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System Dynamics

Modelling and Simulation

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Foreword

The world, today, is passing through a period of great turmoil, socially, politically and environmentally, in spite of the numerous technological wonders that are taking place almost everyday. One needs to take a systems view of the influencing factors and their interactions and impacts in order to find the root causes of these problems and to arrive at viable policy options. System dynamics provides such an approach. The book authored by Professor Bala, Professor Fatimah and Professor Noh presents the principles of system dynamics in very simple language and illustrates its use with the help of five real-life case studies.

This book is divided into two parts. The first part of the book presents, in a very simple way and starting with the fundamental principles, how complex interactions among the interacting forces can be modelled by capturing their cause–effect interrelations through dynamic models, how the models can be simulated and evaluated to depict reality and how policy interventions can be tested for testing their viability. Although the material covered in this part of the book is not new, the examples supporting the theoretical nuances of the subject covering population growth, grain storage, food security, commodity production, food relief, crop livestock, shrimp farming, crop irrigation and pollution are very interesting and appealing.

In the second part of the book, the authors discuss case studies related to the areas of agriculture, aquaculture and environment in Bangladesh and Malaysia. Both hilsa fish and rice are important for the economy of Bangladesh, just as food security and cocoa production for Malaysia. The case study for solid waste management is well chosen as it is a perennial problem in third-world countries. This part of the book is illustrative of the power of system dynamics methodology as to how it can address many complex issues of today very easily.

I believe that a newcomer to the field of system dynamics will find the book extremely useful and will be highly motivated to use system dynamics and systems thinking in understanding and addressing the issues that arise out of the behaviour of systems that are integral part of their lives.

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September 2014

Preface

This book *System Dynamics: Modelling and Simulation* is a totally new book with numerous examples and case studies for better understanding the complex systems and their changes through modelling and simulation to aid in policy formulation and developing management strategies for sustainable development. This book provides a comprehensive introduction to systems thinking and modelling of complex systems with application to agricultural, aquacultural, environmental and socio-economic systems. Also this book essentially provides the principles of system dynamics with numerous examples and a good number of case studies in agricultural, aquacultural, environmental and socio-economic systems. It covers all aspects of system dynamics starting from systems thinking to participatory model building to provide a tool for policy planning, and the main focus is to aid in policy design.

This book has been written primarily for undergraduate and postgraduate courses on system dynamics, systems engineering, system simulation, agricultural systems and multidisciplinary courses on agricultural, aquacultural, environmental and socio-economic systems. This book can be adopted for courses in electrical engineering and computer science. It will also serve as an excellent reference for practicing system dynamists, system dynamics researchers and policy planners. It is the outcome of several years of teaching and research in system dynamics modelling and simulation with applications in agricultural, aquacultural, environmental and socio-economic systems and also is an updated and a new book on principles of system dynamics.

This book covers the wide spectrum of system dynamics methodology of modelling and simulation of complex systems: systems thinking, causal diagrams, system structure of stock–flow diagrams, parameter estimation and tests for confidence building in system dynamics models with a good number of worked-out examples in diverse fields using STELLA and VENSIM. In case studies, problem statement with dynamic hypothesis is followed by causal loop diagrams, stock–flow diagrams, parameter estimation, model validation and policy design. Exercises have also been included at the end of each chapter for further practices.

The authors have a great pleasure in expressing the acknowledgements which they owe to many persons in writing this book. Professor B K Bala warmly recognises the continuing debt to his teacher, Dr. Donald R. Drew, W. Thomas

