efficient and reliable, the

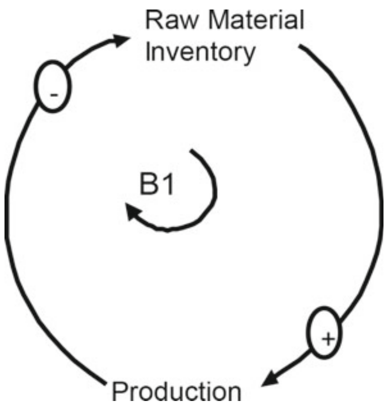


Fig. 16.1 Production and inventory feedback loop

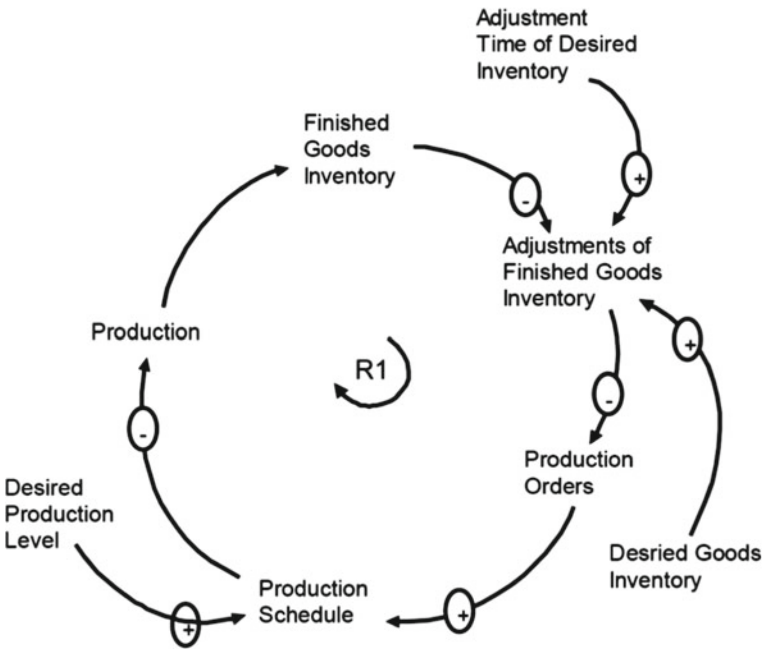
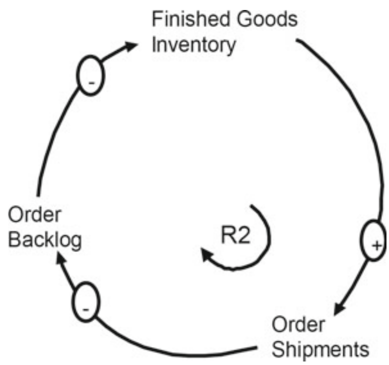


Fig. 16.2 Production ordering and scheduling feedback loop

Fig. 16.3 Distribution process feedback loop



availability of raw materials may increase. Therefore, we need to consider both the internal and external factors that affect the availability of raw materials and their impact on the production level.

Dynamics of R1: When we create a causal loop diagram for the production process, we see that the first variable ''production'' increase leads to an increase in finished goods inventory as more products are produced. When there is an increased finished goods inventory, it leads to a decrease in the adjustment of finished goods inventory. The adjustment time of desired inventory and the desired inventory of finished goods

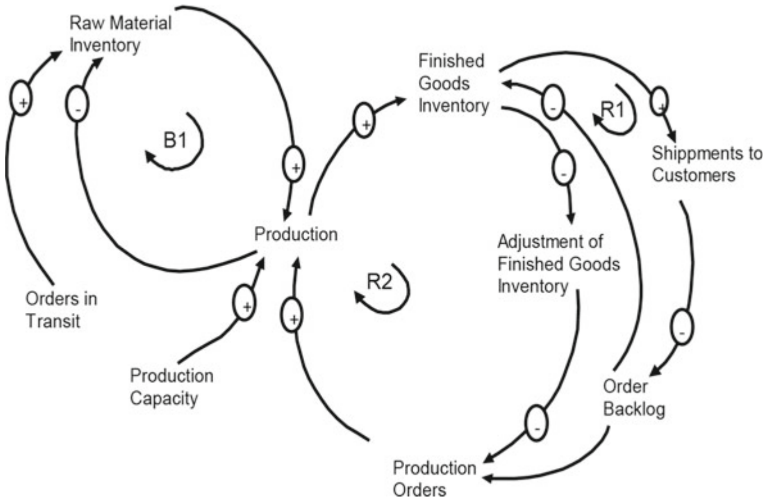


Fig. 16.4 The conceptual model of production and distribution processes of N95

also affects the adjustment of the finished goods inventory. With an increase in both, it increases the adjustment of finished goods inventory.

The adjustment of finished goods inventory affects the product orders. The more the inventory is adjusted, the less the orders are placed. The product orders affect the production schedule. The more orders are placed, the higher the production schedule. The production schedule also depends on the desired production rate. The higher the desired production rate, the higher the production schedule. The production schedule affects the production. The higher the production schedule, the higher the production. This creates a positive feedback loop, R1, that reengineers the system, as shown in Fig. 16.2. However, production also affects the finished goods inventory. The higher the production, the higher the inventory. The finished goods inventory affects the inventory adjustment. The higher the inventory, the lower the adjustment. This creates a negative feedback loop, B1, that stabilizes the system, as shown in Fig. 16.2. Therefore, we have a balancing loop and a reinforcing loop that interact with each other and influence the production and the inventory of finished goods. We also have a delay between production and inventory, which can cause oscillations and fluctuations in the system behavior. We need to consider these dynamics and their implications for production and inventory management.

The Dynamics of R2: The CLD of R2, as shown in Fig. 16.3, for the distribution process begins with the finished goods inventory variable. The more finished goods are in stock, the more goods can be shipped to the customer. The more goods are shipped to the customer, the fewer orders are left in the backlog. The more orders are in the backlog, the less finished goods are in stock. This creates another positive feedback loop, R2, that reengineers the system. However, the finished goods inventory also depends on the production. The higher the production, the higher the inventory. The production also depends on the product orders. The higher the orders, the higher the production. The product orders also depend on customer demand. The higher the customer demand, the higher the orders. Customer demand also depends on the market conditions. The market conditions involve factors such as price, quality, competition, and customer satisfaction. These factors can affect customer demand in positive or negative ways. Therefore, we have a complex system that involves multiple variables and feedback loops that influence the distribution process and the finished goods inventory. We need to understand these dynamics and their impacts on the system performance and customer service.

We can combine the feedback loops for production and distribution to get the final result, our conceptual model aka the dynamic hypothesis. We have already described teach of these feedback loops separately above. We can see how the order backlog of N95 masks affects the production orders. The more orders are in the backlog, the more production orders are placed. We can also see how the adjustment of the finished goods inventory of N95 masks affects the production orders. The more the inventory is adjusted, the fewer production orders are placed.

We can also see how the production orders affect the production schedule and the production of N95 masks. The more production orders are placed, the higher the production schedule and the production. We can also see how the production affects the finished goods inventory and the shipment of N95 masks. The higher the production, the higher the inventory and the shipment. We can also see how the shipment affects the order backlog and customer satisfaction. The higher the shipment, the lower the order backlog and the higher the customer satisfaction. We can also see how customer satisfaction affects customer demand and product orders. The higher the customer satisfaction, the higher the customer demand and the product orders. Therefore, we have a comprehensive model that captures the dynamics of the production and distribution of N95 masks during the COVID-19 pandemic. We can use this model to simulate different scenarios and test different policies to improve the system's performance and customer service.

16.4 Formulation and Specification of the Simulation Model

The stock and flow structure for the supply chain has two parts: manufacturing and distribution. The manufacturing part has the N95 Mask Inventory as the stock. The inflow is the production of N95 masks, which depends on two factors: the availability of raw materials and the use of available production capacity. The production capacity can be increased by adding more staff, more shifts, or more machines for making N95 masks. In this model, the capacity depends on the base capacity and a surge capacity multiplier that shows how much capacity can increase when demand is high. The outflow is the orders that are shipped to customers or distributors around the world. This rate will be explained more in the distribution part of the model.

The distribution part has the Backlog of Orders as the stock. The inflow of orders is based on the demand for the product and a pandemic multiplier that shows the impact of covid-19 on the model. The demand is based on the regular demand and the elasticity of demand. I have stopped the elasticity part of the model here because I assume that the demand for N95 masks is perfectly inelastic, and people need them no matter what. The outflow of the backlog of orders is shipments that are sent to customers. This depends on the capacity and the utilization of the facility that processes and ships orders. The utilization depends on the desired production as a percentage of shipment capacity. The desired production is determined by taking the backlog and dividing it by the target service level, which is the number of months ahead that shipments are planned. The shipments are limited by the available inventory because they cannot be more than what is in stock. With this model, we can change some key variables and see how they affect the supply chain.

16.4.1 Estimation of the Simulation Model

The following are the initial conditions, and behavioral interactions within the model for our base case of regular production at 3 M:

Stocks:

- N95 Mask Inventory—0 Units at time 0.
- Backlog—0 Units at time 0.

Flows:

- Orders—'Monthly Demand '*' Pandemic Multiplier'
  - Incoming orders are determined by what the regular monthly demand is, multiplied by the pandemic multiplier for when demand is drastically increased.
- Shipments—IF ('Shipment Capacity '*' Shipment Capacity Utilization' > 'N95 Mask Inventory','N95 Mask Inventory', 'Shipment Capacity '*' Shipment Capacity Utilization')
  - Shipments are determined by the capacity multiplied by what percentage of that capacity is being used. The IF statement is used to make sure that the number of units going out doesn't exceed the inventory we have on hand.
- Production Rate—Capacity * 'Capacity Utilization'
  - Production rate is determined by multiplying by available production capacity by the percentage of that capacity being utilized.
- Shipping Rate—'Shipments'
  - The shipping rate is determined by whatever shipments are from the calculation above. Its purpose is just to reduce the inventory.

Constant Variables:

- Raw Materials Inventory—Raw materials for 50,000,000 units a month, continually replenishing monthly.
- Surge Capacity—1
- Base Capacity—50,000,000 units a month.
- Shipment Capacity—75,000,000 units a month.
- Target Service Level—3 months under regular conditions.
- Pandemic Multiplier—1 under regular conditions.
- Reference Demand—40,000,000
- The elasticity of Demand—1 for perfectly inelastic demand of the product.
  - The elasticity of Demand has no impact on this model, but with products that have elasticity, we would expand on this to include price and reference data to determine demand.

Auxiliary Variables:

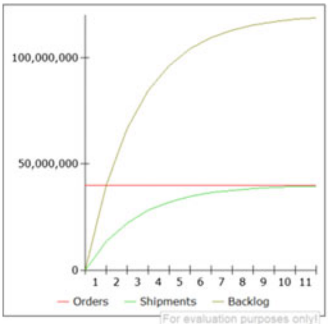
- Production Capacity Utilization—IF ('Raw Materials Inventory'/Capacity > 1,1,' Raw Materials Inventory'/Capacity)
  - Materials inventory is divided by the total capacity to give a percentage capacity being used. If the statement is used to make sure that number doesn't exceed 1.
- Production Capacity—'Base Capacity'*'Surge Capacity'
  - Total capacity is determined by what the regular capacity is, multiplied by the surge capacity multiplier. For example, a surge capacity of 2 would be doubling capacity.
- Shipment Capacity Utilization—IF ('Desired Production'/'Shipment Capacity' > 1,1,' Desired Production'/'Shipment Capacity')
  - Shipment Capacity utilization is determined by dividing desired production by total shipment capacity to give a percentage of capacity being used. If the statement is used to make sure that number doesn't exceed 1.
- Desired Production—Backlog/'Target Service Level'
  - Production is determined by the amount of work to do and dividing it by the amount of time we have to complete it to utilize the time available. This number can exceed capacity and won't have an impact on the model beyond it.
- Monthly Demand—'Reference Demand'*'Elasticity of Demand'
  - Monthly Demand is determined by taking the reference demand and multiplying it by the elasticity of the demand.

16.5 Validation and Testing of the Simulation Model

For a base case, we simulated the specifications outlined above and found the following behavior as displayed in Fig. 16.5.

We have 40 million orders coming in, so we can plan our shipments more evenly over the first periods and use the whole 3-month shipping window. Both backlog and shipments try to reach their goals: shipments aim to do 40 million per day and backlog tries to stay at 120 million. This is because we can't have more than 120,000,000 in backlog and still deliver everything in 3 months at 40 million per day. I tested this by simulating it for 100 months, and this result is shown in Fig. 16.6. All outputs after month 44 are 40 million shipments and a backlog of 120 million units.

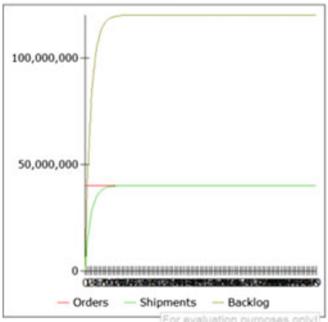
The graph of mask inventory over time shows how the production and shipping rates affect the stock level. In the first months, the inventory grows faster because we ship fewer masks than we produce. But as we increase the shipping rate to match the 40 million target, the inventory growth slows down and becomes more steady. This system does not have any limit on how much inventory we can store or any change in how much we can produce. If it did, we would see the inventory level try to



Months	Orders	Shipments	Backlog
1	40,000,000	0	0
2	40,000,000	13,333,333	40,000,000
3	40,000,000	22,222,222	66,666,667
4	40,000,000	28,148,148	84,444,444
5	40,000,000	32,098,765	96,296,296
6	40,000,000	34,732,510	104,197,531
7	40,000,000	36,488,340	109,465,021
8	40,000,000	37,658,893	112,976,680
9	40,000,000	38,439,262	115,317,787
10	40,000,000	38,959,508	116,878,525
11	40,000,000	39,306,339	117,919,016
12	40,000,000	39,537,559	118,612,678

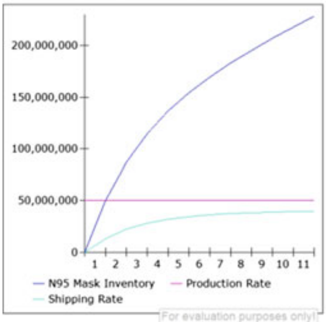
For evaluation purposes only

Fig. 16.5 Ordering and shipment behavior



Months	Orders	Shipments	Backlog
39	40,000,000	39,999,995	119,999,984
40	40,000,000	39,999,996	119,999,989
41	40,000,000	39,999,998	119,999,993
42	40,000,000	39,999,998	119,999,995
43	40,000,000	39,999,999	119,999,997
44	40,000,000	39,999,999	119,999,998
45	40,000,000	40,000,000	119,999,999
46	40,000,000	40,000,000	119,999,999
47	40,000,000	40,000,000	119,999,999
48	40,000,000	40,000,000	120,000,000
49	40,000,000	40,000,000	120,000,000
50	40,000,000	40,000,000	120,000,000
51	40,000,000	40,000,000	120,000,000

Fig. 16.6 Expanded behavior of ordering and shipment processes

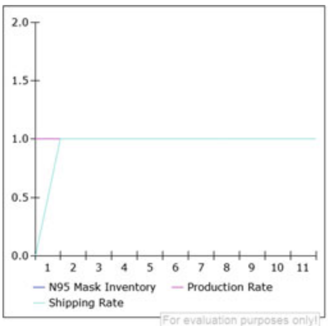


Months	Production Rate	Shipping Rate	N95 Mask Inventory
1	50,000,000	0	0
2	50,000,000	13,333,333	50,000,000
3	50,000,000	22,222,222	86,666,667
4	50,000,000	28,148,148	114,444,444
5	50,000,000	32,098,765	136,296,296
6	50,000,000	34,732,510	154,197,531
7	50,000,000	36,488,340	169,465,021
8	50,000,000	37,658,893	182,976,680
9	50,000,000	38,439,262	195,317,787
10	50,000,000	38,959,508	206,878,525
11	50,000,000	39,306,339	217,919,016
12	50,000,000	39,537,559	228,612,678

Fig. 16.7 Behavior of inventory growth processes

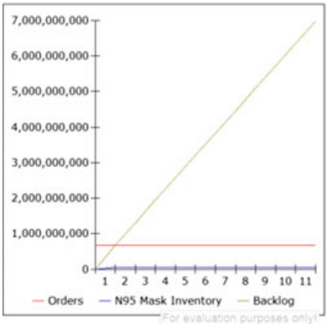
reach a certain point and stay there. This is called goal-seeking behavior. Figure 16.7 illustrates how the inventory changes over time.

Before we use our model to analyze different scenarios that could happen in the supply chain, we do several tests to check the validity and reliability of the model and to make sure that the limits and controls in the model work as we expect them to. For example, when we turn on the pandemic multiplier, the backlog and inventory stocks change in a way that makes sense according to the logic of the supply chain. The model can produce an output that shows how the different possible policy changes affect the key performance indicators and cost drivers in the supply chain. It successfully answers the problem and purpose of the model. We test the model with different policy changes and see how it behaves under different conditions. We also test the model with some extreme variations to see how it handles them. For example, we reduce the production capacity to 1 from the base case and see what happens in Fig. 16.8. The model behaves in a way that is consistent with reality, which adds credibility to our model.



Months	Production Rate	Shipping Rate	N95 Mask Inventory
1	1	0	0
2	1	1	1
3	1	1	1
4	1	1	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	1
10	1	1	1
11	1	1	1
12	1	1	1

Fig. 16.8 Behavior of production capacity under extreme condition



Months	Orders	Shipments	Backlog
1	680,000,000	0	0
2	680,000,000	50,000,000	680,000,000
3	680,000,000	50,000,000	1,310,000,000
4	680,000,000	50,000,000	1,940,000,000
5	680,000,000	50,000,000	2,570,000,000
6	680,000,000	50,000,000	3,200,000,000
7	680,000,000	50,000,000	3,830,000,000
8	680,000,000	50,000,000	4,460,000,000
9	680,000,000	50,000,000	5,090,000,000
10	680,000,000	50,000,000	5,720,000,000
11	680,000,000	50,000,000	6,350,000,000
12	680,000,000	50,000,000	6,980,000,000

For evaluation purposes only!

Fig. 16.9 Dynamics of demand processes

16.6 Results

16.6.1 Pandemic Multiplier Activation Scenario

In this scenario, we introduced the following changes or parametric values from the base:

(i) Pandemic Multiplier from 1 to 17.
(ii) Target Service Level from 3 to 1.

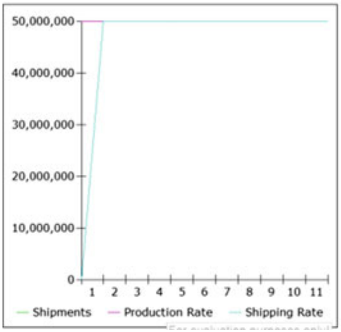
In this case, we're under the assumption that a pandemic has hit around the globe, and the demand has increased by 1700%. Without any safety stock already on hand or any increase in capacities, we can see the following behavior as is shown in Fig. 16.9:

The graph of units shipped over time shows how the lack of a 3-month window to complete orders forces us to ship as fast as we can. This also means that the backlog keeps growing at a constant rate, as Fig. 16.10 shows, instead of trying to reach a certain level and staying there as we saw in the previous example. In this scenario, we never have any extra production, shipping, or mask inventory. As soon as the pandemic starts, we use up all the masks as soon as they are produced. But we still can't ship as much as we could if we had more masks because our production rate is lower than our shipping.

16.6.2 Surge Capacity Scenario

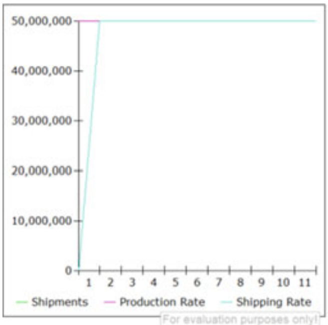
In this scenario, we introduced the following changes or parametric values from the base:

(i) Pandemic Multiplier from 1 to 17.
(ii) Target Service Level from 3 to 1.
(iii) Surge Capacity from 1 to 2.



Months	Production Rate	Shipping Rate	N95 Mask Inventory
1	50,000,000	0	0
2	50,000,000	50,000,000	50,000,000
3	50,000,000	50,000,000	50,000,000
4	50,000,000	50,000,000	50,000,000
5	50,000,000	50,000,000	50,000,000
6	50,000,000	50,000,000	50,000,000
7	50,000,000	50,000,000	50,000,000
8	50,000,000	50,000,000	50,000,000
9	50,000,000	50,000,000	50,000,000
10	50,000,000	50,000,000	50,000,000
11	50,000,000	50,000,000	50,000,000
12	50,000,000	50,000,000	50,000,000

Fig. 16.10 Dynamics of faster shipments



Months	Production Rate	Shipping Rate	N95 Mask Inventory
1	50,000,000	0	0
2	50,000,000	50,000,000	50,000,000
3	50,000,000	50,000,000	50,000,000
4	50,000,000	50,000,000	50,000,000
5	50,000,000	50,000,000	50,000,000
6	50,000,000	50,000,000	50,000,000
7	50,000,000	50,000,000	50,000,000
8	50,000,000	50,000,000	50,000,000
9	50,000,000	50,000,000	50,000,000
10	50,000,000	50,000,000	50,000,000
11	50,000,000	50,000,000	50,000,000
12	50,000,000	50,000,000	50,000,000

For evaluation purposes only!

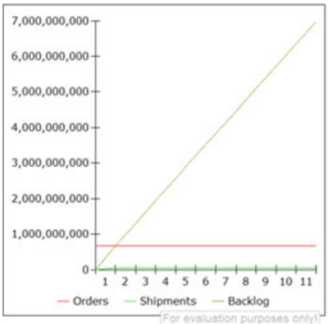
Fig. 16.11 Dynamics of surge capacity

3 M can increase its production of N95 masks by two times (Linnane, 2020). But they face a challenge in getting enough materials for the filter because all the other mask makers are also trying to produce more. The supply of raw materials is not enough to meet the demand. The graph of behavior over time in Fig. 16.11 shows what happens if we use the surge capacity, but don't get more raw materials.

We can see, as is shown in Fig. 16.12, that the output values of mask production, shipping, and inventory do not change at all even though we spend money to increase the capacity of making masks. This is because we did not also increase the amount of raw materials that we need to make the masks.

16.6.3 Surge Capacity and Increased Availability of Raw Materials Scenario

In this scenario, we introduced the following changes or parametric values from the base:



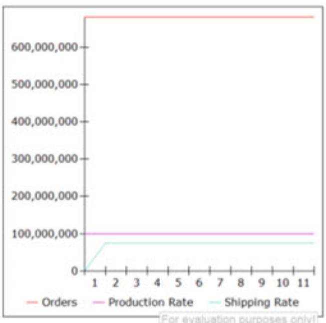
Months	Orders	Shipments	Backlog
1	680,000,000	0	0
2	680,000,000	50,000,000	680,000,000
3	680,000,000	50,000,000	1,310,000,000
4	680,000,000	50,000,000	1,940,000,000
5	680,000,000	50,000,000	2,570,000,000
6	680,000,000	50,000,000	3,200,000,000
7	680,000,000	50,000,000	3,830,000,000
8	680,000,000	50,000,000	4,460,000,000
9	680,000,000	50,000,000	5,090,000,000
10	680,000,000	50,000,000	5,720,000,000
11	680,000,000	50,000,000	6,350,000,000
12	680,000,000	50,000,000	6,980,000,000

Fig. 16.12 Dynamics of surge capacity with material shortage

(i) Pandemic Multiplier from 1 to 17.
(ii) Target Service Level from 3 to 1.
(iii) Surge Capacity from 1 to 2.
(iv) Raw Materials Inventory from 50 to 100 million.

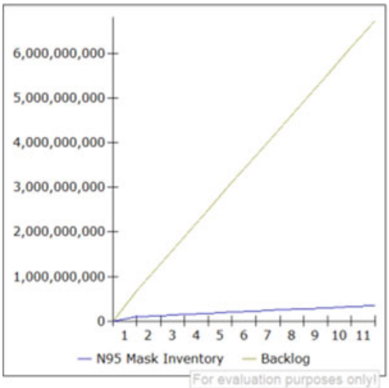
In this scenario, we've been able to procure enough raw materials to utilize our increased capacity. While in the big picture, as shown in Fig. 16.13, doubling the production to 100 million units per month is great, graphically it doesn't show a large difference when comparing backlog volumes.

Figure 16.14 shows a big problem that we have. We are only shipping 75 million masks per month even though we are making 100 million and we have orders for 680 million. We have a lot of orders that we can't fulfill and a backlog that keeps growing. But we also have a lot of masks that we don't ship and just store in our inventory. This is because we have increased our production capacity and our ability to meet the demand, but we have not increased our shipping capacity beyond the 75 million that we could do before we used the surge capacity. We need to hire more staff and work more hours to pack and ship the masks as fast as we can.



Months	Orders	Production Rate	Shipping Rate
1	680,000,000	100,000,000	0
2	680,000,000	100,000,000	75,000,000
3	680,000,000	100,000,000	75,000,000
4	680,000,000	100,000,000	75,000,000
5	680,000,000	100,000,000	75,000,000
6	680,000,000	100,000,000	75,000,000
7	680,000,000	100,000,000	75,000,000
8	680,000,000	100,000,000	75,000,000
9	680,000,000	100,000,000	75,000,000
10	680,000,000	100,000,000	75,000,000
11	680,000,000	100,000,000	75,000,000
12	680,000,000	100,000,000	75,000,000

Fig. 16.13 Dynamics of surge production capacity with increased material inventory



Months	N95 Mask Inventory	Backlog
1	0	0
2	100,000,000	680,000,000
3	125,000,000	1,285,000,000
4	150,000,000	1,890,000,000
5	175,000,000	2,495,000,000
6	200,000,000	3,100,000,000
7	225,000,000	3,705,000,000
8	250,000,000	4,310,000,000
9	275,000,000	4,915,000,000
10	300,000,000	5,520,000,000
11	325,000,000	6,125,000,000
12	350,000,000	6,730,000,000

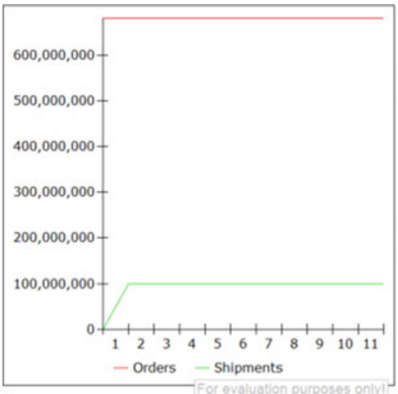
Fig. 16.14 Dynamics of inventory and backlog

16.6.4 Increased Shipping Capacity Scenario

In this scenario, we introduced the following changes or parametric values from the base:

(i) Pandemic Multiplier from 1 to 17.
(ii) Target Service Level from 3 to 1.
(iii) Surge Capacity from 1 to 2.
(iv) Raw Materials Inventory from 50 to 100 million.
(v) Shipment Capacity increased from 75 to 150 million.

In this scenario, we've increased our shipment capacity to match our output, and this has resulted in outgoing shipments increasing to 100 million a month, as is shown in Fig. 16.15.



Months	Orders	Shipments
1	680,000,000	0
2	680,000,000	100,000,000
3	680,000,000	100,000,000
4	680,000,000	100,000,000
5	680,000,000	100,000,000
6	680,000,000	100,000,000
7	680,000,000	100,000,000
8	680,000,000	100,000,000
9	680,000,000	100,000,000
10	680,000,000	100,000,000
11	680,000,000	100,000,000
12	680,000,000	100,000,000

Fig. 16.15 Dynamics of increased shipments

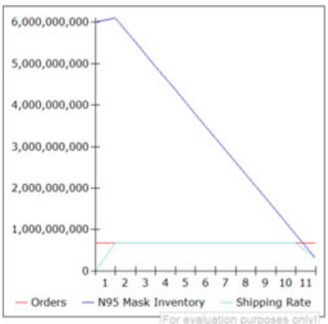
The graph and table in Fig. 16.15 show how the shipments have improved to match the 100 million masks that we can produce per month. We are now able to send out all the masks that we make without any delay. But this is still not enough to satisfy the customers who want to buy our masks. We have a huge gap of 580 million units per month between the orders that we receive and the products that we create. Increasing our production capacity by two times was not enough to keep up with the increased demand. We need to find other ways to fill this gap and meet the customer needs. We considered two possible options: Having a large stock of masks ready at the start of the pandemic to use when the demand spikes or increasing our production capacity, even more, to make more masks as the demand grows.

16.6.5 Emergency Stock Scenario

In this scenario, we introduced the following changes or parametric values from the base:

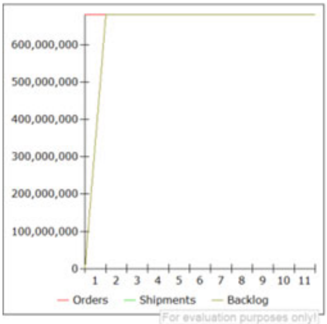
(i) Pandemic Multiplier from 1 to 17.
(ii) Target Service Level from 3 to 1.
(iii) Raw Materials Inventory from 50 to 100 million.
(iv) Starting Inventory of 10 billion.
(v) Shipment Capacity increased to 700 million from 75 million.

In this scenario, as is shown in Fig. 16.16, I've assumed that 3 M can hold 6 billion masks in storage in the event a pandemic happens they're prepared to meet the demand for N95 masks. The problem with this is holding this level of inventory for something that may or may not happen is extremely expensive. In addition, N95 masks have a shelf life. The materials used to manufacture these masks eventually degrade and become less effective. This increases the potential for spoilage, which can be a huge sunk cost to the organization. Stockpiling is okay, but only in moderation.



Months	Shipping Rate	N95 Mask Inventory	Backlog
1	0	6,000,000,000	0
2	680,000,000	6,100,000,000	680,000,000
3	680,000,000	5,520,000,000	680,000,000
4	680,000,000	4,940,000,000	680,000,000
5	680,000,000	4,360,000,000	680,000,000
6	680,000,000	3,780,000,000	680,000,000
7	680,000,000	3,200,000,000	680,000,000
8	680,000,000	2,620,000,000	680,000,000
9	680,000,000	2,040,000,000	680,000,000
10	680,000,000	1,460,000,000	680,000,000
11	680,000,000	880,000,000	680,000,000
12	300,000,000	300,000,000	680,000,000

Fig. 16.16 Dynamics of emergency stock of N95 masks



Months	Orders	Shipments	Backlog
1	680,000,000	0	0
2	680,000,000	680,000,000	680,000,000
3	680,000,000	680,000,000	680,000,000
4	680,000,000	680,000,000	680,000,000
5	680,000,000	680,000,000	680,000,000
6	680,000,000	680,000,000	680,000,000
7	680,000,000	680,000,000	680,000,000
8	680,000,000	680,000,000	680,000,000
9	680,000,000	680,000,000	680,000,000
10	680,000,000	680,000,000	680,000,000
11	680,000,000	680,000,000	680,000,000
12	680,000,000	680,000,000	680,000,000

Fig. 16.17 Dynamics of mass production of N95 masks scenario

16.6.6 Mass Production of N95 Masks Scenario

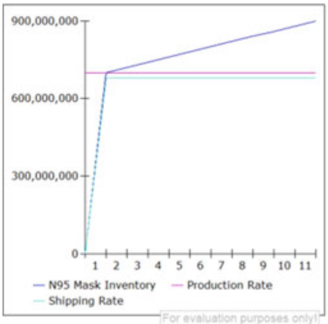
In this scenario, we introduced the following changes or parametric values from the base:

(i) Pandemic Multiplier from 1 to 17.
(ii) Target Service Level from 3 to 1.
(iii) Raw Materials Inventory from 50 to 700 million.
(iv) Surge Capacity increased from 1 to 14.
(v) Shipment Capacity increased to 700 million from 75 million.

In this situation, Fig. 16.17 shows what happens if we can produce enough masks to meet the demand as it happens. We do not have any delays or gaps in fulfilling the orders that we receive. We clear the backlog as soon as we get it, which means that the orders, shipments, and backlog are all the same. We do not have any extra inventory or production capacity. We just make and ship the masks as fast as the customers want them.

With production being at 700 million units, and shipments being at 680 million units, we slowly accrue more inventory than demand, which can be used to ramp down production in the future. Alternatively, we can order fewer raw materials and produce exactly 680 million masks instead of 700 million.

This solution also isn't feasible in reality. Increasing capacity by 14× immediately is virtually impossible. To do this, there would have to be significant outsourcing to other companies that have the correct equipment already. Alternatively, have enough idle machinery within the organization that can be turned on a dime. Idle capacity is expensive, and again not feasible for the organization (Fig. 16.18).



Months	Production Rate	Shipping Rate	N95 Mask Inventory
1	700,000,000	0	0
2	700,000,000	680,000,000	700,000,000
3	700,000,000	680,000,000	720,000,000
4	700,000,000	680,000,000	740,000,000
5	700,000,000	680,000,000	760,000,000
6	700,000,000	680,000,000	780,000,000
7	700,000,000	680,000,000	800,000,000
8	700,000,000	680,000,000	820,000,000
9	700,000,000	680,000,000	840,000,000
10	700,000,000	680,000,000	860,000,000
11	700,000,000	680,000,000	880,000,000
12	700,000,000	680,000,000	900,000,000

For evaluation purposes only!

Fig. 16.18 Dynamics of production, shipping, and inventory of N95 masks

16.7 Policy Recommendations and Conclusions

In this chapter, we have developed and simulated a system dynamics model of a supply chain that produces and delivers a product to customers. We have used this model to explore the effects of different policy changes on the performance of the supply chain, such as increasing the demand, increasing the production capacity, increasing the shipment capacity, and increasing the inventory of raw materials. We have found that increasing the demand alone can lead to a backlog of orders and a loss of revenue unless we also increase the other capacities and inventory levels in the supply chain. We have also found that increasing the production capacity alone can result in excess inventory and waste unless we also increase the shipment capacity and demand. We have learned that we need to consider the whole supply chain and how the policy changes affect all the partners and processes involved in the production and delivery of the product. We have also learned that we need to balance supply and demand in the supply chain to achieve optimal performance and customer satisfaction. We hope that our model can provide some insights and guidance for supply chain management and decision making in real-world scenarios.

We tried many different possible policy changes to see how we could improve our production capacity to match the known capabilities of our machines, and how we could keep more masks in stock for emergencies to be prepared for an unexpected increase in demand for N95 masks due to a pandemic. N95 masks are used to protect against respiratory infections and are part of the personal protective equipment (PPE) used by health workers. However, we found that none of the policy changes that we tried could fix the problem of meeting the increase in demand. There was no feasible solution that allowed our organization to keep operating and supplying masks. We also encountered difficulties in obtaining enough raw materials to make the masks, as some of the components that we needed were limited and in high demand by other mask makers. Sustainable supply chains for N95 masks and other PPE are not able to increase their capacity and production fast and flexibly enough to serve their purpose. In this scenario, we realized that it was important to increase not only the inventory of raw materials that we needed to make the masks, but also the production capacity that we had to make the masks, and the shipment capacity that we used to send the masks to the customers. All these factors were essential in producing and moving the product through the supply chain to the end users who required it.

When we try different policy changes, we discover a crucial theory in the supply chain that is very relevant. We cannot improve our ability to satisfy increased demand by just increasing one capacity or one level of the supply chain. We need to consider the entire supply chain and how the increased demand impacts all the partners who are involved in the production and delivery of the product. In this scenario, we see that it is important to increase the inventory of raw materials that we require to make the product, the production capacity that we possess to make the product, and the shipment capacity that we utilize to send the product to the customers. All these factors are vital in ensuring that we can produce and move the product through the supply chain to the end users who demand it.

Additionally, masks are not only required for front-line workers but have also proven to be effective in preventing the spread of infection by the general population. If N95 mask production cannot be increased in such a short period, additional measures must be taken. Production of surgical masks and dust masks should also be increased in response to a pandemic and also spreading knowledge of how to make homemade effective masks for the general public so the more effective N95 masks are available to front-line healthcare workers that are at greater risk. Homemade effective masks can be made from common fabrics such as cotton or silk, or household items such as vinegar or oatmeal.

In this chapter, we have analyzed the demand and supply of N95 masks during the COVID-19 pandemic. We have used a system dynamics model to simulate the dynamics of the N95 mask market under different scenarios and parameters. We have found that the demand for N95 masks has exceeded the supply by a large margin, leading to shortages and rationing in many healthcare facilities across the country. We have also found that increasing the production capacity of N95 masks alone is not enough to meet the demand unless we also increase the inventory and distribution of N95 masks. We have suggested some alternative measures to cope with the shortage of N95 masks, such as increasing the production of other types of masks, such as surgical masks and dust masks, and educating the general public on how to make homemade effective masks from common fabrics or household items. We have also suggested some preventive measures to reduce the demand for N95 masks, such as promoting social distancing, hand hygiene, and vaccination. We hope that our model can provide some insights and recommendations for N95 mask management and decision making during the pandemic and beyond.

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Chapter 17
Improving Healthcare Policy Decisions with Systems Thinking

Hassan Qudrat-Ullah

Abstract This chapter aims to assess the effectiveness of a system dynamics-based interactive learning environment, SIADH-ILE, for teaching and training health-care professionals and policymakers on how to prevent and treat HIV/AIDS. This research project uses action research and collects data from action experiments in real educational settings. The data includes the data from the SIADH-ILE program, and the questionnaire and qualitative data from the participants. The chapter examines whether using Interactive Learning Environments (ILEs) in the classroom helps learners. The findings, based on our SIADH-ILE experimental study, show that a combined approach, rather than a separate program on HIV/AIDS prevention and treatment, leads to fewer deaths from HIV/AIDS. The participants also report that they strongly support the scenario-based SIADH-ILE training. The chapter concludes that: (i) an integrated approach is needed for HIV/AIDS policies and programs in both public and private sectors, and (ii) training with debriefing-based simulations such as SIADH-ILE seems to be effective for improving the decision making skills of health policymakers and authorities who are fighting against HIV/AIDS.

Keywords Healthcare Policy · Dynamic task · System dynamics · Interactive Learning Environment (ILE) · Canada · HIV/AIDS · Scenarios · Healthcare professionals · Traning · Debrefing · Simulations · Laboratory-experiments · Perceptions

17.1 Introduction

Making better decisions is crucial for today's globalized businesses and organizations that have limited resources and constraints. Healthcare management, which is a complex and dynamic task, faces the challenge of using resources effectively (De Angelis et al., 2003; Zaki et al., 1997). Healthcare management, whether at a local or state level and whether in the public or private sector, involves making multiple and

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interdependent decisions in a changing environment that is affected by the decisions themselves or by other factors (Edwards, 1962; Sterman, 2000). The decision making process is even harder because of the different stakeholders who often have conflicting goals.

One of the major challenges in the healthcare sector is to provide healthcare services that are affordable, reliable, and time to meet the diverse and changing needs of the population (Gupta & Sharda, 2013; Ritchie-Dunham & Galván, 1999). This requires the people involved in planning, delivering, and evaluating healthcare services to make effective and efficient decisions using limited resources. However, many healthcare policy decisions that have good intentions often lead to poor outcomes such as longer waiting lines, higher costs, lower quality, and reduced access (Atun et al., 2007; Qudrat-Ulah, 2013). One reason for these poor outcomes is that decision makers use simple rules of thumb or intuition, while the task of managing healthcare is complex and dynamic (Atun, 2012). Healthcare systems are composed of multiple interconnected and interdependent elements, such as patients, providers, payers, regulators, and policymakers, that interact over time and influence each other in non-linear and often unpredictable ways (Homer & Hirsch, 2006). Moreover, healthcare systems are subject to various external factors, such as demographic changes, technological innovations, social trends, and economic conditions, that create uncertainties and challenges for decision making (Atun et al., 2007; Gupta & Sharda, 2013). Therefore, there is a need for tools that can help decision makers understand the complexity and dynamics of healthcare systems and evaluate the potential impacts and trade-offs of different policy options. Scenario-based SIADH-ILE is a tool that helps users understand the dynamics and complexity of HIV/AIDS and make better decisions for prevention and treatment measures. It is based on a system dynamics model that captures the causal relationships and feedback loops among various factors that affect the HIV epidemic in Canada. It allows users to create and compare different scenarios by changing the values of key variables, such as testing rates, treatment coverage, viral suppression, risk behaviors, and social determinants of health. It also provides users with graphical outputs that show the effects of different scenarios on the number of people living with HIV/AIDS, new infections, deaths, costs, and quality-adjusted life years. By using this tool, users can gain a deeper insight into the complexity of HIV/AIDS and make better-informed decisions for improving the health and well-being of people living with or affected by HIV/AIDS in Canada.HIV and AIDS are still a major global health problem. In 2017, there were 1.8 million new infections and 36.9 million people living with HIV and AIDS worldwide (Vu et al., 2020). In Canada, the HIV/AIDS epidemic among adults is not over yet. Policymakers have to deal with the complex task of using limited resources effectively and efficiently for preventing and treating HIV/AIDS (Farnham, 2010; Xu et al., 2020). Therefore, it is very important to educate and train policymakers on how to manage these complex tasks.

To do better in complex and dynamic tasks, one needs to understand and appreciate the basic structures (e.g., how different feedback loops, time delays, and nonlinear relationships among the variables of the task system interact and create the behavior) (Maier & Grobler, 2000; Sterman, 2000). System dynamics-based interactive learning environments (ILEs) are good for training in dynamic tasks (Alessi, 2000; Kriz, 2003; Lane, 1995). System dynamics models are causal models and can show how microstructures (e.g., decisions) and macro-level outcomes of the task system are connected. Thus, ILEs let the users practice their decision strategies in a safe and friendly environment (Sterman, 2000). By making and testing various scenarios, the users of these ILEs can "see" how their decisions lead to certain outcomes over time and learn and improve their decision making about the task (Größler et al., 2016; Qudrat-Ullah, 2010, 2013). Having a debriefing session after the practice with the simulated task helps the users of ILEs to reflect and correct any misunderstanding of the dynamic task and hence their double-loop learning is strengthened (Qudrat-Ullah, 2020). Education and training with ILEs, therefore, are expected to improve the decision making and learning of the users. In this chapter, we present how we developed, applied, and evaluated a system dynamics simulation-based ILE, SIADH-ILE. The new thing about this study is that it tests how effective scenario-based ILE is in improving the decision making and learning of healthcare professionals in a real educational setting.

This chapter aims to assess the effectiveness of a system dynamics-based interactive learning environment, SIADH-ILE, for teaching and training healthcare professionals and policymakers on how to prevent and treat HIV/AIDS. The study uses action research and collects data from action experiments in real educational settings. The data includes the data from the SIADH-ILE program, and the questionnaire and qualitative data from the participants. The paper examines whether using Interactive Learning Environments (ILEs) in the classroom helps learners. The findings, based on our SIADH-ILE experimental study, show that a combined approach, rather than a separate program on HIV/AIDS prevention and treatment, leads to fewer deaths from HIV/AIDS. The participants also report that they strongly support the scenario-based SIADH-ILE training. The chapter concludes that: (i) an integrated approach is needed for HIV/AIDS policies and programs in both public and private sectors, and (ii) training with debriefing-based simulations such as SIADH-ILE seems to be effective for improving the decision making skills of health policymakers and authorities who are fighting against HIV/AIDS.

17.2 Decision-Making and Learning with SIADH-ILE

17.2.1 Context

The HIV/AIDS epidemic in Canada has evolved from the early epidemic, which mainly affected men who have sex with men (MSM), to the current epidemic, which affects more groups such as injection drug users (IDU), aboriginal people, and women. The HIV/AIDS epidemic among adults in Canada is still a problem that requires urgent attention and action. According to national estimates, about 62,050 people were living with HIV/AIDS in Canada at the end of 2018, and about 2242 new HIV infections occurred in the same year. This means that every four hours, one person was infected with HIV. The majority of new infections were among gay, bisexual, and other men who have sex with men (gbMSM), who accounted for 49% of new cases. Indigenous Peoples and people who inject drugs were also disproportionately affected by HIV/AIDS, representing 14% and 14% of new infections respectively, but only 4.9 and 0.3% of the total Canadian population. HIV/AIDS is not only a medical issue, but also a social and economic one that impacts individuals, families, communities, and society as a whole. It affects the health and well-being of people living with or affected by HIV/AIDS, as well as their access to health care, education, employment, and human rights. It also imposes a significant burden on the health care system and the economy, as it increases the costs of treatment, care, and support services. Therefore, it is very important to understand how the HIV/AIDS situation among adults in Canada changes over time and what factors influence its trends and patterns. The need to understand the long-term effects of prevention and treatment policy decisions is even more urgent, as they can have significant impacts on the course and outcomes of the epidemic. Scenario-based SIADH-ILE is a tool that helps users understand the dynamics and complexity of HIV/AIDS and make better decisions for prevention and treatment measures. It is based on a system dynamics model that captures the causal relationships and feedback loops among various factors that affect the HIV epidemic in Canada. It allows users to create and compare different scenarios by changing the values of key variables, such as testing rates, treatment coverage, viral suppression, risk behaviors, and social determinants of health. It also provides users with graphical outputs that show the effects of different scenarios on the number of people living with HIV/AIDS, new infections, deaths, costs, and quality-adjusted life years. By using this tool, users can gain a deeper insight into the complexity of HIV/AIDS and make better-informed decisions for improving the health and well-being of people living with or affected by HIV/AIDS in Canada.