Rice professor of systems engineering, Virginia Polytechnic Institute and State University, USA, who introduced him to system dynamics at the Asian Institute of Technology, Bangkok, Thailand. Thu authors also express sincere acknowledgements to Professor P K J Mohapatra, Indian Institute of Technology, Kharagpur, India who is the Father of System Dynamics in India has written the foreword of this book. The authors have a great pleasure in expressing the acknowledgements to Dr. Serm Janjai, Department of Physics, Silpakorn University, Nakhon Pathom, Thailand, for his encouragement and support in the preparation of this book and my colleague Professor Ashraful Haque, Department of Farm Power and Machinery, who read the manuscript and made many helpful suggestions. I owe my thanks to Mrs. Emmy Farhana Alias, Institute of Agricultural and Food Policy Studies, Universiti Putra Malaysia, Malaysia, for her help in the preparation of the manuscript and Dr. Itsara Masiri of the Department of Physics, Silpakorn University, Nakhon Pathom, Thailand, for the assistance in graphics and in drawing the beautiful figures.

Selangor, Malaysia

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Kusairi Mohd Noh

Contents

Part II Cases and Applications

Part I

Concepts, Methodology and Techniques

1 Introduction

This chapter introduces the complexity and change of the dynamic systems, systems thinking and system dynamics as a methodology of systems thinking. Feedback system concepts and mode of behaviour of dynamic systems are highlighted. Model and simulation are defined, systems thinking methodology outlined and usefulness of models are discussed.

1.1 Introduction to Complexity and Change of the Dynamic Systems

We live in a complex world, and it is always at a change. Also we are confronted with complex agricultural, biological, aquacultural, environmental, technological and socio-economic problems which we need to understand and manage for sustainable development. In global context we debate seriously on global warming and its impacts on agriculture, energy and environment and also find reports on economic cycles causing financial panics, and in regional and local levels, we often find price fluctuations and food insecurity in the developing countries to mention some of the problems of complex and dynamic systems. Figure 1.1 shows the price fluctuations of wheat, maize and rice in the international markets as an example of the dynamic and complex problem which caused devastating consequences for hundreds of millions of people and negatively impacted many more. How can we understand and manage these complex systems? If yes, how can we do it? We need improved knowledge and analytical capabilities to understand and manage food price volatility and reduce hunger and malnutrition (Hajkowicz et al. 2012). System dynamics methodology based on feedback concepts to handle non-linearity, multi-loop and time-lag characteristics of complex dynamic systems can be applied to model and simulate such complex dynamic systems to understand the dynamics of systems and design management policy for sustainable development.

Indeed, we can understand and design management strategies, but we need some structures or guiding principles to understand and manage the complexity and

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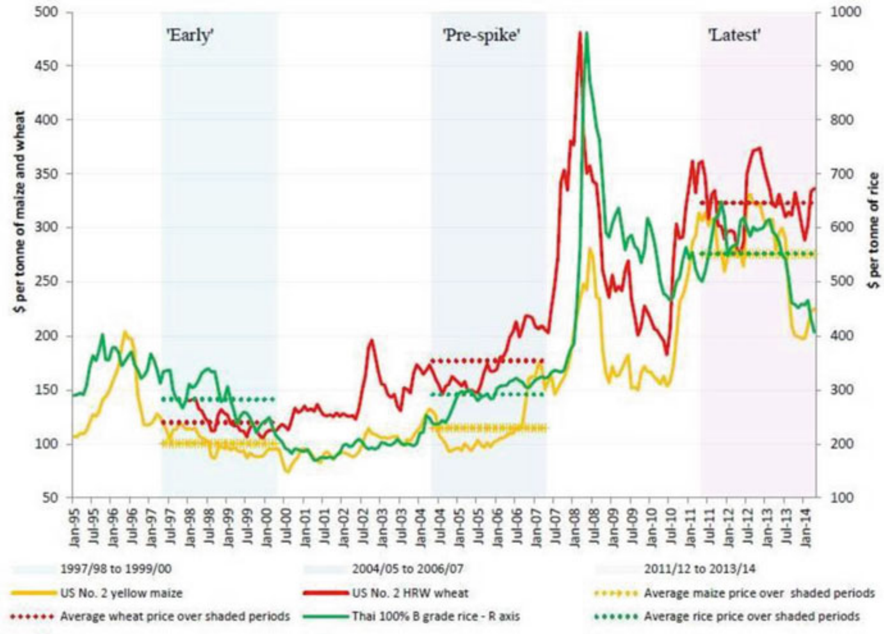