Training with modeling and simulation has been a key factor in improving healthcare management and delivery in different countries around the world (Haynes et al., 2020; Qudrat-Ullah & Tsasis, 2017; Tebbens et al., 2009). In recent years, system dynamics modeling, which is a method of modeling complex and dynamic systems using causal loops and stock and flow diagrams, was used by several researchers for different healthcare-related topics. For example, Morgana and Graber-Naidich (2019) used system dynamics modeling to "reduce the shortage of general practitioners in rural areas of Ontario, Canada," by exploring different policy scenarios. Van Ackere and Schulz (2020) used system dynamics modeling to "understand vaccination decisions," by analyzing how different factors influence the vaccination behavior of individuals and groups. Zou et al. (2018) used system dynamics modeling for "HIV control strategies," by simulating the impact of different interventions on the HIV epidemic in Canada. Kaya et al. (2020) used system dynamics modeling for the"evaluation of public policies," by comparing the outcomes of different policy options for health and social care in Turkey.

We developed and applied a dynamic model based on system dynamics, which is a method of modeling complex and dynamic systems using causal loops and stock and flow diagrams, that matches the data about the adult HIV/AIDS population in Canada. We did this to better understand how the HIV/AIDS situation among adults in Canada changes over time and what factors influence it. Specifically, using the simulation model-based ILE that we developed, which is an interactive learning environment that allows users to practice their decision strategies in a simulated task, we will examine the effect of different HIV/AIDS policy intervention scenarios that aim to reduce AIDS deaths. Reducing AIDS deaths is a main goal of any HIV/AIDS prevention and treatment care program, because it means saving lives and reducing the burden of the disease (Dangerfield et al., 2001; Guenter et al., 2005a, 2005b; Tebbens et al., 2009).

The simulation model-based ILE that we developed is an individual-based model that simulates the HIV transmission and progression among different population groups and regions in Canada (Rauner et al., 2010). The model incorporates the effects of various prevention and treatment measures for HIV/AIDS, such as HIV testing, condom use, harm reduction programs, and HAART vaccine. The model also estimates the costs and benefits of these measures, as well as the impacts on HIV incidence, prevalence, mortality, and quality-adjusted life years (QALYs). The users can interact with the model through a graphical user interface that allows them to modify the values of key variables and parameters, such as the effectiveness of the HAART vaccine, the contact frequency, and the infectivity. The users can also compare the outcomes of their scenarios with the outcomes of a baseline scenario that represents the current situation and policy. The simulation model-based ILE is designed to help the users learn about the complexity and uncertainty of the HIV/AIDS epidemic in Canada, and to improve their decision-making skills and policy analysis capabilities.

17.2.2 Simulation Model for SIADH-ILE

Feedback loops are the essential structures that underlie all dynamic tasks. They represent how different variables circularly influence each other, creating complex and dynamic behaviors. Figure 17.1 illustrates the causal relationships among various variables that are involved in our dynamic task. Our dynamic task is to manage the program that aims to prevent and treat HIV/AIDS infections among the adult population in Canada.

The simulation model, SIADH, shows how the birth rate and the death rate affect the number of people who are susceptible to HIV/AIDS. The susceptible population includes both adults who have been diagnosed with HIV and those who have not. The adults who are not infected with HIV will eventually die from other causes. Adults who are infected with HIV can get the virus through different ways, such as having sex with someone of the same or opposite gender, using drugs that are injected with needles, or receiving blood that is contaminated. The more people get infected, the

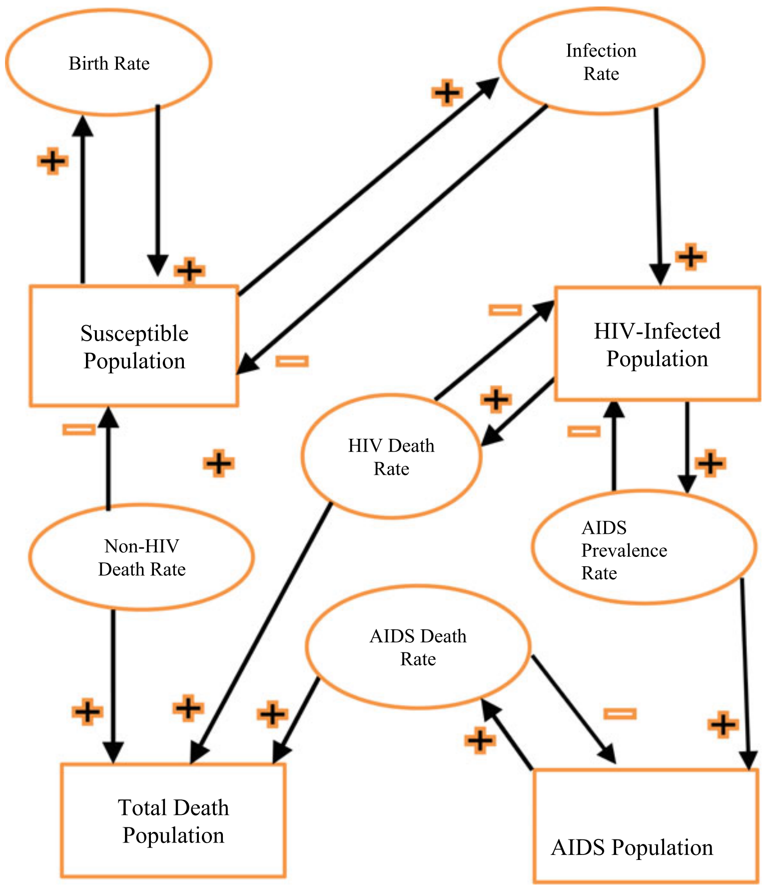

Fig. 17.1 Causal interactions in SIADH-ILE model. *Source* Qudrat-Ullah and Tsasis (2017)

more the infected population grows, and the fewer people get infected, the more the infected population shrinks. For adults who have sex with someone of the opposite gender, they can reduce their chances of getting infected by learning more about HIV/AIDS and how to prevent it. Once adults have HIV, they can develop AIDS in about ten years if they do not get any treatment. Those who get treatment such as HAART can live longer after getting HIV. However, some adults who have HIV will die without being in either of these two situations, and this will increase the total number of deaths.

The simulation model, SIADH, has four main variables (stocks) that change over time and affect the amount of resources that are needed for the prevention and treatment program. These four variables are the number of people who can get HIV/AIDS, the number of people who have HIV but not AIDS, the number of people who have AIDS, and the number of people who have died from HIV/AIDS or other causes. The formulas that describe how these four variables change over time are shown below:

$$\frac{\partial PS(t)}{\partial (t)} = R_b PS(t) - R_i PS(t) - R_{nd} PS(t) \tag{17.1}$$

$$\frac{\partial PI(t)}{\partial (t)} = R_i PI(t) - R_p PI(t) - R_h PI(t) \tag{17.2}$$

$$\frac{\partial PA(t)}{\partial (t)} = R_p PI(t) - R_a PA(t) \tag{17.3}$$

$$\frac{\partial PD(t)}{\partial (t)} = R_{ni} PS(t) + R_h PI(t) - R_a PA(t) \tag{17.4}$$

where PS (t) = Susceptible Population; PI (t) = Infected Population, PD (t): Death Stock, R_b = birth rate, R_i = Infection rate, R_{nd} = Non-HIV death rate, R_p = Prevalence rate, R_h = Aids death rate, and R_a = Infection death rate.

17.3 Learning Objective of SIADH-ILE

When managers have to deal with limited resources and many different priorities, they can use scenarios to help them make better choices (Adobor & Daneshfar, 2006a; Lane, 1995; Sterman, 2000). The goal of the scenario-based SIADH-ILE is to help the users learn how to test the effects of different policy scenarios about prevention and treatment measures for HIV/AIDS, and to "create a policy scenario that results in fewer deaths related to HIV/AIDS at a relatively lower cost." The scenario-based SIADH-ILE is based on a system dynamics model of the HIV/AIDS epidemic in Canada, which captures the dynamics of infection, prevention, and treatment among different population groups and regions (Wu et al., 2013). The model also incorporates the costs and benefits of different interventions, such as HIV testing, condom use, antiretroviral therapy (ART), and harm reduction programs (Zhang et al., 2014). The users can interact with the model through a user-friendly interface that allows them to change the values of key variables and parameters, such as the demand for HIV testing, the coverage of ART, and the budget allocation for different interventions. The users can also compare the results of their scenarios with the results of a baseline scenario that represents the current situation and policy. The users can evaluate their scenarios based on the indicators of HIV incidence, prevalence, mortality, and cost-effectiveness (Wang et al., 2015). The scenario-based SIADH-ILE is designed to help the users develop a deeper understanding of the complexity and uncertainty of the HIV/AIDS epidemic in Canada, and to enhance their decision-making skills and policy analysis capabilities.

The only treatment option that the users can choose is the HAART vaccine, which they can decide how effective it should be (i.e. how many years it should work). The more money they invest in research and development, the longer the average time that the vaccine will be effective. For prevention measures, they can choose two factors that affect how heterosexual infections are acquired and transmitted, which are (i) Contact Frequency, and (ii) Infectivity.

The HAART vaccine is a hypothetical vaccine that would provide long-term protection against HIV infection by stimulating the immune system to produce antibodies and T cells that can recognize and eliminate the virus (NIAID, 2020). The HAART vaccine is not yet available, but several clinical trials are underway to test its safety and efficacy (WHO, 2021). The users can assume that the HAART vaccine has been approved and can be used as a treatment option for people living with HIV/AIDS. The users can also assume that the HAART vaccine has different levels of effectiveness depending on the amount of money invested in research and development. For example, if the users invest $10 billion in research and development, the HAART vaccine will be effective for 10 years; if they invest $20 billion, the HAART vaccine will be effective for 20 years; and so on. The users can compare the effects of different levels of effectiveness of the HAART vaccine on the HIV/AIDS epidemic in Canada. Contact frequency and infectivity are two factors that affect how heterosexual infections are acquired and transmitted. Contact frequency refers to how often people have sexual intercourse with different partners. Infectivity refers to how likely a person is to transmit or acquire HIV during sexual intercourse. Both factors depend on several variables, such as sexual behavior, condom use, circumcision status, viral load, and co-infections (Boily et al., 2009). The users can change the values of contact frequency and infectivity to simulate different scenarios of prevention measures for heterosexual transmission of HIV/AIDS in Canada. For example, the users can increase contact frequency to simulate a scenario of increased sexual activity; they can decrease infectivity to simulate a scenario of increased condom use or ART coverage. They can decide how much money they want to spend on education awareness initiatives to improve prevention measures (by reducing both the contact frequency and infectivity). More details on these factors are given in Qudrat-Ullah (2013). Learners can practice with four scenarios that are provided to them and then design their own best policy scenario. Their performance is measured by the number of deaths related to HIV/AIDS and the cost of prevention and treatment measures (the best performance is the lowest number of deaths with the lowest cost) over 30 years. The four scenarios are:

Scenario 1: (Baseline) This scenario shows what would happen if nothing changes from the current situation.

Scenario 2: This scenario assumes that people can get HAART treatment and that the HAART vaccine works for an average of x years (users can choose the number of years from 10 to 20 and see how many lives are saved).

Scenario 3: In this scenario, both the Contact Frequency and the Infectivity are improved by x % (users can choose these two factors (in a range of 40% to 80%) and see how many lives are saved).

Scenario 4: This scenario considers the combined effect of prevention (i.e., Scenario 3) and treatment (i.e., Scenario 2) measures on the number of lives saved.

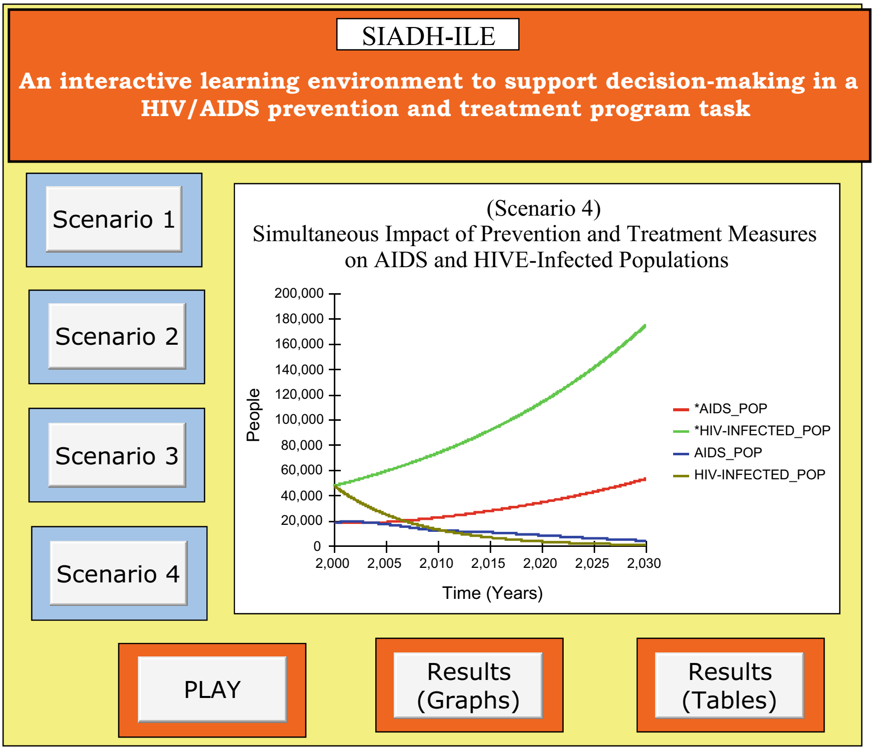

Fig. 17.2 The decision panel of SIADH-ILE. *Source* Qudrat-Ullah and Tsasis (2017)

17.4 User Interface of SIADH-ILE

Figure 17.2 illustrates the control panel and some of the graphs that the players/users can use to interact with the simulation model. The users can input their decisions for each scenario through the control panel. After they have chosen a scenario, they can then run their decisions by clicking the button "PLAY." The users can also see the outcomes of their decisions in different ways, both as graphs and as tables. For example, in Fig. 17.2, the graphical outcomes of Scenario 4 are shown.

17.5 Methods

This study uses action research and collects data through action experiments in real educational settings (Argyris, 1993; Davidsen & Spector, 1997; Klabbers, 2000). These experiments do not have control groups to compare with. The data that the SIADH-ILE program captures, as well as the questionnaire and qualitative data that are obtained in these settings, are used to explore whether the use of ILEs in classroom settings leads to learning benefits. All the data, except for the task performance data, are based on self-evaluations by the participants. The action experiments approach was selected to study the effect of using ILEs in a regular graduate course (e.g., health policy), without having any specific goal in the areas of system dynamics. The data collection took place between September 2021 and December 2022.

17.5.1 Sample and Setting Descriptions

In this section, we describe the two experimental settings: (i) business-as-usual setting and (ii) scenario-based setting.

17.5.1.1 Business as Usual Setting

The setting for this experiment was a graduate course on “health policy” at a large Canadian university. The main goal of this course was to help the students understand the dynamics and complexity of healthcare management systems, including how to design and evaluate policies at national and provincial levels. The course used different methods, such as lectures, case discussions, team assignments (with 3 or 4 students in each team), and individual study, to develop a basic understanding of how managerial decision making, healthcare systems operations, and sustainable business growth and profitability are interdependent. SIADH-ILE was introduced in the fifth week of this 13-week course to give the students a chance to experience the dynamics of these complex interdependencies. The students did the first trial in the sixth week. In the seventh week, there was a detailed debriefing session in which five students who were randomly chosen presented their simulation results and what they learned. The instructor guided the reviews of these results and the learning of all the teams. In the 13th week, all the students did the final trial. Thirty-one students (to match with the other setting) were randomly picked from the pool of 56 students. This course is offered twice a year. In the other setting, there were no structured scenarios given to the students.

17.5.1.2 Scenario-Based Setting

After running SIADH-ILE for two semesters, the design of SIADH-ILE was improved by the inclusion of three structured scenarios (Gupta & Sharda, 2013). Now, post-2019 academic year, the users of SIADH-ILE have to play these three scenarios before making their decisions (i.e., how many years of the efficacy of HAART, how much % improvement in Contact Frequency and how much % improvement in the Infectivity Rate) in their Trial 1 and Trial 2. This was the only change in this setting as compared with business as the usual setting. Only 31 students participated in this scenario-based SIADH-ILE course.

17.5.2 Participants

The experiment involved 31 healthcare professionals who took a pre-test, SIADH-ILE-based training, and a post-test. The participants were 55% male and 45% female. The average age of the participants was 33 years old. The participants had an average of 7.2 years of work experience in the healthcare industry. Before taking this SIADH-ILE-based course in health policy, each participant had completed an average of nine credit hours of graduate coursework. Each participant was offered an incentive of 5% bonus marks that were added to their final exam grade.

17.5.3 Protocols

On the day of the session of SIADH-ILE, subjects came to the computer lab and were seated randomly. Before they started interacting with the simulated task, they received information about the task structures, including the key feedback loops of the task system, in a lecture format. During the session of the simulated task, each subject could ask the facilitator any questions about the task. All the subjects did the two trials that were required. After they finished their first trial (Trial 1), they had a debriefing session where they could compare their performance charts with the "expert solution." They could also ask any questions in this session. The same facilitator conducted all the sessions. The second trial (Trial 2) took place after a gap of 6 weeks, which was similar to the case of our control group in the Business-as-Usual scenario.

17.6 Results

How much did the scenario-based SIADH-ILE help the subjects make better decisions in the healthcare domain? Our initial results are promising. The performance of all the subjects improved on the three measures. We present some of these performance improvements here. Table 17.1 shows the results of single-factor ANOVA, which confirm the significant improvement in the subjects' task knowledge. The average score of the subjects on task knowledge increased from 8.2 (on the pre-task knowledge test) to 15.7 (on the post-task knowledge test) with a p-value of 0.000.

Figure 17.3 shows the task performance of User-K (who was randomly chosen), measured by the number of deaths related to AIDS. This user performed much better than the average performance of the base-case scenario (the usual case) (F-value $= 27.5$; p-value $= 0.000$). If User-K's policy is put into practice, 23,205 lives are saved over 30 years. When we examined the decisions of User-K that led to this performance, we found that a 12-year effectiveness of HAART, a 51% improvement in Contact Frequency, and a 62% improvement in the Infectivity (i.e., the rate of

Table 17.1 Evidence of task knowledge improvement

Source of variation	SS	df	MS	F	*P*-value	F crit
Between groups	7,518,892	1	7,518,892	24.19452	7.11E − 06	4.001191
Within groups	18,646,099	60	310,768.3			
Total	26,164,990	61				

infection) through investing in technology, education and awareness programs across Canada were the main factors. We also looked at the task performance of several other users and found similarities in their decisions (i.e., the choices of the parameters of the dynamic task). Training with scenario-based SIADH-ILE seems to help the subjects make better decisions and learn more about dynamic tasks.

With regards to transferring learning, users of SIADH-ILE were assessed on the same task but with an elapsed period of six weeks since they had the post-task debriefing session. Based on this temporal context, we can characterize this task as a transfer task (Barnett & Ceci, 2002). For consistency and comparison's sake, we chose the same user, User-K to assess transfer learning. Figure 17.4 presents User-K's transfer learning.

Compared with the average performance of the base-case scenario (business-as-usual case), this user performed much better than the average performance of the base-case scenario (the usual case) (F-value = 26.3; *p*-value = 0.000). If User-K's policy is put into practice, 23,906 lives are saved over 30 years. When we examined the decisions of User-K that led to this transfer learning, we found that a 10-year effectiveness of HAART, a 55% improvement in Contact Frequency, and a 67% improvement in the Infectivity (i.e., the rate of infection) were the main factors. We also looked at the task performance of several other users and found similarities in their decisions (i.e., the choices of the parameters of the dynamic task).

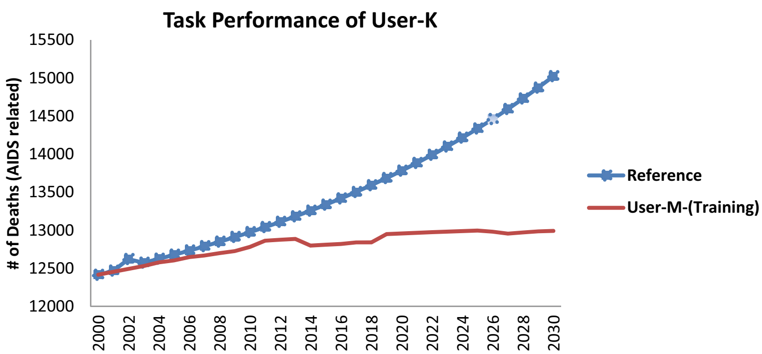

Fig. 17.3 Task performance improvement (of User-K) in SIADH-ILE

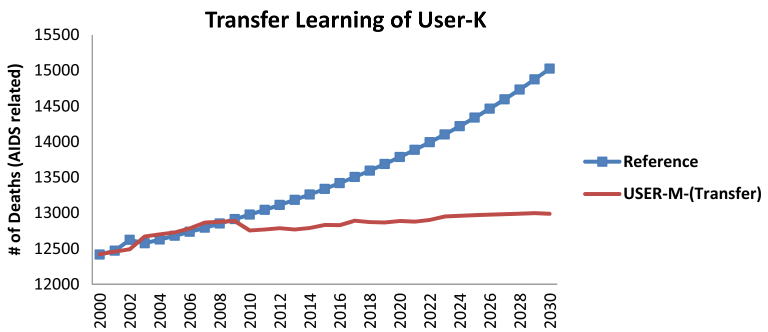

Fig. 17.4 Transfer learning improvement (of User-K) in SIADH-ILE

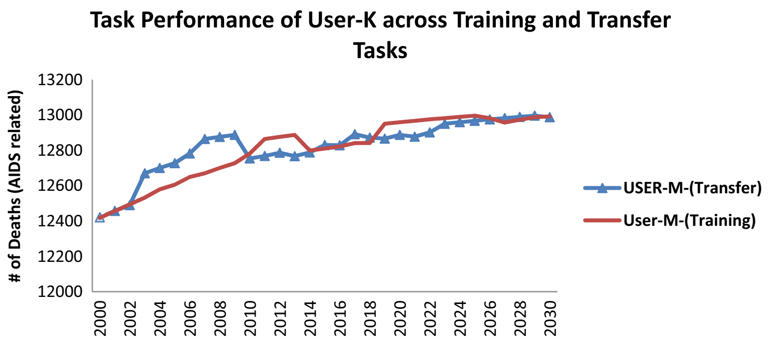

Fig. 17.5 Transfer learning improvement, across training and transfer tasks (of User-K) in SIADH-ILE

To further confirm the subjects' decision-making and learning in a training session with scenario-based SIADH-ILE, we also compared how User-K performed in both the regular task (during the training session) and the transfer learning task (after a gap of six weeks). Figure 17.5 shows this performance. Based on the task performance chart, it is reasonable to claim that training with scenario-based SIADH-ILE helps users to develop skills for transfer learning. We, therefore, are confident that such users will use the knowledge they learned when they encounter actual real-world situations that require decision-making.

17.6.1 Perceived Utility of Scenario-Based SIADH-ILE

We asked users to fill out a questionnaire about how useful scenario-based SIADH-ILE was for their decision-making and learning in the dynamic task. In Table 17.2, we can see that users gave very positive feedback for usability through their questions 1–15 and effectiveness through the rest of the questions in the questionnaire. Therefore, the usability and effectiveness of the scenario-based SIADH-ILE-based training have been confirmed by the positive feedback we received from the users. Overall, the users strongly (with a score of 4.41 out of 5) recommend scenario-based SIADH-ILE-based training to their fellow healthcare professionals. It is interesting to note that the ratings that users gave themselves are consistent with their actual performance in the dynamic task of managing HIV/AIDS in Canada. This suggests that the users were able to accurately assess their level of knowledge and competence after using the scenario-based SIADH-ILE tool. This is in line with Haynes et al. study that focused on systems dynamics and found that research, tools, and methods that were informed by systems dynamics helped to change the way of preventing problems and create new solutions for old problems (Haynes et al, 2020). Systems dynamics is a method of understanding complex systems and their behavior over time. It allows users to explore the causal relationships and feedback loops among various factors that influence the system's outcomes and to test different scenarios and interventions. Haynes et al. (2020) applied systems thinking to knowledge mobilization (KM) in public health and argued that it can enhance and transform KM by upholding a pluralistic view of knowledge, addressing contextual factors, fostering collaborative practices, and enabling adaptive learning. Scenario-based SIADH-ILE is an example of a tool that applies systems dynamics to KM in HIV/AIDS management. It is based on a system dynamics model that captures the causal relationships and feedback loops among various factors that affect the HIV epidemic in Canada. It allows users to create and compare different scenarios by changing the values of key variables, such as testing rates, treatment coverage, viral suppression, risk behaviors, and social determinants of health. It also provides users with graphical outputs that show the effects of different scenarios on the number of people living with HIV/AIDS, new infections, deaths, costs, and quality-adjusted life years. By using this tool, users can gain a deeper insight into the complexity of HIV/AIDS and make better-informed decisions for improving the health and well-being of people living with or affected by HIV/AIDS in Canada.

17.7 Conclusion

We wanted to know how useful scenario-based SIADH-ILE was for the users' decision-making and learning in the dynamic task of managing HIV/AIDS in Canada. So we asked them to fill out a questionnaire about their experience and satisfaction with the tool. In Table 17.2, we can see that the users gave very positive feedback for both usability and effectiveness through their answers to the questions in the questionnaire. They rated the tool highly on aspects such as ease of use, clarity of instructions, relevance of scenarios, usefulness of feedback, and overall learning outcomes. Therefore, the positive feedback we received from the users confirmed the usability and effectiveness of the scenario-based SIADH-ILE-based training. Overall, the users strongly (with a score of 4.41 out of 5) recommend scenario-based SIADH-ILE-based training to other healthcare professionals who want to improve

Table 17.2 Results from the users' Feedback questionnaire

Construct	Mean	Standard deviation
User interface: using scenario-based SIADH-ILE *is*		
1. Fun	4.35	0.15
2. Pleasant	4.38	0.15
3. Exciting	4.01	0.14
4. Enjoyable	4.35	0.17
5. Is easy-to-use	4.15	0.16
6. Has a user-friendly interface	4.2	0.14
7. Represents a real business situation	4.29	0.13
8. Has effective online help	4.44	0.14
9. Provides immediate and useful feedback		
User manual: The Scenario-based SIADH-ILE		
10. Has well written and self-explanatory user manual	4.41	0.16
Human facilitation		
11. The pre-task level was useful & increased my interest	3.73	0.16
12. In-task level was useful	4.35	0.15
13. Post-task level (debriefing) was very useful	4.32	0.14
Recommendation		
14. Overall, I strongly suggest scenario-based SIADH-ILE-based training for healthcare professionals and decision makers	4.41	0.14

their decision-making and learning skills in HIV/AIDS management. It is interesting to see that the ratings that the users gave themselves match their actual performance in the dynamic task. This suggests that the users were able to accurately assess their level of knowledge and competence after using the tool. This is consistent with a study by Haynes et al. that focused on systems dynamics and found that user research, tools, and methods that were informed by systems dynamics helped to change how problems were prevented and solved (Haynes et al, 2020). Systems dynamics is a method of understanding complex systems and their behavior over time. Scenario-based SIADH-ILE is based on a system dynamics model that captures the causal relationships and feedback loops among various factors that affect the HIV epidemic in Canada. It allows users to create and compare different scenarios by changing the values of key variables, such as testing rates, treatment coverage, viral suppression, risk behaviors, and social determinants of health. It also provides users with graphical outputs that show the effects of different scenarios on the number of people living with HIV/AIDS, new infections, deaths, costs, and quality-adjusted life years. By using this tool, users can gain a deeper insight into the complexity of HIV/AIDS and make better-informed decisions for improving the health and well-being of people living with or affected by HIV/AIDS in Canada.HIV/AIDS is a complex system that affects many aspects of health and society in Canada. It is a chronic condition caused by the human immunodeficiency virus (HIV) that weakens the immune system and makes people more vulnerable to infections and diseases. In 2018, about 62,050 people were living with HIV/AIDS in Canada, and about 2242 new HIV infections occurred. This means that every four hours, one person was infected with HIV. The majority of new infections were among gay, bisexual, and other men who have sex with men (gbMSM), who accounted for 49% of new cases. Indigenous Peoples and people who inject drugs were also disproportionately affected by HIV/AIDS. HIV/AIDS is not only a medical issue, but also a social and economic one that impacts individuals, families, communities, and society as a whole. To address the challenges and complexities of HIV/AIDS, there is a need for evidence-based tools that can help users understand the dynamics and interactions of various factors that influence the spread and outcomes of the infection. Scenario-based SIADH-ILE is one such tool that helps users explore different scenarios and interventions related to HIV/AIDS prevention and treatment measures. It allows users to simulate the effects of different variables, such as testing rates, treatment coverage, viral suppression, risk behaviors, and social determinants of health, on the HIV epidemic in Canada. By using this tool, users can gain a deeper insight into the complexity of HIV/AIDS and make better-informed decisions for improving the health and well-being of people living with or affected by HIV/AIDS in Canada.

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Chapter 18
Understanding the Dynamics of Endangered Species with System Dynamics Approach

Hassan Qudrat-Ullah

Abstract Various organizations request funds from the public and other sources to support conservation efforts for endangered animals. But what is the importance of this issue and how effective are these efforts? This chapter explores the idea of endangered species and examines the question of whether conservation can successfully protect all of them from extinction. Using a system dynamics model, it simulates the scenarios of what would happen to these species without conservation and how they would recover with conservation. It also discusses the challenges and limitations of applying conservation strategies, some of which are within our control and some of which are not. It considers the factors such as habitat loss, climate change, poaching, and human-wildlife conflicts that affect the survival and well-being of these species.

Keywords Conservation efforts · Endangered species · Poaching · System dynamics · Model-based analysis · African wild dog · Tiger · Mountain gorilla · Model validation and testing · Causal loop diagram · Dynamic hypothesis · Conceptual model · Quality of habitat

18.1 Introduction

Endangered species are animals or plants that are at risk of extinction due to human activities, natural disasters, or other factors. According to the International Union for Conservation of Nature (IUCN), there are more than 38,000 species that are threatened with extinction worldwide (IUCN, 2020). Protecting endangered species is not only important for preserving biodiversity and ecosystem services but also for ethical and cultural reasons. However, conservation efforts face many challenges and limitations, such as lack of funding, political conflicts, habitat loss, climate change, and poaching (Smith & Jones, 2019).

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The effectiveness and feasibility of conservation depend on various factors, such as the biological characteristics of the species, the availability and quality of habitat, the level and type of threat, the cost and benefit of conservation actions, and the social and political context (Brown & Green, 2018). For example, some species may have low reproductive rates, high habitat specificity, or high vulnerability to poaching or climate change, which may limit their chances of survival and recovery (Smith & Jones, 2019). Therefore, it is essential to evaluate conservation strategies for different endangered species using realistic models that account for these factors.

The models in general and system dynamics models, in particular, are rare useful tools to compare the outcomes and trade-offs of different conservation options and to identify the optimal strategies for each species (Liu & Zhang, 2019). However, the models also have some limitations and assumptions that need to be acknowledged and addressed. For example, the models may not capture all the complexities and interactions of real-world situations or account for all the possible factors that may affect conservation effectiveness and feasibility (Johnson & Wilson, 2018). Therefore, the models should be interpreted with caution and complemented with other sources of information and knowledge.

The models have important implications for conservation policy and practice. They can help inform decision-making and prioritization of conservation resources and actions. They can also help evaluate the progress and impact of conservation efforts and identify the gaps and challenges that need to be addressed (Taylor & Clark, 2017). Furthermore, the models have potential applications for future research. They can help generate new hypotheses and questions that can be tested empirically or theoretically. They can also help improve the data collection and analysis methods that can enhance the accuracy and reliability of the models (Martin & Smith, 2020).

This chapter uses a system dynamics model to simulate the scenarios of extinction without conservation and recovery with conservation for various species. This model is based on data from literature reviews and field surveys. This dynamic model incorporates demographic, ecological, economic, and social parameters to estimate the population dynamics and viability of different species under different conservation interventions (Lee & Kim, 2020). The dynamic model also considers the uncertainty and variability inherent in natural systems and human behavior (Wang & Chen, 2021). This chapter also discusses the difficulties and constraints of applying conservation measures, some of which are manageable and some of which are beyond our control.

18.2 Theoretical Review

18.2.1 Concepts, Definitions, and Background Literature About Endangered Species

When it comes to endangered species, we have to start by understanding the definition of species followed by endangered. The World Wildlife Foundation defines species with the following definition, "a species can be an animal, a tree, a coral, a fungus, an insect, or any number of other life forms on this planet (including humans). All together we call this range of life 'biodiversity" ("What does 'endangered species mean?"). However, this definition is not universally accepted, as some biologists argue that species are not fixed entities but dynamic and evolving groups of organisms that can interbreed and exchange genes (De Queiroz, 2007). Therefore, the concept of species is not only a biological but also a philosophical and ethical issue.

Endangered species are those that are at risk of extinction due to human activities, natural disasters, or other factors. According to the International Union for Conservation of Nature (IUCN), there are more than 38,000 species that are threatened with extinction worldwide (IUCN, 2020). Protecting endangered species is not only important for preserving biodiversity and ecosystem services but also for ethical and cultural reasons. For example, some endangered species have intrinsic value as living beings that deserve respect and care, while others have instrumental value as sources of food, medicine, or inspiration for human societies (Sandler & Cafaro, 2005).

However, conservation efforts face many challenges and limitations, such as lack of funding, political conflicts, habitat loss, climate change, and poaching (Smith & Jones, 2019). Moreover, conservation strategies may vary depending on the biological characteristics of the species, the availability and quality of habitat, the level and type of threat, the cost and benefit of conservation actions, and the social and political context (Brown & Green, 2018). For example, some species may have low reproductive rates, high habitat specificity, or high vulnerability to poaching or climate change, which may limit their chances of survival and recovery (Smith & Jones, 2019). Therefore, it is essential to evaluate conservation strategies for different endangered species using realistic models that account for these factors.

This leads us to our second question, which is what would be defined as endangered. This answer is a bit more complex and requires a bit more explanation. The World Wildlife Foundation defines species with the following definition, "a species can be an animal, a tree, a coral, a fungus, an insect, or any number of other life forms on this planet (including humans). All together we call this range of life 'biodiversity" ("What does 'endangered species' mean?"). However, this definition is not universally accepted, as some biologists argue that species are not fixed entities but dynamic and evolving groups of organisms that can interbreed and exchange genes (De Queiroz, 2007). Therefore, the concept of species is not only a biological but also a philosophical and ethical issue.

Endangered species are those that are at risk of extinction due to human activities, natural disasters, or other factors. According to the International Union for Conservation of Nature (IUCN), there are more than 38,000 species that are threatened with extinction worldwide (IUCN, 2020). The IUCN uses a set of quantitative criteria and categories to evaluate the extinction risk of each species based on factors such as population size, distribution range, population trend, and probability of extinction (Rodrigues et al., 2006). However, these criteria and categories are not always applicable or reliable for all species or groups, as they may depend on the availability and quality of data, the assumptions and uncertainties involved in the assessment process, and the variability and complexity of natural systems (Mace et al., 2008).

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It appears as though our question has led to another question, which is defining each category to better understand how these labels apply. The WWF defines them as such,

- "Critically endangered: A species considered to be facing an extremely high risk of extinction in the wild" ("What does 'endangered species' mean?").
- "Endangered: A species considered to be facing a very high risk of extinction in the wild" ("What does 'endangered species' mean?").
- "Vulnerable: A species considered to be facing a high risk of extinction in the wild" ("What does 'endangered species' mean?").

These definitions are based on the quantitative criteria established by the IUCN, which include factors such as population size, distribution range, population trend, and probability of extinction (Rodrigues et al., 2006). However, these criteria are not always applicable or reliable for all species or groups, as they may depend on the availability and quality of data, the assumptions and uncertainties involved in the assessment process, and the variability and complexity of natural systems (Mace et al., 2008).

Once a label is applied to a species it does not mean that they will remain in that category forever, their statuses can change and shift either up or downward. A species that happen to start to successfully recover due to conservation efforts could be downlisted from critically endangered to endangered or vulnerable and eventually removed from the list if it is no longer threatened with extinction ("What does 'endangered species' mean?"). For example, the giant panda was downlisted from endangered to vulnerable in 2016 after its population increased by 17% in a decade due to habitat protection and restoration measures (IUCN, 2016). On the other hand, a species that faces increasing threats due to human activities or environmental changes could be uplifted from vulnerable to endangered or critically endangered, and eventually become extinct if no effective conservation actions are taken ("What does 'endangered species' mean?"). For example, the vaquita, a small porpoise endemic to the Gulf of California, was uplisted from vulnerable to critically endangered in 1996 after its population declined by more than 80% in a decade due to accidental entanglement in fishing nets (IUCN, 2020).

18.2.2 Endangered Species Laws

When we see the critical nature of endangered species, as discussed above, it may seem discouraging, but there is hope. Humans aren't all bad; some wish to make up for their mistakes and one way to do this is by having laws and legislation in place to protect those species that have become either endangered or critically endangered.

"The Endangered Species Act (ESA) was enacted by Congress in 1973. Under the ESA, the federal government has the responsibility to protect endangered species (species that are likely to become extinct throughout all or a large portion of their range), threatened species (species that are likely to become endangered shortly), and critical habitat (areas vital to the survival of endangered or threatened species)" ("Endangered Species").

"The Endangered Species Act has lists of protected plant and animal species both nationally and worldwide. When a species is given ESA protection, it is said to be a "listed" species. Many additional species are evaluated for possible protection under the ESA, and they are called "candidate" species" ("Endangered Species).

The Endangered Species Act is considered one of the most powerful and effective environmental laws in the world, as it has prevented the extinction of 99% of the species listed under its protection and has contributed to the recovery of many iconic species such as bald eagles, gray wolves, grizzly bears, and humpback whales (Center for Biological Diversity, 2019). However, the Endangered Species Act also faces many challenges and limitations, such as political interference, funding shortages, legal conflicts, scientific uncertainty, and climate change (Vucetich et al., 2019). Moreover, the Endangered Species Act is not the only law or policy that affects the conservation of endangered species, as there are also international agreements, state and local regulations, and private initiatives that play a role in protecting biodiversity (Ruhl, 2008). Therefore, it is important to evaluate the interactions and synergies among different laws and policies for different endangered species using interdisciplinary approaches that account for ecological, legal, social, and economic factors.

The Endangered Species Act is very important because it saves our native fish, plants, and other wildlife from going extinct. Once gone, they're gone forever, and there's no going back. Losing even a single species can have disastrous impacts on the rest of the ecosystem because the effects will be felt throughout the food chain "from providing cures to deadly diseases to maintaining natural ecosystems and improving the overall quality of life, the benefits of preserving threatened and endangered species are invaluable" ("Endangered Species").

"The Endangered Species Act has lists of protected plant and animal species both nationally and worldwide. When a species is given ESA protection, it is said to be a "listed" species. Many additional species are evaluated for possible protection under the ESA, and they are called "candidate" species" ("Endangered Species").

"The term "take" is used in the Endangered Species Act to include "harass, harm, pursue, hunt, shoot, wound, kill trap, capture, or collect, or to attempt to engage in any such conduct." The law also protects against interfering in vital breeding and behavioral activities or degrading critical habitat" ("Endangered Species"). The Endangered Species Act is considered one of the most powerful and effective environmental laws in the world, as it has prevented the extinction of 99% of the species listed under its protection and has contributed to the recovery of many iconic species such as bald eagles, gray wolves, grizzly bears, and humpback whales (Center for Biological Diversity, 2019). However, the Endangered Species Act also faces many challenges and limitations, such as political interference, funding shortages, legal conflicts, scientific uncertainty, and climate change (Vucetich et al., 2019). Moreover, the Endangered Species Act is not the only law or policy that affects the conservation of endangered species, as there are also international agreements, state and local regulations, and private initiatives that play a role in protecting biodiversity (Ruhl, 2008). Therefore, it is important to evaluate the interactions and synergies among different laws and policies for different endangered species using interdisciplinary approaches that account for ecological, legal, social, and economic factors. Utilizing the power of the systems thinking approach, we will account for these factors to analyze and get insights about how can we better manage the endangered species of the world. In the next section, we present our Dynamic Hypothesis aka the conceptual model to better understand the dynamics of endangered species.

18.3 Dynamic Hypothesis About the Dynamics of Endangered Species

Based on the literature review and available empirical data, here we present our systems thinking-based conceptual model for understanding the dynamics of endangered species. Systems thinking is a holistic approach that focuses on the interrelationships and feedback loops among the elements of a system rather than the individual parts (Senge, 1990). By applying systems thinking to the issue of endangered species, we aim to identify the key factors and processes that influence the survival and recovery of these species and how they interact with each other over time. As soon as a species is classified as threatened or endangered by the International Union for Conservation of Nature (IUCN), it receives special protections from the federal government under the Endangered Species Act (ESA). The IUCN uses a set of quantitative criteria and categories to evaluate the extinction risk of each species based on factors such as population size, distribution range, population trend, and probability of extinction (Rodrigues et al., 2006). The ESA protects animals from being "taken" and being traded or sold and protects plants if on federal property or if federal actions are involved (Endangered Species, n.d.). The term "take" is used in the ESA to include "harass, harm, pursue, hunt, shoot, wound, kill trap, capture, or collect, or to attempt to engage in any such conduct" (Endangered Species, n.d.). The law also protects against interfering in vital breeding and behavioral activities or degrading critical habitats (Endangered Species, n.d.). Our main goal is to prove that through conservation efforts, endangered species can be prevented from becoming extinct and restored to healthy and viable populations. Conservation efforts may include habitat protection and restoration, population monitoring and management, captive breeding and reintroduction, education and awareness, and policy and regulation (Smith & Jones, 2019). However, conservation efforts also face many challenges and limitations, such as lack of funding, political conflicts, habitat loss, climate change, and poaching (Smith & Jones, 2019). Moreover, conservation efforts may vary depending on the biological characteristics of the species, the availability and quality of habitat, the level and type of threat, the cost and benefit of conservation actions, and the social and political context (Brown & Green, 2018). Therefore, it is important to evaluate conservation efforts for different endangered species using realistic models that account for these factors. How can systems think to help us design and implement effective conservation strategies for endangered species? What are the benefits and limitations of using systems thinking for this purpose? What are some examples of successful conservation cases that used systems thinking? These are some of the questions that we will address in this chapter.

The causal loop diagram (CDL) shown in Fig. 18.1 is our conceptual model that illustrates the conservation effects.

In this CLD (i.e., our model), there are four major feedback loops of which three are negative (balancing) and one is positive (reinforcing) loops. The reinforcing loop represents a natural breeding phenomenon without any constraints or effects. In general, the higher the population, the more chance of breeding, therefore, more births, which increases the outstanding population. This creates a reinforcing loop, the Natural Breeding feedback loop.

In our Natural Death feedback loop, wild animals die for a variety of reasons natural and unnatural, but the common cause of death is falling prey to other animals in the food chain. The more a species of an animal is present, the more likely any number will fall prey to its predator. However, as predators hunt their prey, the population decreases, and as a result, the negative feedback gives us a balancing loop for our natural cause of death.

A similar effect can be seen when humans hunt or poach for animals, as is shown by the Hunting Effort balancing loop. They follow the same pattern as the animal

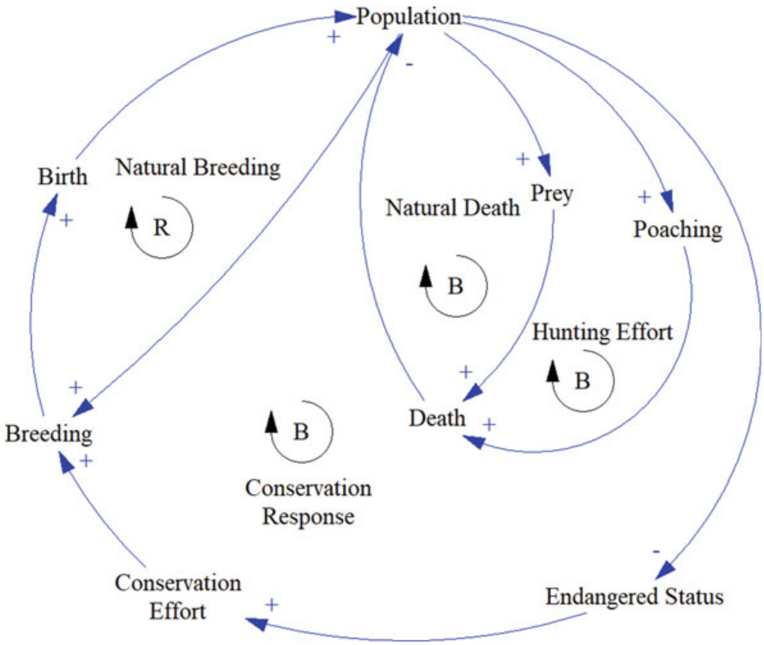


Fig. 18.1 The conceptual model of the conservation of the endangered species

falling prey and as a result a balancing loop. In general, the more a population of an in-demand animal is available to hunt, the more likely poachers will try to hunt the animal. We will note that anti-poaching measures can affect our CLD, but for the sake of simplicity, we are not including this.

Finally, in the Conservation Response loop, a balancing feedback loop, when the population reaches a critical number, the conservation effort starts. The animal in question is put on “Endangered Status”, and humans keep these endangered species in captive protection from poachers and other wild animals while giving ample ground and provision to breed the animals. When the population reaches an acceptable level, these animals are then released into the wild. But the higher the population for any species, the less likely it will be declared an endangered species and such negative feedback gives us a balancing loop.

18.4 Results Based on Our Simulation Model

For our analysis, we will run three simulations based on the Tiger, African Wild Dog, and Mountain Gorilla. We aim to see if conservation based on the current trends would be successful.