Fig. 1.1 Price fluctuations of wheat, maize and rice in the international market (Steve and Sharada 2014)

changes of complex dynamic systems based on systems approach which considers the whole systems rather than in isolation. Systems approach is rather a rational rather intuitive approach. It depends on some formalised methodology consisting of methods of problem definition, dynamic hypothesis, modelling, policy analysis, etc., and theoretical techniques which are useful for solving models and sub-models of the problem. In essence the systems must be modelled and simulated to understand the systems and design management strategies. Also these must be done before implementation of the management strategies. Forrester's system dynamics methodology provides the methodology—the guiding principles to develop computer models to simulate such complex and dynamic systems to understand the complex systems and design the management strategies. In essence, systems thinking is a formalised methodology consisting of methods of problem definition, dynamic hypothesis, modelling and policy analysis to understand and manage complex and dynamic systems.

As the complexity of our world increases, systems thinking is emerging as a critical factor for success, and even survival. How then can people become skilled systems thinkers? But in the world of complex dynamic systems, everyday experience fails because the time horizon and scope of the systems are so vast—we never experience the majority of the effects of our decisions. When experiments in the real world are impossible, simulation becomes the main way we can learn effectively about the dynamics of complex systems. System dynamics is the most appropriate technique to simulate complex and dynamic systems based on systems thinking to develop policy scenarios and learn to effectively manage the systems.

1.2 Concepts of Systems and System Dynamics

System dynamics is a methodology based on feedback systems borrowed from control theory, and it can handle easily the non-linearity and time-delay and the multi-loop structures of the complex and dynamic systems. Forrester's methodology provides a foundation for constructing computer models to do what the human mind cannot do—rationally analyse the structure, interactions and modes of behaviour of complex social systems, thus providing a framework whereby strategies can be tested and trade-offs can be performed, while options are still open. Many software such as STELLA, VENSIM, and POWERSIM are nowadays available which have revolutionised the system dynamics modelling. Furthermore, these software are icon operated and allow us to model virtually any process or system.

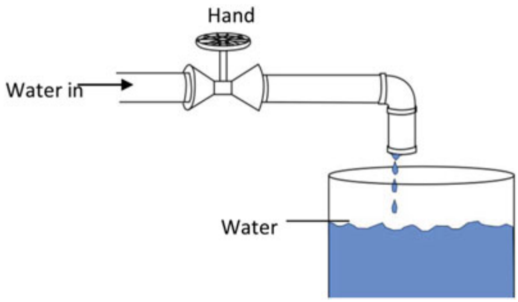
1.3 Open and Feedback Systems

We have discussed about some complex and dynamic systems in Sect. 1.1. What is meant by a system? Here system means a grouping of parts that operate together for a common purpose. For a simple example, a tractor is a system of components that work together for providing cultivation. A system may include people as well as physical parts. A family is a system for living and raising children. Systems may include biological as well as economic components, and such systems are known as bioeconomic systems. Agricultural and aquacultural systems are examples of bioeconomic systems. Crop irrigation system is an example of an agricultural system, while prawn production system is an example of aquacultural system. Also price forecasting is an economic system. In aquacultural system aquatic animals are raised to maturity in an economic manner. A system may include physical, economic, social, biological, technological and political components, and such a system is highly complex. For example, agricultural production systems with climate change in an agricultural system consists of physical, biological, social, technological, environmental, economic and political components and their interactions.