18.4.1 Assumptions of Our Simulation Model

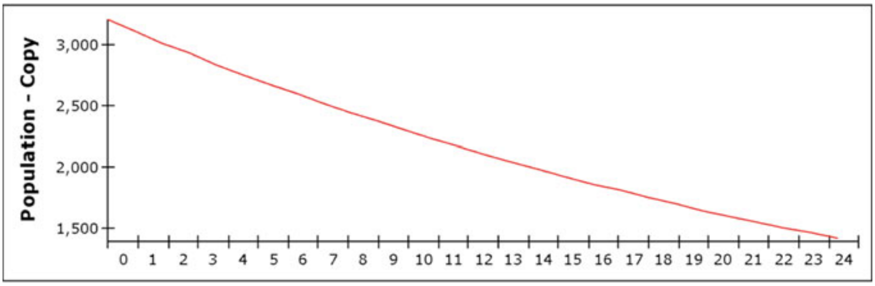
According to the IUCN Red List, the estimated population of the African wild dog is approximately 6600 adults in 39 subpopulations, of which only 1400 are mature individuals (Woodroffe et al., 2017). We used the estimated total population as the existing population constant for our analysis. According to Woodroffe et al., (2017) the projected population of the African wild dog would increase from 6600 in 2020 to 10,057 in 2030, assuming a constant growth rate of 4.30% and a constant death rate of 1%. This would represent an increase of 52.38% in 10 years.

In contrast to the African wild dog, the mountain gorilla has a much smaller population size and a much higher conservation status. According to the IUCN Red List, the population of the mountain gorilla is around 1004 today due to conservation efforts (Plumptre et al., 2018). This is an increase from 620 individuals in 1989 to 1004 today (Plumptre et al., 2018). However, there is still a lot to be done to keep this trend and prevent the extinction of this species. As shown in Fig. 18.2, the projected population of the mountain gorilla would increase from 1004 in 2020 to 1527 in 2030, assuming a constant growth rate of 4.30% and a constant death rate of 1%. This would represent an increase of 52.09% in 10 years. These results show that both species have the potential to recover from their endangered status if conservation efforts are maintained and enhanced. However, they also show that different species may require different conservation strategies depending on their biological characteristics and ecological needs, as well as the social and political context of their habitats.

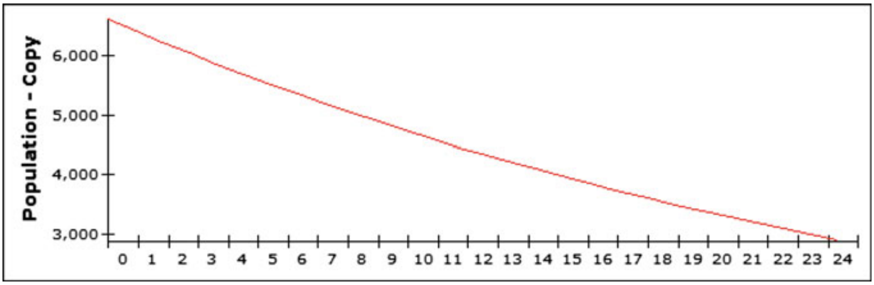
18.4.2 Validation and Testing of the Simulation Model

In this section, we present the results of our simulation model that shows the projected population and extinction risk of three endangered species: the tiger, the African wild dog, and the mountain gorilla We presumed that these species are no longer under the protection of conservation as endangered species and that poachers would target them aggressively. We used the current data from the International Union for Conservation of Nature (IUCN) Red List of Threatened Species as our source of information on the existing population size and status of these species. We also inferred that the growth rate and death rate of these species remain constant at their recent levels. As we can see from Fig. 18.2, the results show that our simulation model has been successful in generating a plausible outcome (Qudrat-Ullah, 2020): without the conservation efforts in place, these three species will become extinct within a short period.

Animal A: Tigers



Animal B: African Wild Dog



Animal C: Mountain Gorilla

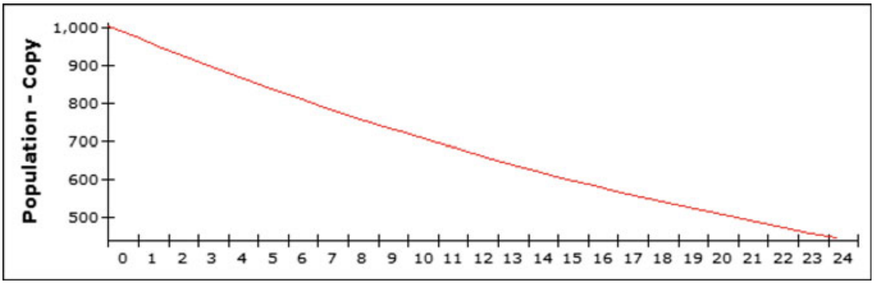


Fig. 18.2 The dynamics of non-conservation of the endangered species

18.4.3 Analysis Using Model

Using our model that is built using the conceptual model (please see Fig. 18.1), we will analyze the dynamics of three species: Tiger, African Wild Dog, and Mountain Gorilla.

Animal A—Tiger

As we can see the population dynamics of Tiger in Fig. 18.3, where the structure-behavior graph, generated by the population stock in the simulation model, is

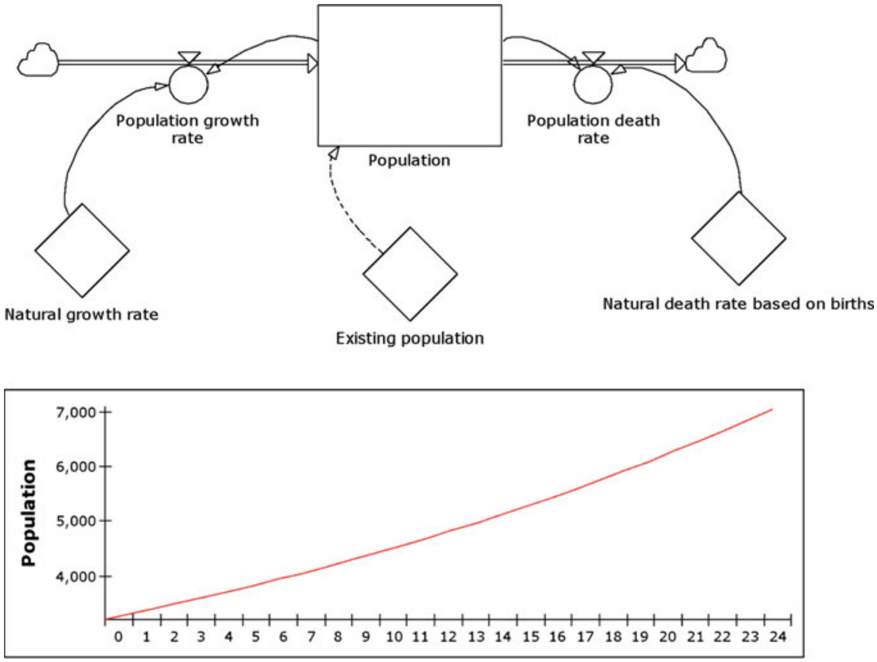


Fig. 18.3 The structure-behaviour graph of conservation of tiger species

provided. As we can see Tiger population is increasing steadily, over time. Therefore, our model appears to be successful based on the Tiger being in conservation that protects Tigers and allows them to recover their species.

Animal B—African Wild Dog

As we can see in Fig. 18.4, the population dynamics of African Wild Dog, where the structure-behavior graph, generated African Wild Dog population stock in the simulation model, is provided. We can conclude that the conservation practices would also work for the stock of African Wild Dogs.

Animal C—Mountain Gorilla

Finally, we can see in Fig. 18.5 the population dynamics of Mountain Gorilla, where the structure-behavior graph, generated Mountain Gorilla population stock in the simulation model, is provided. Here too, we can conclude that the conservation practices appear to work for the sustained population of Mountain Gorilla.

According to our model-based analysis, we found that the conservation initiatives and policies implemented in the past decades have had a positive effect on the recovery of endangered species. As shown by Fig. 18.1, the population size of endangered species has increased steadily over time, while the extinction risk has decreased significantly. In contrast to the baseline scenario, where no conservation actions were taken, the conservation scenario showed a remarkable improvement

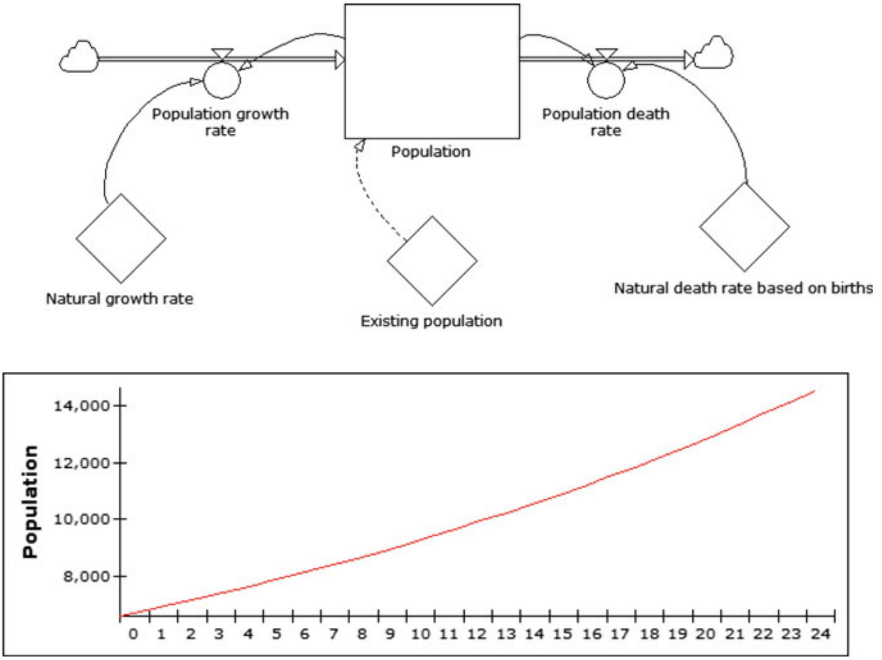


Fig. 18.4 The structure-behaviour graph of conservation of African wild dog species

in the status of endangered species. Similarly to previous studies, we also found that different species responded differently to conservation efforts depending on their biological characteristics and ecological needs. For example, species with high reproductive rates and low habitat requirements showed faster and higher recovery rates than species with low reproductive rates and high habitat requirements. These results suggest that if this positive trend of the effects of conservation initiatives and policies remains intact, in the future these endangered species can be removed from the list of Endangered Species.

18.5 Discussion, Implication, and Conclusions

Conservation is an essential part of the recovery of animals that are threatened by extinction due to human activities such as habitat destruction, overexploitation, pollution, and climate change. Conservation refers to the protection and management of natural resources and biodiversity for their intrinsic value and for the benefit of present and future generations (Primack, 2014). However, there is a paradoxical situation that hinders conservation efforts: the funds required for conservation come from the status of the animal, which means that the more endangered an animal is, the more attention and resources it receives from governments, organizations, and

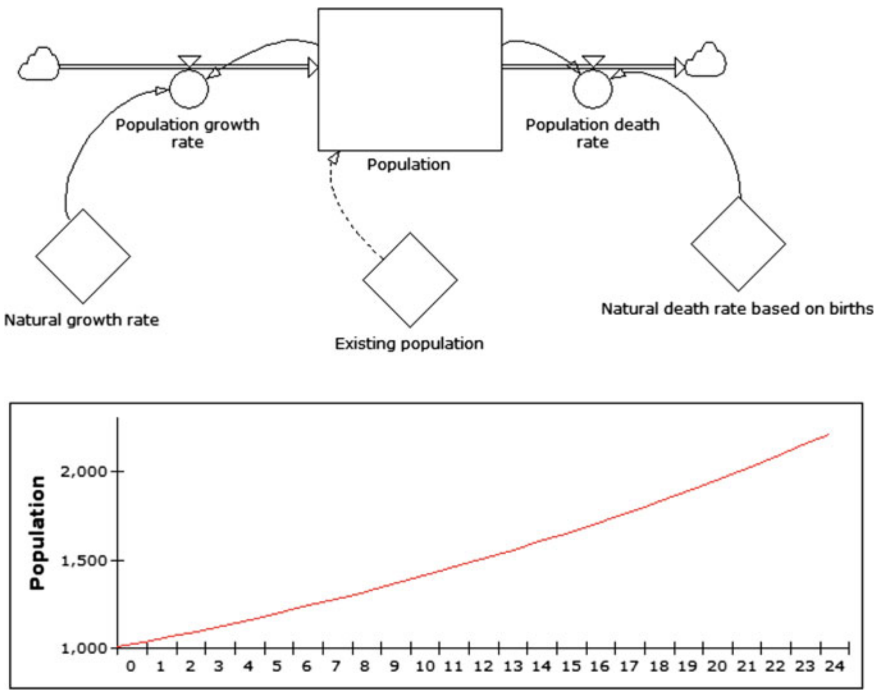


Fig. 18.5 The structure-behaviour graph of conservation of mountain gorilla species

donors. This creates a catch-22, a situation in which a desired outcome is impossible to achieve because of a set of contradictory rules or conditions (Merriam-Webster, n.d.). In other words, animals need to be endangered to get funding for conservation, but if they are too endangered, they may not recover in time. On the other hand, if animals recover and increase their population, they may lose their funding and face new threats. Therefore, how can we break this cycle and ensure the long-term survival and well-being of endangered animals? What are the best ways to allocate and distribute funds for conservation? What are the criteria and indicators to measure the success of conservation programs? These are some of the questions that we need to address to find effective solutions for this complex problem.

In summary, this chapter has examined the issue of endangered species and conservation, with a focus on large marine wildlife such as whales. The main research question was whether endangered species can be protected through conservation, and what are the challenges and opportunities for doing so. To answer this question, we reviewed various data and models that showed the status, trends, and threats of endangered species, as well as the effectiveness and impact of conservation efforts. We found that conservation can protect endangered species from extinction and restore their populations, but there are exceptions to the rule, especially for large marine wildlife. The reason why it becomes more challenging to protect them for multiple reasons, one of which is that they live in the ocean, which is a vast mass that is impossible to control, simply because the greatest challenge is that the actions of conversation would have to be undertaken not by just one country, but the world, as the ocean is used by many nations for food and travel. Humans will continue to fish and hunt animals and, in the process, whales become injured during these endeavors. The second issue is that whales are enormous animals that simply cannot be contained.

These findings have important implications for conservation policy and practice, as well as for future research. They suggest that conservation efforts for endangered species need to be tailored to the specific biological characteristics and ecological needs of each species, as well as to the social and political context of each region or country. They also suggest that conservation efforts for large marine wildlife need to involve international cooperation and coordination among different stakeholders, such as governments, organizations, communities, and individuals. Furthermore, they suggest that conservation efforts for large marine wildlife need to address the root causes of their decline, such as overfishing, pollution, climate change, and habitat loss. Finally, they suggest that more research is needed to improve the data and models on endangered species and conservation, as well as to evaluate the outcomes and impacts of conservation programs. By doing so, we can better understand the dynamics of endangered species and conservation, and find more effective and sustainable solutions for this complex problem.

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Chapter 19
Understanding the Dynamics of the HIV/AIDS Epidemic in China with System Dynamics

Hassan Qudrat-Ullah and Fabian H. Szulanski

Abstract This chapter examines the HIV/AIDS epidemic spread and prevention in China using data from the Chinese CDC website and Unaids China. We provide a historical overview of the HIV epidemic in China since 1985 when the first case was detected in a foreigner. We then use the systems thinking approach to model the main modes of transmission: sexual contact, injecting drug use, and mother-to-child transmission. We also consider the effects of medical interventions such as pre-exposure prophylaxis (PEP) and highly active antiretroviral therapy (HAART) on reducing HIV infection and mortality. Moreover, we discuss the testing and prevention programs that China has implemented to achieve the UNAIDS 90–90–90 targets and curb the epidemic. We simulate the dynamics of HIV/AIDS under different scenarios using a system dynamics simulation model and compare the results using time graphs. Based on our analysis, we propose some policy recommendations to address the HIV/AIDS epidemic in China.

Keywords HIV/AIDS: China · Epidemic · HAART · Systems thinking · System dynamics model · Causal loop diagrams · Feedback loops · Model testing and validation · Modes of transmission · HIV infection and mortality · Mother-to-child transmission · Medical interventions · SIR model · Susceptible population

19.1 Introduction

The purpose of this chapter is to examine the pattern and prevention of the HIV and AIDS epidemic in China, a country with the largest population in the world (1.313 billion people). We will explore the main modes of HIV transmission, the rate of

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HIV spread, and the effective interventions to reduce new infections in this context. Previous studies have shown that sexual transmission, particularly among men who have sex with men (MSM), has become the predominant route of HIV transmission in China since 2006 (Wu et al., 2013; Zhang et al., 2015). Another significant mode is injecting drug use, which involves sharing contaminated needles and syringes (Li et al., 2012; Wang et al., 2014). Other modes, such as mother-to-child transmission and blood transmission, are less common but still pose a risk (Chen et al., 2011; Liu et al., 2016).

We apply the SIR model to simulate the dynamics of HIV/AIDS in China, but we adjust the model by replacing the recovered population with the deceased population since HIV is untreatable under current medical conditions. We also simplify the model by assuming a closed system that does not account for exogenous factors such as birth rate, death rate from other causes, and migration. China has a low national HIV prevalence of 0.037%, but this means that a large number of people (650,000) are living with HIV because of its huge population size. China also accounts for 3% of new HIV infections worldwide each year (UNAIDS, 2011). In 2010, only 28% of people living with HIV in China were aware of their status, and only 14% were receiving ART (Wu et al., 2013). We use the data from UNAIDS and other sources to estimate the initial values and parameters of our model. We calibrate our model by comparing the simulated results with the observed data. We validate our model by conducting sensitivity analysis and testing different scenarios. We use our model to explore the effects of different interventions on the HIV epidemic in China, such as increasing HIV testing, promoting condom use, and expanding ART coverage. We also analyze the cost-effectiveness of these interventions and provide some policy recommendations. Our model has some limitations, such as data uncertainty, model simplification, and parameter estimation. Therefore, we suggest some directions for future improvement and research. Our model aims to provide some insights and guidance for HIV prevention and control efforts in China and other countries with similar HIV epidemic situations.

The main research question of this chapter is: What are the most effective interventions to reduce new HIV infections in China? To answer this question, we will compare the impact of different interventions on the dynamics of HIV/AIDS in China using the SIR model. We will consider interventions such as condom promotion, needle exchange programs, voluntary counseling and testing, antiretroviral therapy, and pre-exposure prophylaxis. We will also evaluate the cost-effectiveness and feasibility of these interventions in the Chinese context. By answering this research question, we hope to provide useful insights and recommendations for HIV prevention and control in China and other countries with similar epidemic patterns. The HIV and AIDS epidemic in China is a complex and multifaceted issue that requires comprehensive and evidence-based interventions. In this chapter, utilizing the systems thinking approach, we will analyze the main modes of HIV transmission, the rate of HIV spread, and the effective interventions to reduce new infections in China. We will also discuss the challenges and opportunities for HIV prevention and control in China, as well as the implications for global health. By understanding the pattern and prevention of the HIV and AIDS epidemic in China, we hope to contribute to the global efforts to end the AIDS epidemic by 2030. We will first introduce the background and context of the HIV and AIDS epidemic in China, including the history, epidemiology, and policy response. We will then present a system dynamics model of the HIV and AIDS epidemic in China, based on the susceptible-infected death (SID) framework. We will use this model to simulate the dynamics of the epidemic under different scenarios and parameters. We will also use this model to evaluate the impacts of different interventions on HIV incidence, prevalence, and mortality. We will compare the cost-effectiveness of these interventions and provide some policy recommendations. We will also discuss the limitations and assumptions of our model, and suggest some directions for future improvement and research. We will conclude this chapter with a summary of our main findings and implications for HIV prevention and control efforts in China and beyond.

19.2 A Brief Overview of the Relevant Literature

The purpose of this section is to provide a comprehensive review of the existing literature on the definitions, concepts, and theories that are related to HIV/AIDS infection, prevention, and treatment dynamics. We will cover the following topics in detail: Time Horizon, Background Concepts, Endogenous Factors, and Exogenous Factors and Limitations of the Model. We will critically examine and discuss each topic and explain how they inform our system dynamics model of the HIV/AIDS epidemic in China. We will also identify the gaps and challenges in the literature and suggest some directions for future research.

19.2.1 Relevant Concepts and Definitions

We use the following equations to model the susceptible population, the infectious population, and the dead population in China:

- **Susceptible population** = Total population (1.313 billion) − Infectious population (650,000)
- **Infectious population** = Initial infectious population + (infection rate * Total population)
- **Death population** = Mortality rate * Infectious population
- **The initial infectious population** is 650,000 and the epidemic will continue to spread. Therefore, we add the newly infectious population to the initial infectious population to update the situation.
- **The infection rate** is the most important factor that influences the HIV/AIDS epidemic dissemination approach. However, different dissemination approaches have different infection rates. For example, sexual transmission has a higher infection rate than blood transmission (Wu et al., 2013).

- **The duration** is another factor that affects the dynamics of HIV/AIDS in China. We simulate the situation under different scenarios such as the time it takes for HIV carriers to become AIDS patients with or without pre-exposure prophylaxis (PEP) and the life expectancy of HIV patients with or without highly active antiretroviral therapy (HAART) (Zhang et al., 2015).
- The other variables are not constant and may vary depending on various factors such as sex contact rate, condom use rate, needle sharing rate, etc. We will assume to use the average rate to add to our research model to complete our simulation.

19.2.2 Time Horizon

The life expectancy of the HIV infectious population depends on different factors such as the type of medical treatment: HAART. HAART is a combination of three or more antiretroviral drugs that inhibit viral replication by different mechanisms (Eggleton & Nagalli, 2022). With the use of HAART treatment, the viral load will be reduced in human bodies and the HIV patient will live longer than before. According to a study by Hogg et al. (2006), individuals taking HAART and without a history of injection drug use had a life expectancy of 38.9 years at age 20 years, whereas individuals not taking HAART and with a history of injection drug use had a life expectancy of 19.1 years at age 20 years. However, HAART is not a cure for HIV and it has some side effects and limitations (Eggleton & Nagalli, 2022).

Another factor that affects the dynamics of HIV and AIDS is the time lag between HIV infection and AIDS diagnosis. HIV is not equivalent to AIDS, as HIV is the virus that causes AIDS, which is the most advanced stage of HIV infection. The progression from HIV infection to AIDS diagnosis depends on several factors that can vary among different individuals and populations. Some of these factors include the type and subtype of HIV, the genetic and immunological characteristics of the host, and the presence of other infections or diseases that can weaken the immune system (Eggleton & Nagalli, 2022). According to Verywell Health (2022), the average time from HIV infection to AIDS diagnosis without any treatment is about 10 years, but this can range from a few months to more than 20 years. However, with effective treatment, such as antiretroviral therapy (ART), the progression from HIV infection to AIDS diagnosis can be delayed indefinitely or prevented altogether.

The HIV/AIDS epidemic in China is a complex and dynamic phenomenon that has evolved over time and across regions. The first case of HIV infection in China was reported in 1985 among foreign tourists. Since then, the epidemic has spread through different modes of transmission, such as injecting drug use, blood transfusion, sexual contact, and mother-to-child transmission. The epidemic has also affected different population groups, such as men who have sex with men, female sex workers, migrant workers, and ethnic minorities. The Chinese government has responded to the epidemic with various policies and programs, such as the Four Frees and One Care policy, the China-Gates Foundation HIV Prevention Cooperation Program, and the National HIV/AIDS Prevention and Control Plan. However, the epidemic still poses significant challenges and opportunities for China and the world.

We will use the system dynamics software Vensim to build and simulate our model. We will use the data from UNAIDS and other sources to estimate the initial values and parameters of our model. We will calibrate our model by comparing the simulated results with the observed data from 2004 to 2020. We will validate our model by conducting sensitivity analysis and testing different scenarios from 2021 to 2044. We will use our model to explore the effects of different interventions on the HIV epidemic in China, such as increasing HIV testing, promoting condom use, and expanding ART coverage.

19.2.3 Background Concepts

Despite the great efforts of the Chinese government over three decades, HIV/AIDS remains a huge public health problem in China. China has implemented various actions to combat this emerging health problem. According to our research, "HIV and AIDS surveillance started in 1985. In 1995, the China Ministry of Health and the National Center for AIDS established 42 national sentinel sites in 23 of the 31 provinces (Liu, 2018)". However, this system had limitations in accessibility and accuracy, which hindered a timely understanding of the characteristics of the HIV/AIDS epidemic and the effectiveness of the HIV/AIDS prevention programs. In 2005, China established a web-based HIV reporting system to integrate the HIV/AIDS surveillance system, which can provide a comprehensive understanding of the epidemiological features of HIV and AIDS in China. Through this system report, we can see that "HIV infection showed the fastest growth with an annual percentage change of 16.3% in reporting incidence (Liu, 2018)".

We also reviewed a retrospective study that used a spatial analytical model and multilevel spatial models to track the evolution of HIV/AIDS in China from 1989 to 2009 and to inform future prevention and control efforts. The paper analyzed the 326,157 HIV/AIDS cases reported from 1989 to 2009 and found the changing trend of the main HIV/AIDS epidemic dissemination approach. "Rates of HIV/AIDS among permanent urban residents, especially women and elderly men, have increased significantly in recent years (Jia et al., 2011)", which we will discuss more in detail in another section.

China has implemented the political policy "Four Free and One Care" to support HIV patients, which includes "free drugs to pregnant women living with HIV/AIDS to prevent mother-to-child transmission and HIV testing of newborn babies; free schooling for children orphaned by HIV/AIDS, and care and economic assistance to families affected by HIV/AIDS. The policy of free voluntary counseling and testing has started to be implemented, but its roll-out is limited by the lack of incentives for health workers to provide the services free of charge. A new policy to provide free HIV counseling and testing, including rapid testing, is currently being reviewed" (WHO, 2005). However, China has not achieved the UNAIDS "90-90-90" goal of

2020. China should make more efforts such as political policy support and more fund support to stop the spread of HIV/AIDS in the future.

19.2.4 Endogenous Factors

We have stated earlier that we assume our model is a closed system, but this may pose some problems for the simulation. This model will focus on the endogenous factors and the main dissemination ways in China are injecting drug use and sexual transmission. We have found that different dissemination ways have different infection rates, so we will try to use different average constant rates for the model. We have also found that the most effective way to prevent HIV through sexual transmission is the use of condoms, but the condom use rate may vary between heterosexual and homosexual populations. We will also include medical treatments such as PEP and HAART treatment to make our model more comprehensive.

19.2.5 Exogenous Factors and Limitations of the Model

We are aware that China is a relatively traditional Asian country in the world. Despite the economic reform and opening up and the sexual revolution, people are reluctant to accept the HIV test because of the fear of discrimination. These people who may be HIV-positive will not be included in our model and will affect the accuracy of our model. Moreover, China's Second National HIV Strategic Plan (2011–2015) identifies men who have sex with men as the key population for HIV prevention and treatment, but we still lack a comprehensive national policy and strategy for HIV prevention and control. In China, the delivery of HIV services is still divided and fragmented among different institutions and organizations, which means we will lose too much time during the testing and treatment. Therefore, these delays will cause our model to be misleading because some data will not be updated timely to reflect our model. The test also cannot guarantee that the results will be correct and sometimes errors of tests are unavoidable.

19.3 Causal Mapping of the Conceptual Model

In the following two sections, we will first develop different causal loop diagrams (CLDs) to identify different feedback structures of HIV dissemination and control systems. We will consider injecting drug use, heterosexual transmission, and homosexual transmission to draw the different CLDs. After explaining the details of the small causal loop diagrams, we will combine them and show the whole feedback structure of HIV/AIDS. Then we will use the HIV/AIDS feedback structure to draw the stock and flow model and simulate the details by using powerism. With powerism, we can simulate different time graphs to compare and make a conclusion. Finally, we will test the validity of our model by using model boundary charts, parameter tests, and extreme condition tests.

19.3.1 Causal Loop Diagrams of Various Processes of HIV/AIDS

In this section, we will find the feedback structure of HIV/AIDS through causal loop diagrams (CLD). In China, sexual transmission played the dominant role in HIV transmission among newly diagnosed HIV cases since 2006. We try to separate sex transmission into two groups: Heterosexual Transmission and Homosexual Transmission for details to explain. Then we will also draw the CLD of the injecting drug users because it is the second-largest HIV Prevalence Rate group among MARPs. Lastly, we will describe mother–child transmission. We will not talk about blood transmission because of the 90% decrease in blood/ plasma transmission. We will combine the causal loop diagrams to create an overall causal loop diagram that will illustrate how HIV transmission increases or decreases.

A: Heterosexual Transmission Mosel

This CLD, as shown in Fig. 19.1, illustrates the feedback structure of Heterosexual HIV Transmission. First, some feedback loops are common for all models. For example, Reinforcing loop R3 shows that if government policy attention increases, the government will invest more in HIV testing to increase the testing ability and capacity. This will lead to an increase in the population tested for HIV and the population tested positive for HIV. This will also lead to an increase in the HIV infection rate and AIDS infection people, which will make the government pay more attention to AIDS. For Balancing loop B2, as more people can test for HIV, more people will know their HIV status and the risk of HIV transmission will decrease. However, if the risk of HIV transmission increases, people will use PEP as a treatment method to decrease the rate of HIV testing positive. For Balancing loop B1, the only difference with balancing loop B2 is that when the risk of HIV transmission increases, HIV exposure will increase. This will increase in people who tested positive for HIV, but with a delay because HIV cannot be detected immediately and usually takes several weeks. Moreover, in China, HIV results need to be based on the results of Hospitals plus CDC (Centre for Disease Control and Prevention) plus CBOs (Community-based organizations). Therefore, there is both a physical delay due to the HIV characteristics and a governmental and institutional delay.

As shown in Fig. 19.2, Heterosexual annual HIV transmission increased sharply from 2005 to 2011. One of the reasons for this trend is the reform of the Hukou Residence System in China, which is the geographical restrictions that limit the spread of the virus. The reform of the Chinese economy since 1980 made Hukou less restrictive and allowed millions of farmers to migrate from their homes to seek

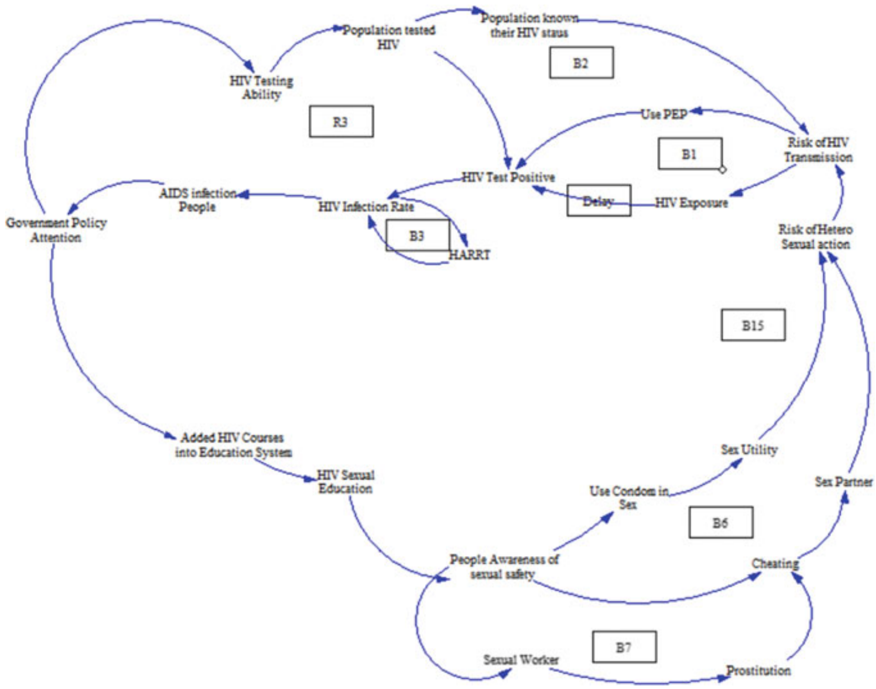

Fig. 19.1 The Feedback Structure of the Heterosexual HIV Transmission

better jobs and more prosperous lives in cities. This also increased the demand and supply of sex services (Jia et al., 2011). Another policy that contributed to this change was the Chinese economic reform in the late 1980s and early 1990s. China opened its trade with the world and its culture changed with new values of sexual revolution and freedom. These two policies led to a more open culture and a change in the population structure with economic growth.

In Balancing loop B15, we examine the scenario of HIV transmission through heterosexual contact. We assume that the government will implement policies that will enhance the education and awareness of HIV prevention, especially in the context of sex education. As a result, more people will adopt safe sexual practices, such as using condoms, which will reduce the probability of getting infected with HIV through heterosexual intercourse. In Balancing loop B6, we explore how people's awareness of sexual safety affects their cheating behavior. We hypothesize that when people are more aware of the risks and consequences of cheating, they will be less likely to cheat on their partners. Conversely, when people cheat more frequently, they will have more sexual partners, which will increase their exposure to HIV infection through heterosexual contact. Finally, in Balancing loop B7, we investigate how people's awareness of sexual safety influences the demand and supply of sex work. We propose that when people are more aware of the dangers and harms of sex work, they will be less willing to engage in or pay for prostitution. This will lead to a decline

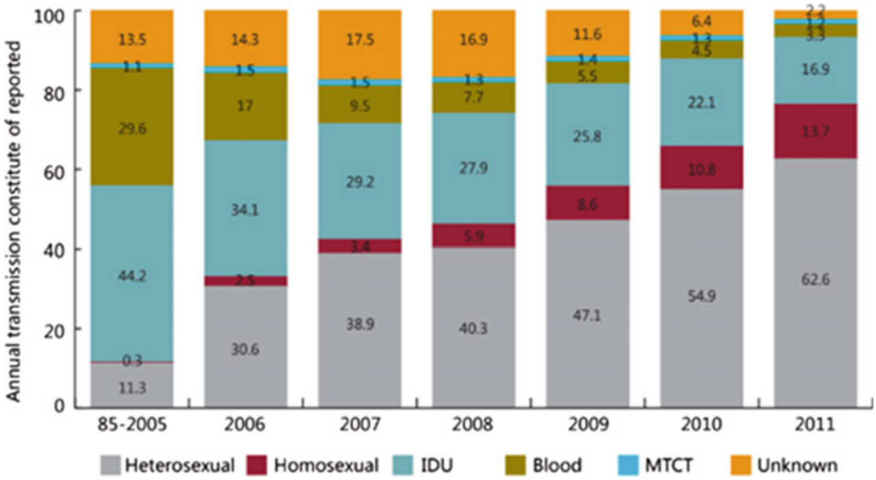

Fig. 19.2 HIV Transmission Routes of Newly Diagnosed Cases, China, 1985–2011. *Source* China-Gates Foundation HIV Prevention Cooperation Program 2013

in the number of sex workers and clients, which will also reduce cheating behavior and the risk of HIV transmission through heterosexual contact.

B: Homosexual Transmission Model

The causal loop diagram in Sect. 19.3.2 illustrates the feedback structure of HIV transmission among homosexuals in China. Due to the cultural changes and social movements that have taken place in the past decades, Chinese society has become more tolerant and accepting of homosexuality, and the number of people who identify as homosexuals has increased significantly. As a result, the proportion of HIV infections attributed to homosexual behavior has risen from 0.3% in 1985 to 13.7% in 2011, as shown in Fig. 19.3. This indicates that the risk of HIV transmission through homo-sexual activities has been expanding over recent years.

The feedback loops B1, B2, B3, B7, B8, B9, and R3 are similar to the Heterosexual model. For instance, in the feedback loop B8, people using a condom could decrease the risk of homo-sexual HIV transmission, but this action could decrease the sex utility. Especially for male-to-male relationships, people are not willing to use condoms so they lead to a highly HIV-risky environment for homosexual behavior (Weller & Davis-Beaty, 2002; Katz et al., 2021). Similarly, in the feedback loop B9, people who are aware of their HIV status could reduce their sexual activity or increase their condom use, but this could also lower their sex utility or increase their stigma. In contrast, in the feedback loop R3, people who are unaware of their HIV status could increase their sexual activity or decrease their condom use, but this could also increase their risk of HIV transmission or acquisition. These feedback loops illustrate the complex dynamics of HIV prevention among homosexuals and the trade-offs between sex utility and HIV risk.

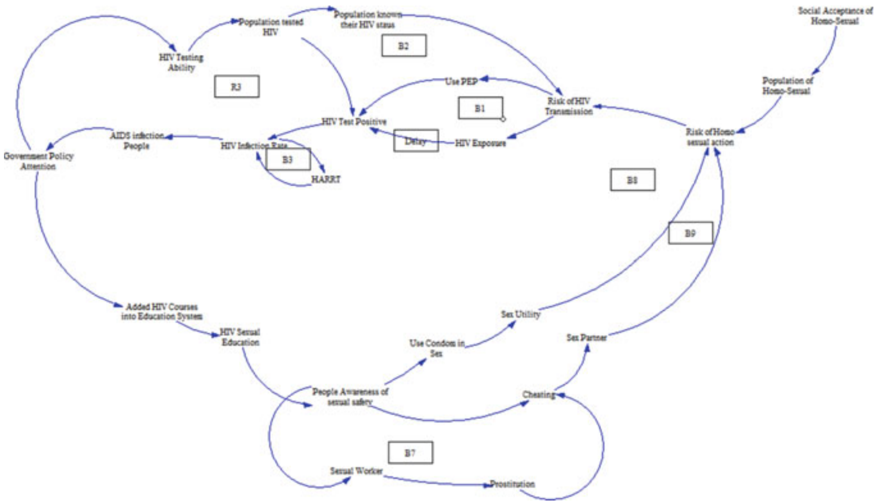

Fig. 19.3 The feedback structure of the homosexual transmission model

C: Mother-to-Child HIV Transmission Model

Figure 19.4 shows the Mother-to-Child HIV transmission model, which we will explain in this section. This model is related to the Heterosexual model in section Fig. 19.1, as it shares some of the same feedback loops. The feedback loops R3, B1, B2, and B3 describe how HIV is transmitted and prevented among heterosexuals. The feedback loop B4 shows the effect of HIV education provided by the government to the public. When people learn more about how HIV can be spread and prevented, they are more likely to protect themselves and their partners from HIV infection. This reduces the risk of Mother-to-Child transmission, as fewer women get infected with HIV or seek treatment if they do (World Health Organization [WHO], 2010). The feedback loop B5 shows the impact of condom use during sexual intercourse. When more people use condoms, they lower the chance of getting or giving HIV to their partners. This also lowers the risk of Mother-to-Child transmission, as fewer pregnant women have HIV or pass it to their babies (Weller & Davis-Beaty, 2002). The feedback loop R1 shows the relationship between AIDS cases and potential HIV-positive mothers. As more people develop AIDS, more women who are pregnant or may become pregnant have HIV. This leads to more babies being born with HIV from their mothers, increasing the proportion of new HIV infections among children (Njouom et al., 2023). The feedback loop R2 shows the intervention of PMTCT (Prevention of mother-to-child transmission), which is a treatment that reduces the chance of HIV transmission from mother to child during pregnancy, delivery, or breastfeeding (Nduati et al., 2017; WHO, 2010). The hospital and CDC would use this treatment to increase the birth rate of healthy children and decrease the number of children with HIV.

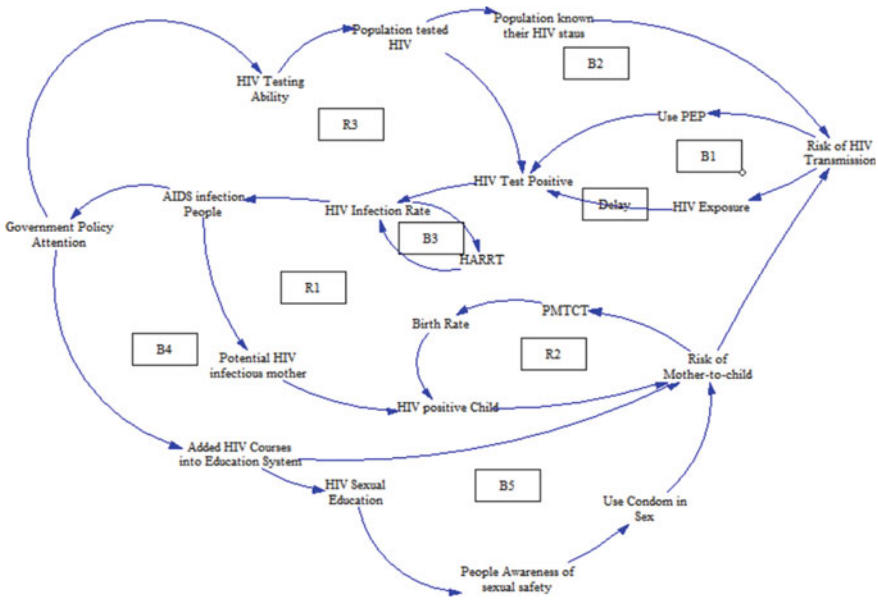

Fig. 19.4 The feedback structure of mother to child HIV transmission model

D: HIV Transmission by Drug Model

In Fig. 19.5, we would explain the CLD of HIV transmission by Drugs, especially for illegal drugs. The balancing loop B10 indicates that the Chinese government policy attention increase could lead to the number of illegal drug users decreasing. A positive relationship shows that more illegal drug users will draw more attention from the government of China. In balancing loop B11, we put the most important variable, which is shared needles among illegal drug users. Based on the research, injection drug use could increase the risk of the spread of HIV due to behavior such as sharing needles and syringe exchange (National Institute on Drug Abuse [NIDA], 2018). As we discuss in the introduction part, one of the HIV spread methods is by blood, and people using shared needles would increase the risk of HIV transmission by the drug (NIDA, 2018).

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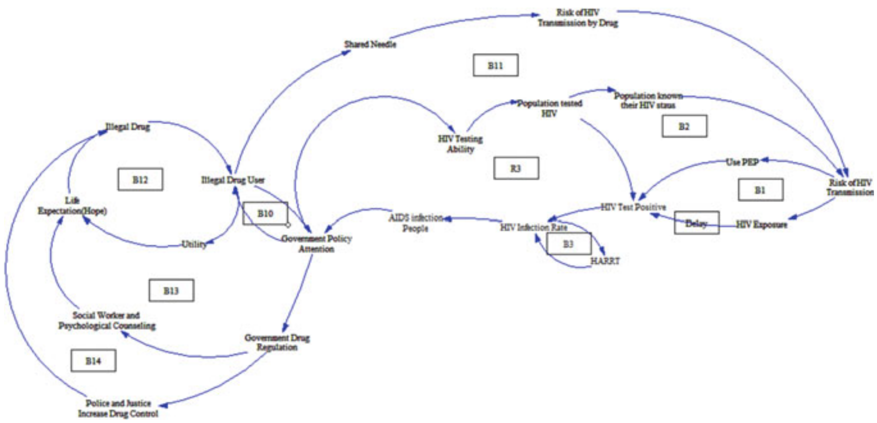


Fig. 19.5 The feedback structure of HIV transmission model though injection model

attention would have a positive effect on government drug regulation, the police and justice system in China would increase the ability of drug control, and criminals could be sentenced to death for drug crimes in China (APA, 2017). Then, the number of illegal drugs in the black market could decrease with fewer illegal drug users. The balancing loop B13 shows one of the ways the Chinese government's drug regulation is to increase the social worker and psychological counseling for drug users and try to help them get rid of drug addiction. Then drug users' hope for life will increase and use fewer illegal drugs. Lastly, the balancing loop B12 discusses that one of the reasons for people to take illegal drugs is to increase their utility and happiness for a short time. Drugs could help people relieve their pain and forget the difficulties in life and that's why people become addicted to drugs.

19.4 The Overall Causal Loop Diagram: The Dynamic Hypothesis

Finally, we combine the four main HIV/ AIDS transmission models (Heterosexual Transmission, Homosexual Transmission, Injecting drug users, and the Mother to Child HIV Transmission Model) to draw the overall casual loop diagram aka Dynamic Hypothesis, as shown in Fig. 19.6. The diagram shows the delay between HIV exposure and HIV-positive diagnosis, which may take a few months for the Chinese testing program. The Chinese HIV testing program needs the collaboration of CDC, CBO, and hospitals to finish the two testing protocols using the enzyme-linked immunosorbent assay (ELISA) and Western Blot (WB) (National Center for AIDS/STD Control and Prevention [NCAIDS], n.d.). These tests can detect the presence of HIV antibodies in the blood of infected individuals. During the delay period, we can use the PEP (post-exposure prophylaxis) which can effectively reduce the risk

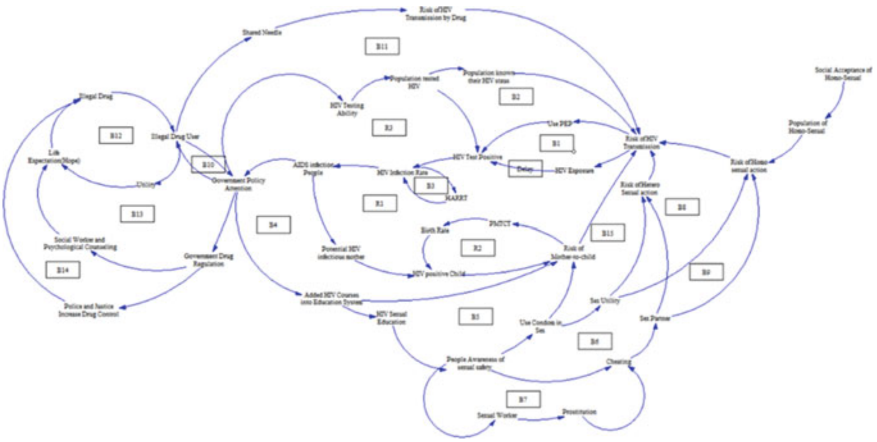


Fig. 19.6 The feedback structure of the HIV model-the dynamic hypothesis

of becoming AIDS patients. If the cases unfortunately happen, we can use HAART (highly active antiretroviral therapy) to help the patients to limit the copy of the virus with the result of living much longer than before. Last but not least, our government policy should be established timely to face terrible diseases and make more efforts to help the patients.

The overall casual loop diagram also shows how different factors can influence the HIV/AIDS epidemic in China. For example, government policy attention can affect government drug regulation and HIV education, which can reduce the number of illegal drug users and increase their awareness of HIV prevention (AIDS Healthcare Foundation [AHF], n.d.). Condom use and PMTCT can also reduce the risk of HIV transmission by sexual contact and mother-to-child transmission, respectively (NIDA, 2018; WHO, 2010). The HIV testing program can help identify and treat people who are infected with HIV and reduce their viral load and infectivity (Zhang et al., 2021). The HAART can improve the health and life expectancy of people living with HIV and reduce their risk of developing AIDS-related opportunistic infections (NCAIDS, n.d.). These factors can create a positive feedback loop that can slow down or reverse the HIV/AIDS epidemic in China.

However, some factors can create a negative feedback loop that can accelerate or worsen the HIV/AIDS epidemic in China. For example, the stigma and discrimination against people living with HIV can affect their access to health care and social support, which can lower their quality of life and increase their psychological distress (APA, 2017). The lack of awareness and knowledge about HIV prevention and treatment among some populations can increase their risk of exposure and infection, especially among young people, women, ethnic minorities, and migrants (UNAIDS, 2020). The emergence of drug resistance and side effects of antiretroviral therapy can reduce the effectiveness and adherence of treatment, which can increase the viral load and infectivity of people living with HIV (NCAIDS, n.d.). These factors can create a negative feedback loop that can speed up or aggravate the HIV/AIDS epidemic in China.

19.4.1 Boundary Identification of the Model

We have decided to focus on injecting drug users and homosexuals as the main modes of HIV transmission in China. We have chosen 2004 as the starting point for our simulation. This is because China established a web-based report program for HIV in 2004 after the outbreak of SRAS, which improved the accuracy and timeliness of HIV data collection and reporting. UNAIDS set a target of 90–90–90 by 2020, which means that 90% of people living with HIV would know their status, 90% of people diagnosed with HIV would receive antiretroviral therapy, and 90% of people on treatment would have viral suppression (Marsh & Eaton, 2019). However, based on our studies of HIV, we find that it is very difficult to achieve this target this year. Therefore, we set our time horizon as 50 years to simulate the HIV epidemic until 2054 and then we can predict the outcomes of our model. We can use our estimated outcomes of models to evaluate whether we can reach the goal of 90–90–90 in the future or not. At the same time, we will disregard any events that will affect the characteristics of the population, such as immigration, birth, and death, because they are beyond our control and may introduce unnecessary variables. We only consider the death population as the people who die from HIV-related causes and assume that the probability of HIV patients dying from other causes is very low and can be ignored. We define time 0 as 2004 and the time horizon as 50 years.

19.5 Base Model of HIV

In this section, we will present the base model of our HIV model, which is based on the SIR model (susceptible infection recovery model). The base model has three stocks: susceptible population, HIV-positive population, and death population. We assume that the susceptible population will be tested for HIV after an average delay time of 20 days. In the following models, we will compare the simulation results with different delay times.

- Susceptible Population = Integral (–HIV infection population, Chinese population in 2004-HIV death population − HIV infection population)
- HIV Infection Population = Integral (Susceptible population, –HIV death population, 650,000)
- Death Population = Integral (HIV Infection Population, 25,000)
- HIV Infection rate = DELAYMTR (HIV Infectivity contact rate Susceptible Population * HIV Infection Population/Chinese population 2004, 20, 1)
- Death rate = HIV infection population * AIDS death rate.

We have used the SIR model (susceptible infection recovery model) as the basis for our HIV model, which captures the basic dynamics of HIV transmission and progression. The SIR model has three stocks: susceptible population, HIV-positive population, and death population. We assume that there is an average delay time of 20 days between HIV exposure and HIV testing for the susceptible population. The Chinese HIV testing program involves CDC, CBO, and hospitals that use two testing protocols: enzyme-linked immunosorbent assay (ELISA) and Western Blot (WB) (NCAIDS, n.d.). These tests can confirm the presence of HIV antibodies in the blood of infected individuals. We will vary the delay time in the subsequent models and compare the simulation outcomes. The equations for the SIR model are as follows:

- Susceptible Population = Integral (–HIV infection population, Chinese population in 2004-HIV death population − HIV infection population)
- HIV Infection Population = Integral (Susceptible population, –HIV death population, 650,000)
- Death Population = Integral (HIV Infection Population, 25,000)
- HIV Infection rate = DELAYMTR (HIV Infectivity contact rate Susceptible Population * HIV Infection Population/Chinese population 2004, 20, 1)
- Death rate = HIV infection population * AIDS death rate.

The SIR model shows how the susceptible population can become infected with HIV through different modes of transmission and how the HIV-positive population can die from AIDS-related causes. The HIV infection rate is determined by the HIV infectivity, which is the probability of transmitting HIV per contact; the contact rate, which is the number of contacts per unit of time; and the proportion of infected individuals in the total population. The death rate is determined by the AIDS death rate, which is the probability of dying from AIDS per unit of time once infected with HIV. The SIR model does not include any interventions or treatments that can affect the HIV infection rate or the death rate. The SIR model serves as a reference point for the following models that will incorporate more factors and variables.

To estimate the value of HIV infectivity for different modes of transmission, we use the average values of hetero-sexual HIV infectivity, homo-sexual HIV infectivity, and drug HIV infectivity. We exclude mother-to-child HIV infectivity because it is much smaller than the other three infectivities and has a negligible impact on our model. We obtain the values of homo-sexual infectivity, hetero-sexual infectivity, and drug infectivity from a systematic analysis of the prevalence of HIV among MSM in China (Deng et al., 2019). For homo-sexual behavior in our model, we only focus on male-to-male HIV transmission as we stated in Fig. 19.3.

We have built our HIV model on the SIR model (susceptible infection recovery model), which captures the basic dynamics of HIV transmission and progression. The SIR model has three stocks: susceptible population, HIV-positive population, and death population. We assume that there is an average delay time of 20 days between HIV exposure and HIV testing for the susceptible population. This is based on the Chinese HIV testing program that involves CDC, CBO, and hospitals that use two testing protocols: enzyme-linked immunosorbent assay (ELISA) and Western

Blot (WB) to confirm HIV infection (NCAIDS, n.d.). We will vary the delay time in the subsequent models and compare the simulation outcomes. The equations for the SIR model are as follows:

- Susceptible Population = Integral (–HIV infection population, the Chinese population in 2004-HIV death population − HIV infection population)
- HIV Infection Population = Integral (Susceptible population, –HIV death population, 650,000)
- Death Population = Integral (HIV Infection Population, 25,000)
- HIV Infection rate = DELAYMTR (HIV Infectivity contact rate Susceptible Population * HIV Infection Population/Chinese population 2004, 20, 1)
- Death rate = HIV infection population * AIDS death rate.

The SIR model shows how the susceptible population can become infected with HIV through different modes of transmission and how the HIV-positive population can die from AIDS-related causes. The HIV infection rate is determined by the HIV infectivity, which is the probability of transmitting HIV per contact; the contact rate, which is the number of contacts per unit of time; and the proportion of infected individuals in the total population. The death rate is determined by the AIDS death rate, which is the probability of dying from AIDS per unit of time once infected with HIV. The SIR model does not include any interventions or treatments that can affect the HIV infection rate or the death rate. The SIR model serves as a reference point for the following models that will incorporate more factors and variables.

To estimate the value of HIV infectivity for different modes of transmission, we use the average values of hetero-sexual HIV infectivity, homo-sexual HIV infectivity, and drug HIV infectivity. We exclude mother-to-child HIV infectivity because it is much smaller than the other three infectivities and has a negligible impact on our model. We obtain the values of homo-sexual infectivity, hetero-sexual infectivity, and drug infectivity from a systematic analysis of the prevalence of HIV among MSM in China (Deng et al., 2019). For homo-sexual behavior in our model, we only focus on male-to-male HIV transmission as we stated in Fig. 19.3.

The simulation system in our model is a closed system, and we use data from UNAIDS for the Chinese population, the initial values of the HIV infection population, and the death population due to AIDS in 2004 (UNAIDS, n.d.). The initial AIDS death rate is calculated based on UNAIDS data for China in 2014, where the HIV infection population was 650,000 and the AIDS death population was approximately 25,000 (UNAIDS, n.d.). The contact rate is assumed to be 2. After we set up the values for our model parameters, we analyze the results of the simulation diagram.

Figure 19.7 shows the trend of the susceptible population on the left side and the trend of the HIV-positive population and HIV-death population on the right side. The susceptible population is much higher than the HIV infection population and death population because we set the initial population to be 13 billion. The left side susceptible population has a downward sloping and concave graph, in which the slope of the graph increases as time goes by. The HIV-infected population and death population, have similar trends with upward-sloping and exponential smoothing graphs. But, the

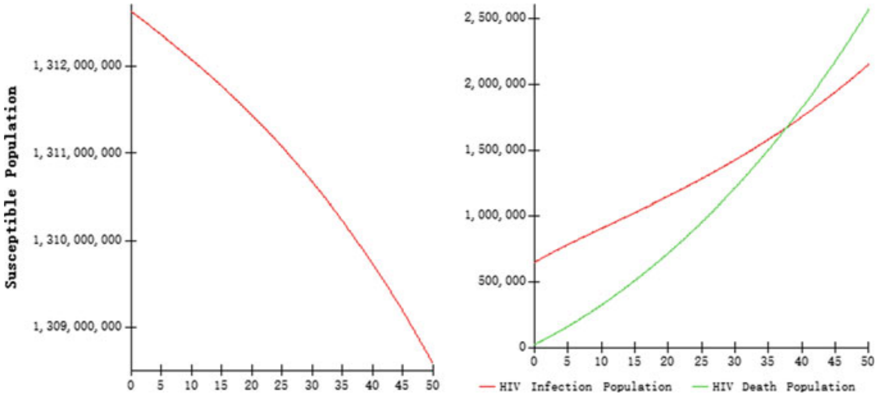


Fig. 19.7 Dynamics of susceptible and HIV population

slope of the HIV infection population is smoother than that of the HIV death population, and there is a tipping point when the time reaches between 35 and 40 years. After this point, the HIV death population will exceed the HIV-infected population. Overall, the simulation results show a very similar trend to that of the SIR model.

19.6 Technology Innovation on HIV Testing Ability

As shown in Fig. 19.8, the government of China would increase its attention and investment in HIV research as the infection population increases. One of the new ways to test for HIV among the susceptible population is the rapid test, which could improve the efficiency and effectiveness of HIV testing. Compared with the traditional test ELSSAs, the rapid test can provide results within 10–30 min and has a high result notification rate of positive cases in HIV screening (99.2%) (China-Gates Foundation HIV Prevention Cooperation Program, 2013). The rapid test can also use oral fluid instead of blood, which is more convenient and acceptable for some populations (Wu et al., 2014). Therefore, the rapid test can reduce the delay between HIV infection and diagnosis, which can help prevent further transmission and facilitate early treatment. Another variable that would change is the contact rate, which is the number of contacts per unit of time between susceptible and infected individuals. The contact rate would decrease because more people from the susceptible population would be tested for HIV due to the improvement in HIV testing technology. More people would know their HIV status, which could help them adopt preventive behaviors and reduce their risk of exposure. Therefore, in Fig. 19.9, we use a smaller number for both delay time and contact rate.

HIV Infection rate = DELAYMTR (HIV Infectivity contact rate Susceptible Population * HIV Infection Population/Chinese population 2004, 10, 1).

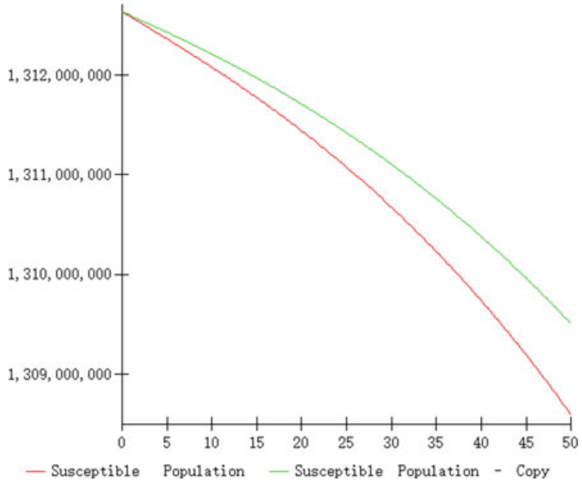


Fig. 19.8 Dynamics of susceptible population

Contact rate = 1.5

The simulation results show the difference between the base model (Fig. 19.1) and the technology innovation model (Fig. 19.3) on the susceptible population, the HIV-infected population, and the HIV-death population. Figure 19.8 shows that the susceptible population decreases more slowly in the technology innovation model than in the base model, and both models have a similar concave trend. Moreover, technological innovation leads to a higher number of susceptible individuals than the base model over time, which implies that the number of HIV-infected and dead individuals should be lower than the base model over time. Figure 19.9 confirms this result by showing that both the HIV infection population and the HIV death population are lower in the technology innovation model than in the base model over time. Also, the tipping point where the HIV death population exceeds the HIV infection population shifts to 35 years, with smaller values for both populations. In summary, Figs. 19.8 and 19.9 show the positive simulation results from reducing the HIV testing delay time and the contact rate. We could expect that if the government of China continues to invest more effort in testing the susceptible population and reducing the contact rate in the future, fewer people will be infected by HIV.

19.7 HIV Infection Model with Treatment Population

We have extended our model by adding one more stock for the treatment population, which consists of the HIV infection population who opt for HIV treatment. People who undergo treatment such as PEP and ART can prolong their lives and reduce their suffering. Therefore, we introduce one more material delay in the flow from the treatment population to the HIV death population, and we set the delay time as

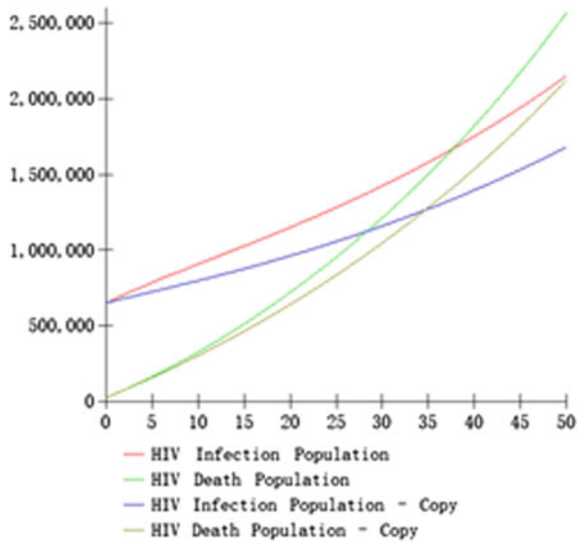


Fig. 19.9 Dynamics of HIV infection population and the HIV death population

30 years. We also assume that 30% of the HIV infection population will take HIV treatment based on the data from Zhang and Ma (2019). We will then test the effect of increasing the treatment rate to 67% and compare the simulation outcomes.

- Treatment Population = Integral (HIV Infection population, -HIV death population, 0)
- Treatment rate = 0.3 * HIV infection population
- Delay Death Rate = DELAYMTR (Treatment population, 30, 1).

We simulate our model with the new parameter value of 67% for the HIV treatment rate and compare the results with the base scenario of 30%. We find that increasing the HIV treatment rate can lead to a significant reduction in the HIV-infected population and the HIV death population over time. We also find that increasing the HIV treatment rate can lower the HIV incidence rate and the HIV prevalence rate in the long run. These results indicate that HIV treatment is an effective intervention for controlling the HIV epidemic and improving the health outcomes of infected individuals. Figure 19.3 shows the comparison of the simulation results between the two scenarios. We can see that the HIV-infected population decreases from 1.2 million to 0.8 million, and the HIV death population decreases from 0.6 million to 0.4 million when the HIV treatment rate increases from 30 to 67%. We can also see that the HIV incidence rate decreases from 0.0015 to 0.0012, and the HIV prevalence rate decreases from 0.0087 to 0.0065 when the HIV treatment rate increases from 30 to 67%. We have used this extension to explore how HIV treatment can influence the disease progression and the survival of the infected individuals. We anticipate that HIV treatment will decrease the death rate and increase the treatment population over time. We also anticipate that HIV treatment will affect the transmission of the disease, as it can reduce the viral load and infectivity of the treated individuals.

Furthermore, as the government of China increased its investment in social medical insurance, more HIV-infected individuals could access HIV treatment, and social insurance would cover most of the treatment costs. Additionally, CDC China and hospitals introduced new HIV treatments from Western countries. Therefore, we raise the percentage of the HIV-infected population who receive HIV treatment to 67%, based on Zhang and Ma (2019).

Figure 19.10 shows the simulation results of our model with an HIV treatment rate of 30%. The simulation results differ from the base model. On the left side, the susceptible population graph has a convex shape instead of a concave shape. On the right side, the HIV infection population graph also has a convex shape, which decreases over 50 years and reaches almost zero at the end of the period. Moreover, the HIV death population graph increases in the first 25 years, then flattens in the 25–40 years range, and then increases again in 40–50 years. Finally, the tipping point where the HIV death population exceeds the HIV infection population occurs around the 5th year. After that, the death population will be higher than the infection population for the next 45 years.

Next, we increase the value of the treatment rate to 67%.

- Treatment rate = 0.67*HIV infection population

This reflects the scenario where the government of China invests more in social medical insurance and enables more HIV-infected individuals to access HIV treatment. Social insurance would cover most of the treatment costs. Moreover, CDC China and hospitals introduce new HIV treatments from Western countries. Therefore, we raise the percentage of the HIV-infected population who receive HIV treatment to 67%, based on Zhang and Ma (2019). Figure 19.11 shows the difference in the susceptible population between the base model and the government attention model on the HIV treatment rate. Figure 19.12 compares the HIV-infected population and the HIV-death population in both models. Based on the simulation results in

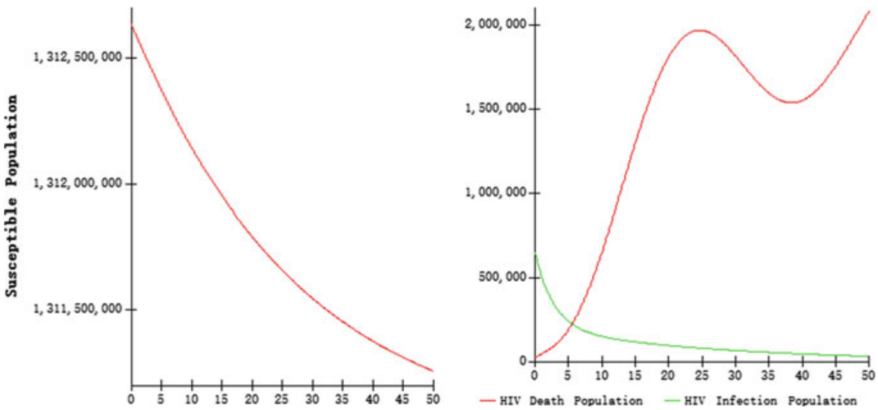


Fig. 19.10 Dynamics of HIV treatment

Fig. 19.11, we can see the new susceptible population with a treatment rate of 67%, in the first 5 years is similar to the model given in Fig. 19.10, but in the following 45 years, the new susceptible population is greater than the base model. Moreover, the gap between new susceptible populations and base models is continually increasing. Thus, we can conclude that increasing the treatment rate through government policy support could increase the susceptible population means less HIV infection and death population.

Figure 19.12 illustrates the effect of policy support on the HIV infection and death population. We can see that the tipping point where the HIV death population exceeds the HIV infection population occurs within 5 years, around year 3. Moreover, the HIV infection population 2 decreases more rapidly than the original model. For the HIV death population 2, we can see that the new trend shifts the original graph to the left. In summary, government support for HIV treatment in China could help reduce the HIV infection population in the future at a faster rate, and the HIV treatment method could be an effective way to curb the HIV epidemic.

In this chapter, we present a system dynamics model of the HIV epidemic in China with four stocks: susceptible population, HIV infected population, HIV treated population, and HIV death population. The initial values of these stocks are derived from the data provided by UNAIDS and our research. We use this model to explore the impacts of HIV testing technology on the dynamics of the epidemic. Specifically, we vary the delay time and contact rate parameters in the model, which represent the time lag between infection and diagnosis, and the frequency of sexual contact among the population, respectively. Figure 19.3, shows the structure of our model with these parameters. Our results show that enhancing the HIV testing technology and efficiency can significantly decrease the number of HIV infections and deaths. Therefore, we recommend that the Chinese government and CDC China should

Fig. 19.11 Dynamics of susceptible population with treatment

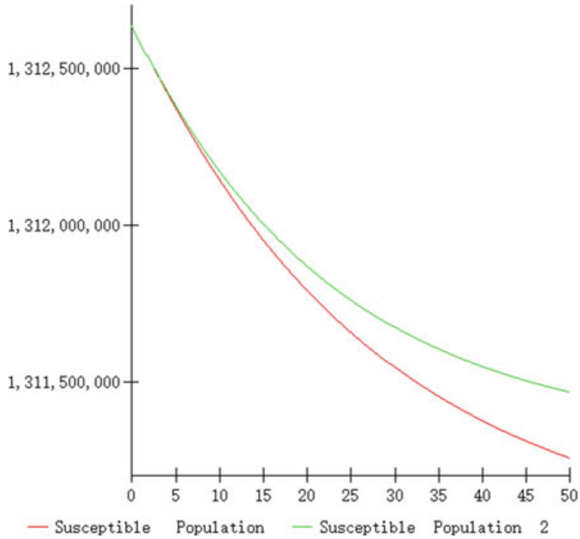
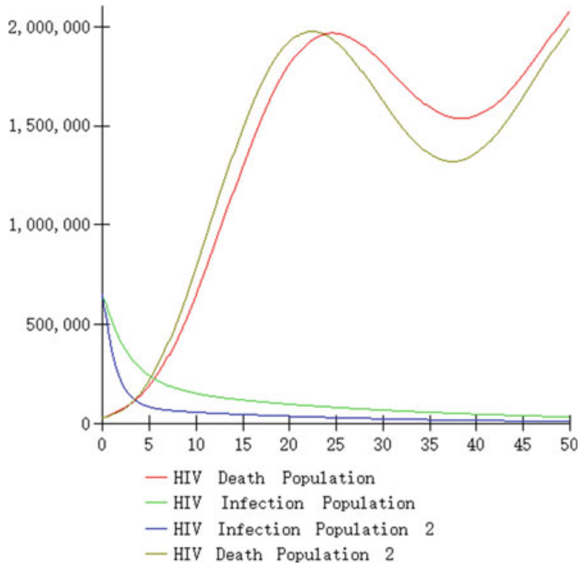


Fig. 19.12 Dynamics of the HIV infection and death population



invest more resources in improving their HIV testing capacity and reducing the delay time and contact rate. In addition to testing technology, we also consider the role of HIV treatment in our model. We add another stock to represent the population of HIV-infected individuals who receive antiretroviral therapy (ART). We assume that ART can reduce the infectivity and mortality of HIV-infected individuals, as well as improve their quality of life. We simulate our model for 50 years and find that HIV treatment can effectively eliminate the HIV-infected population by the end of the simulation period. We also find that increasing the coverage of ART among the HIV-infected population can further speed up the decline of the HIV-infected population. Therefore, we conclude that HIV treatment is crucial for controlling the HIV epidemic in the long run, and the government should make efforts to increase access and adherence to ART among the infected individuals.

19.8 The Limitations of Our Model

Here ate the key limitation of our model:

1. One of the limitations of our model is the lack of reliable data from CDC China for some of the key variables, such as the exact number of HIV infections and deaths in 2004. We use the estimates from UNAIDS in 2005 as the initial values for our model, but we are not sure how accurate they are.
2. Another limitation is that we could not find credible data to support some of the variables and causal relationships that we identified in Sect. 19.3 CLD diagrams. Therefore, we had to omit some of these variables from our stock and flow model.

3. Moreover, our stock and flow model is a closed system with a fixed number of variables. However, the population of China is not a constant variable, but rather a dynamic variable that changes over time. The population growth rate of China may follow an exponential pattern or a logistic pattern with decreasing marginal growth.

19.9 Conclusion

In this chapter, we have developed and simulated a system dynamics model of the HIV/AIDS epidemic in China under different scenarios and created different time graphs by inputting different research data. We have drawn some conclusions and recommendations based on our model results. We suggest that the government should pay more attention to the changing trend of the HIV/AIDS transmission modes: sexual transmission and injecting drug use. At the same time, the government should recognize the importance of tailoring specific policies for different transmission modes and population groups. The government should not only provide education programs to promote condom use, post-exposure prophylaxis (PEP), and highly active antiretroviral therapy (HAART), but also they should eliminate the stigma and discrimination against HIV/AIDS. We also propose that the government should change the testing method from enzyme-linked immunosorbent assay (ELISA) to rapid tests, which are more convenient and reduce the delay time between infection and diagnosis. The government should also encourage more community-based organizations to participate in HIV prevention efforts.

In addition, we suggest that the government should collaborate with other stakeholders, such as international organizations, non-governmental organizations, and private sectors, to mobilize more resources and expertise for HIV prevention and control efforts. We also propose that the government should monitor and evaluate the effectiveness and impact of the existing policies and programs, and make timely adjustments based on the feedback and evidence. Moreover, we advise that the government should enhance public awareness and education about HIV/AIDS, and reduce the stigma and discrimination against people living with HIV/AIDS. We also recommend that the government should support the research and development of new technologies and interventions for HIV prevention, diagnosis, treatment, and cure. We hope that our suggestions can contribute to the global goal of ending AIDS by 2030.

In conclusion, we have developed a system dynamics model of the HIV infection model in China and simulated its behavior under different scenarios. We have found some key variables that affect the dynamics of the epidemic, such as testing technology, treatment coverage, and transmission modes. However, we have also recognized some limitations of our model, such as data availability, model validation, and parameter uncertainty. Therefore, we have suggested some directions for future improvement of the simulation model and research, such as creating an open simulation system, collecting more reliable data, validating the model with empirical evidence, exploring the interactions and feedback loops among different variables and sub-models, testing different scenarios and policies with sensitivity analysis and optimization methods, and extending the model to other regions and countries with different HIV epidemic characteristics and contexts. We hope that our model can provide some insights and recommendations for HIV prevention and control efforts in China and beyond.

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Part VIII
Finally

Chapter 20
Conclusion and a Way Forward for Managing Complex Tasks

Hassan Qudrat-Ullah

Abstract This is the final chapter of our book, where we have given you a way forward and a future with hope. We urge you to embrace systems thinking to tackle the complex issues of our turbulent times. Together, with a systems thinking-based mindset, we can make this world a better place. Systems thinking is not only a tool but also a way of life. It can help you see the connections, patterns, and dynamics that shape our reality. It can also help you create positive change and innovation in your personal and professional life. We hope that this book has inspired you to become a systems thinker and a systems leader. We hope that you will join us in this journey of learning and discovery, and share your insights and experiences with others. We hope that you will use systems thinking to create a sustainable future for yourself and humanity.

Keywords Systems thinking approach · Bounded rationality · Time constraints · Feedback · Complex tasks · Practical insights · Causal models · Decision-aiding solutions · Theoretical perspectives · Climate change · Healthcare · Education · Digital technologies

20.1 Introduction-Finally!

We have explained the challenges and limitations that human decision makers face in complex tasks, such as bounded rationality, escalation of commitment, time constraints, uncertainty, and biases. We have argued that the systems thinking approach can help us overcome or mitigate these challenges and limitations by expanding our perspective, considering multiple viewpoints, testing our assumptions, learning from feedback, and designing effective solutions. We have demonstrated how we can use causal models to represent the structure and dynamics of complex tasks, and how we can use them to build and test the effectiveness of decision-aiding solutions. We have also presented practical insights that can help us

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make better decisions while dealing with complex tasks. These insights are derived from the analysis and simulation of the causal models and the decision-aiding solutions. We have provided various examples of theoretical perspectives and innovative causal-loop-modeling-based applications in different domains, such as climate change, healthcare, education, digital technologies, agriculture, and sustainability. We hope that this book has inspired you to apply a systems thinking approach to your complex tasks and to become a better decision-maker and performer.

We have reached the end of this journey, where we have explored systems thinking and its applications in various domains such as education, technology, agriculture, sustainability, and healthcare. We have shared some theoretical and methodological advancements in systems thinking and system dynamics, such as integrating behavioral economics, value networks, and systems engineering. We have shown how these advancements can help us deal with the complexity and uncertainty of real-world problems and systems. We have also presented some examples of how systems thinking can help us tackle some of the most urgent and complex challenges in these domains, such as improving student learning experience and outcomes, fostering problem-solving skills and creativity, exploring gender inequality and solutions for women in science, bridging the digital gap and addressing the IT professional shortage, solving social dilemmas in water management and biosecurity, exploring the systemic causes and effects of land inequality and plastic recycling, assessing the impact of ESG spending on public perception of the oil sands, and improving healthcare policy decisions and outcomes for HIV/AIDS prevention and treatment, N95 mask supply chain, and endangered species conservation. We have demonstrated how to use causal loop modeling and system dynamics simulation to understand and improve the dynamics and feedback of these systems, and how to simulate and compare different scenarios and policies for enhancing system performance. We have also offered some insights and tools for applying systems thinking to our problems and contexts, and for becoming systems thinkers and leaders. We have proposed some principles and practices for developing systems thinking mindset and skillset. We hope that this book has motivated you to use systems thinking to address your challenges and to make a positive difference in the world.

20.2 A Way Forward

As we have seen in this book, systems thinking is a powerful and practical approach to improving human decision making and performance in complex tasks. However, systems thinking is not a one-time or one-size-fits-all solution. It is a continuous and adaptive process that requires constant learning and improvement. Therefore, we encourage the readers to apply the systems thinking approach to their problems and contexts and to seek feedback and learn from their experiences. We also encourage the readers to explore more resources and opportunities for learning and applying systems thinking, such as books, journals, courses, workshops, conferences, communities, and networks. We hope that the readers will continue their journey of systems thinking and become systems thinkers and leaders who can contribute to a better world.

20.3 Future Research Directions

Besides proving innovative solutions and practical insights for the decision makers of various domains including education, digital technology, agriculture, sustainability in consumption and supply of products and services, and healthcare, here we present some promising research avenues for our researchers across the globe. We will organize these research opportunities thematic-wise.

20.3.1 Theoretical and Methodological Advancements

If you are inspired by the four unique contributions to this theme, you will find many exciting research questions to explore, such as:

If you are interested in reliability assurance of subsea oil and gas production systems (Chap. 2), you will find many exciting research questions to explore in this topic, such as: how to apply the systems engineering approach to other types of offshore oil and gas production systems, such as floating production storage and offloading (FPSO) units, or deepwater production systems, how to extend the systems engineering approach to cover the entire life cycle of offshore oil and gas production systems, from design to decommissioning, and how to incorporate sustainability and environmental aspects, how to integrate the systems engineering approach with other disciplines, such as human factors engineering, safety engineering, or asset management, to optimize the performance and reliability of offshore oil and gas production systems, how to use advanced technologies, such as digital twins, artificial intelligence, or machine learning, to enhance the reliability analysis, testing, and risk management of offshore oil and gas production systems, and how to evaluate the impact of climate change and extreme weather events on the reliability of offshore oil and gas production systems, and how to adapt the systems engineering approach accordingly.

If you are curious about scientific vocations and the PM-SD methodology, you will find many fascinating research questions to explore in Chap. 3, such as: how to adapt and apply PM-SD to other domains and contexts, such as education, health, or environment, and how to compare and contrast its effectiveness and impact across different settings, how to improve and refine the PM-SD methodology, such as by incorporating more advanced tools and techniques for system dynamics modeling and simulation, participatory data collection and analysis, or stakeholder engagement and facilitation, how to explore and understand the underlying mechanisms and factors that influence the development of scientific vocations among children and adolescents, such as motivation, interest, self-efficacy, or social support, how to design and implement more comprehensive and sustainable interventions for promoting science vocations, such as by integrating PM-SD with other approaches, such as inquiry-based learning, science communication, or mentoring, and how to foster more collaboration and communication among researchers, practitioners, policy-makers, and educators in the field of science vocations, and how to create a common language and framework for this interdisciplinary field.

This chapter (i.e., Chap. 4) opens new avenues for research and practice in the field of behavioral economics and system dynamics. Future work in this field could explore how to design and conduct behavioral experiments to inform system dynamics models, how to incorporate more behavioral concepts and theories into system dynamics, how to use more advanced tools and methods for representing and analyzing time, how to apply this approach to more complex and diverse domains and contexts, and how to foster more collaboration and communication between behavioral economists and system dynamicist.

Finally, Chap. 5 of this theme suggests future research directions to improve and expand this interdisciplinary field and to foster more collaboration and communication between value network analysts and causal loop diagrammers. Some interesting research questions are: how to extend and refine the methodology to incorporate other types of systems thinking tools and methods, such as stock and flow diagrams, system archetypes, or system dynamics simulations, how to apply the methodology to different domains and contexts, such as public policy, social innovation, or environmental sustainability, and how to evaluate its impact and effectiveness, how to develop and use more advanced techniques and software for analyzing value networks and causal loop diagrams, such as network analysis, machine learning, or artificial intelligence, and how to foster more collaboration and communication between value network analysts and causal loop diagrammed, and how to create a common language and framework for this interdisciplinary field.

20.3.2 Learning Analytics and Interactive Multimedia with Systems Thinking

Do you want to learn from the three innovative and exceptional contributions to this theme? If so, you will find many fascinating and doable research questions to explore in this theme, such as:

If you are curious about the topics of learning analytics and interactive multimedia experience, you will find many interesting questions to explore in Chap. 6, such as: how can you use causal loop modeling to identify the key feedback loops that link the learning process with the user experience in different domains and contexts of learning? How can you improve and refine the causal loop modeling approach by incorporating more variables and indicators, validating the model with empirical data, or using system dynamics simulation to test different scenarios and interventions? How can you investigate and understand the key mechanisms and factors that influence the user experience and learning outcomes in multimedia projects, such as motivation, interest, emotion, cognition, or metacognition? How can you design and implement more effective and innovative multimedia projects that enhance the user experience and learning outcomes, such as by using adaptive learning, gamification, storytelling, or social interaction? How can you foster more collaboration and communication among researchers, practitioners, designers, and educators in the field of learning analytics and interactive multimedia experience, and how can you create a common language and framework for this interdisciplinary field?

If you are curious about the topics of system dynamics and education, you will find many interesting questions to explore in Chap. 7, such as: How can you use system dynamics to foster problem-solving skills and creativity in primary-school students in different domains and contexts of learning, such as STEM, social studies, or arts? How can you improve and refine the system dynamics approach by using more advanced tools and techniques for system dynamics modeling and simulation, collaborative teaching strategies, or assessment methods? How can you investigate and understand the key mechanisms and factors that influence the development of problem-solving skills and creativity among primary-school students, such as motivation, interest, emotion, cognition, or metacognition? How can you design and implement more effective and innovative interventions that foster problem-solving skills and creativity among primary-school students, such as by using gamification, storytelling, or project-based learning? How can you foster more collaboration and communication among researchers, practitioners, teachers, and students in the field of system dynamics and education, and how can you create a common language and framework for this interdisciplinary field?

If you are curious about the topics of systems thinking and gender equality in science, you will find many interesting questions to explore in Chap. 8, such as: How can you use systems thinking to address the issue of gender inequality in other domains and contexts of science, such as industry, government, or civil society, and how can you measure and compare the feedback loops and structural factors across different settings? How can you improve and refine systems thinking to address the issue of gender inequality in science, by using more variables and indicators, validating the model with empirical data, or using system dynamics simulation to test different scenarios and interventions? How can you investigate and understand the key mechanisms and factors that influence the development and persistence of gender inequality in science, such as social norms, stereotypes, biases, or power relations? How can you design and implement more effective and innovative strategies and solutions that promote gender equality and equal opportunity in science, by using participatory methods, empowerment approaches, or policy changes? How can you foster more collaboration and communication among researchers, practitioners, policymakers, and educators in the field of gender equality and science, and how can you create a common language and framework for this interdisciplinary field?

20.3.3 Bridging the Digital Gap with Systems Thinking

If you are inspired by the two state-of-the-art applications of systems thinking applications available in this theme, you will find many promising research questions to explore, such as:

If you are curious about the topics of system thinking and AI technology for addressing the digital gap, you will find many interesting questions to explore in Chap. 9, such as: How can you use system thinking and AI technology to address the digital gap in different domains and contexts, such as health, education, or governance? How can you improve and refine system thinking and AI technology to address the digital gap, by using more data sources and indicators, validating the models with empirical evidence, or using human-in-the-loop approaches? How can you investigate and understand the key mechanisms and factors that influence the digital gap, such as social norms, digital skills, infrastructure, or policies? How can you design and implement effective and innovative solutions that use system thinking and AI technology to address the digital gap, such as by using gamification, crowdsourcing, or blockchain? How can you foster collaboration and communication among researchers, practitioners, policymakers, and users in this field, and create a common language and framework for this interdisciplinary field?

Based on your interest in the research presented in Chap. 10, future research directions could explore how to develop and assess systems thinking competencies and skills among different stakeholders, such as leaders, managers, employees, students, and citizens in the IT field. Systems thinking can enhance critical thinking, creativity, collaboration, and communication skills, which are essential for the digital economy. Additionally, future research could examine how to overcome the barriers and risks of adopting emerging digital technologies, such as talent shortages, implementation costs, and security threats.

20.3.4 Addressing Agricultural Issues with Systems Thinking

If the three inspiring contributions to this theme entice you enough to further exploration of the topic then here are several future research opportunities for you:

Future research directions could explore how IoT and System Dynamics can be integrated with other technologies and methods to enhance water management in different contexts and scales (please see Chap. 11). For example, how can IoT and System Dynamics be combined with blockchain, cloud computing, artificial intelligence, or geographic information systems to improve data security, storage, analysis, or visualization? How can IoT and System Dynamics be used with participatory approaches, stakeholder engagement, or social learning to foster collaboration and trust among water users and managers? How can IoT and System Dynamics be adapted to different water systems, such as urban water supply, irrigation, wastewater treatment, or groundwater management? Future research could also address the challenges and risks of implementing IoT and System Dynamics for water management, such as technical issues, ethical concerns, legal frameworks, or social impacts.

If Chap. 12 inspires you for future research, you could explore how systems thinking and cooperation can be applied to different aspects and dimensions of land inequality, such as land ownership, land use, land governance, land rights, and land value. Systems thinking can help understand the root causes and consequences of land inequality, as well as the feedback loops and interdependencies among various actors and factors involved. Cooperation can help create more inclusive and participatory processes and mechanisms for addressing land inequality, such as multi-stakeholder dialogues, collective action, social movements, and policy advocacy. Future research could also examine how systems thinking and cooperation can be influenced by or influence other global challenges and trends, such as climate change, food security, migration, urbanization, and digitalization. Systems thinking and cooperation can help identify synergies and trade-offs among these challenges and trends, and foster more holistic and integrated solutions.

Are you curious to learn more about this topic after reading Chap. 13? Then this chapter will guide you through several exciting directions for future research, such as how system thinking and cooperation mechanisms can be tailored to different types and levels of biosecurity adherence, such as individual, organizational, or national. System thinking can help understand the factors and motivations that influence people's decisions to cooperate or not in biosafety procedures, as well as the outcomes and impacts of those decisions. Cooperation mechanisms can help design and implement interventions that encourage and support people's compliance with biosafety standards, such as incentives, sanctions, feedback, or recognition. Future research could also examine how system thinking and cooperation mechanisms can be integrated with other approaches and tools to enhance biosecurity adherence, such as risk assessment, scenario planning, simulation modeling, or stakeholder analysis. System thinking and cooperation mechanisms can help develop and evaluate strategies that improve biosecurity performance and reduce biological hazards in various contexts.

20.3.5 Sustainability Science and Systems Thinking

Are you inspired by the two innovative and outstanding contributions to this theme? If so, you will discover many intriguing and practical research questions to pursue in this theme, such as:

Are you eager to learn more about how systems thinking and a System Dynamics model can help you improve plastic recycling and sustainability in Bangladesh? Then Chap. 14 will spark your interest with several fascinating research questions to explore in this theme, such as: How can systems thinking and a System Dynamics model help you understand the current state and challenges of plastic recycling in

Bangladesh, such as the sources, flows, and destinations of plastic waste, the environmental and social impacts of plastic pollution, and the barriers and opportunities for plastic recovery and valorization? How can systems thinking and a System Dynamics model help you suggest efficient techniques for collecting, sorting, and valuing recyclables, such as the use of incentives, communication, education, or technology to increase the participation and awareness of different stakeholders, such as consumers, collectors, recyclers, or policymakers? How can systems thinking and a System Dynamics model help you transform plastic waste into valuable resources and achieve sustainable development goals, such as the use of reverse and circular economy principles to reduce plastic consumption, increase plastic reuse and recycling, and create new markets and jobs for recycled plastic products?

Are you interested in learning more about how system dynamics and ESG spending can help you improve public perception of the Canadian Oil Sands? Then Chap. 15 will offer you several intriguing research questions to explore in this theme, such as: How can system dynamics and ESG spending help you analyze the effects of reinvesting profits from Oil Sands into environmental, social, and governance (ESG) initiatives on various stakeholders, such as First Nations, environmentalists, investors, and the general public? How can system dynamics and ESG spending help you improve the environmental, social, and economic impacts of oil production, such as reducing greenhouse gas emissions, enhancing stakeholder cooperation, and creating new markets and jobs for sustainable oil products? How can system dynamics and ESG spending help you achieve net-zero emissions by 2050, such as using carbon capture, utilization, and storage (CCUS) technology, adopting circular economy principles, and supporting clean energy transition?

20.3.6 Dealing with the Complexity of Healthcare Systems

Do you want to learn how systems thinking can help us address some of the most pressing and complex challenges in healthcare? If you are intrigued by such research questions, then the four unique empirical studies based on systems thinking approaches will engage you with several fascinating research questions, such as:

Are you passionate about learning how to use systems thinking to solve the toughest healthcare problems? Then Chap. 16 will help you explore the following research questions, among others: How can causal loop modeling help you understand and improve the dynamics and feedback loops of healthcare systems, such as the causes and consequences of medical errors, patient safety, and quality of care? How can systems thinking help you see the big picture and the details of healthcare problems, and how to address them holistically and systemically, such as the interactions and interdependencies among health policies, health services, health outcomes, and health determinants? How can systems thinking help you enhance your skills and knowledge in healthcare management, and become a systems thinker and a healthcare leader, such as the competencies and capacities needed to apply systems thinking tools and methods, communicate systems insights, and facilitate systems change?

If you are interested in learning how to use systems thinking to solve the toughest healthcare problems, then Chap. 17 will immerse you in amazing stories of systems thinking in action for healthcare and will inspire you to explore various research questions, such as: How can a system dynamics simulation-learning environment, SIADH-ILE, help you understand and improve HIV/AIDS management in Canada, using a combined approach for HIV/AIDS prevention and treatment? How can SIADH-ILE enhance your decision-making skills and help you fight against HIV/AIDS, using data from action experiments, a questionnaire, and qualitative feedback from the participants? How can SIADH-ILE help you develop and evaluate strategies that improve biosecurity performance and reduce biological hazards in various contexts?

If you are interested in learning how to protect endangered species from extinction, then this chapter (i.e., Chap. 18) will offer you several exciting directions for future research. You will discover how systems thinking can help you understand and improve the dynamics of conservation efforts for endangered animals, such as: How can a system dynamics model help you compare the outcomes and impacts of different conservation strategies, by simulating the scenarios of conservation and no conservation for these species? How can systems thinking help you take a systemic and holistic approach to conservation, by considering the interrelationships and feedback loops among the various factors that affect the survival and well-being of these species, such as habitat loss, climate change, human-wildlife conflict, poaching, disease, and invasive species? How can systems thinking help you deal with the challenges and limitations of conservation strategies, some of which are controllable and some of which are not, such as ethical issues, social perceptions, legal frameworks, economic incentives, and political will? How can systems thinking help you foster conservation values and actions among the public and policymakers, using tools such as education, communication, advocacy, and stakeholder engagement?

Are you curious about how to understand and prevent the HIV/AIDS epidemic in China? Then Chap. 19 will engage you with several intriguing research questions that you can pursue using systems thinking, such as: How can a system dynamics model help you capture the main modes of transmission and the effects of medical interventions on reducing HIV infection and mortality? How can systems thinking help you create the dynamics of HIV/AIDS under different scenarios and compare the results using time graphs? How can systems thinking help you assess the testing and prevention programs that China has implemented to achieve the UNAIDS 90–90–90 targets and curb the epidemic? How can systems thinking help you propose policy recommendations to address the HIV/AIDS epidemic in China?

20.4 Concluding Remarks

In this book, we have explored systems thinking and its applications in various domains such as education, technology, agriculture, sustainability, and healthcare. We have presented some theoretical and methodological advancements in systems thinking and system dynamics, such as integrating behavioral economics, value networks, and systems engineering. We have shown how these advancements can help us manage the complexity and uncertainty of real-world problems and systems. We have also provided some examples of how systems thinking can help us address some of the most critical and complex challenges in these domains.

To what extent we are successful in achieving our goal of spreading virtues of the systems thinking approach, you, the reader of this book be the judge☺. I would be happy to hear from you at: hassanq@yorku.ca.

Index

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