Systems may be classified as (a) open systems and (b) feedback systems. In open systems the output responds to input, but output has no influence on the input. Also the input is not aware of its own performance. In an open system, past action does not affect the future action. For example, a watch is not aware of its inaccuracy and does not correct the time itself. In an open system, the problem is perceived and action is taken, but the result does not influence action (Fig. 1.2). Filling up a water tank without controlling the valve is an example of open loop system (Fig. 1.3). When the hand valve is opened, water starts flowing in the tank and the water level

Fig. 1.2 Open system concept

Fig. 1.3 Filling up a water tank without control of the valve



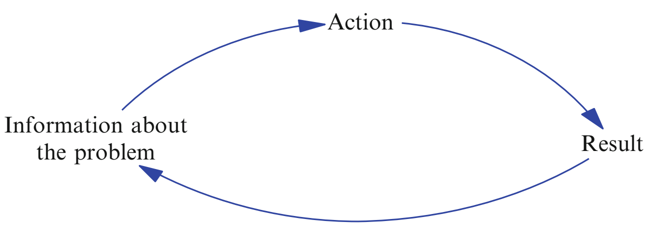


Fig. 1.4 Closed loop system concept

in the tank continues to increase until the hand valve is closed by the user who is not part of the system.

Feedback systems are closed loop systems, and the inputs are changed on the basis of output. A feedback system has a closed loop structure that brings back the results of the past action to control the future action. In a closed system, the problem is perceived, action is taken and the result influences the further action (Fig. 1.4). Thus, the distinguishing feature of a closed loop system is a feedback path of information, decision and action connecting the output to input.

Feedback system may be classified as either positive feedback systems or negative feedback systems. Positive feedback systems generate growth, and negative feedback systems are goal seeking. Population growth system is an example of positive feedback systems. Population multiply to produce more population which increases the growth rate at which the population is increased (Fig. 1.5). Thus, positive feedback system generates growth as shown in Fig. 1.5.

When the room temperature is controlled by a thermostat or temperature controller, the system tries to maintain the set temperature. When the heater is turned on, the temperature increases to set point and then heater is turned off. The temperature reaches ultimately equilibrium and thus, the system is goal seeking. The temperature control system in a room is an example of a negative feedback system (Fig. 1.6).

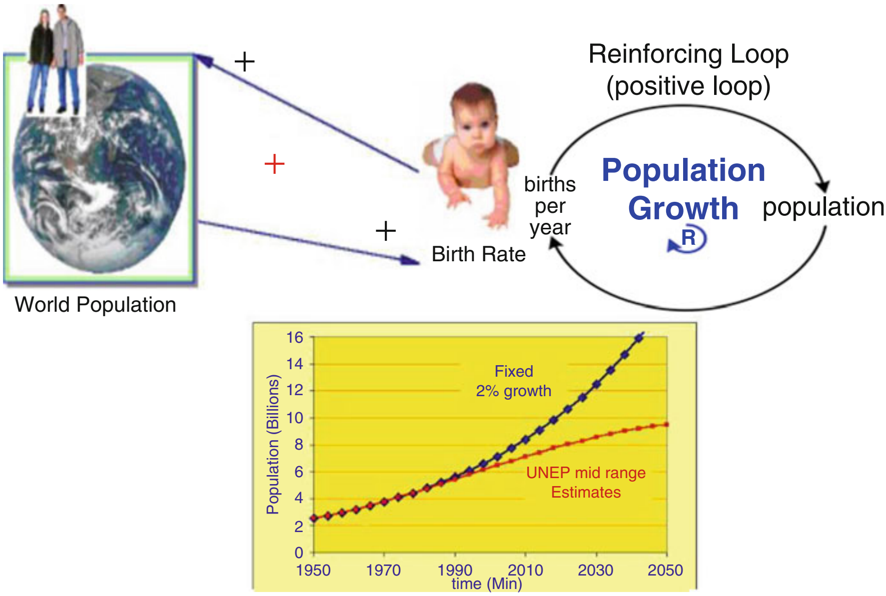


Fig. 1.5 Population growth system

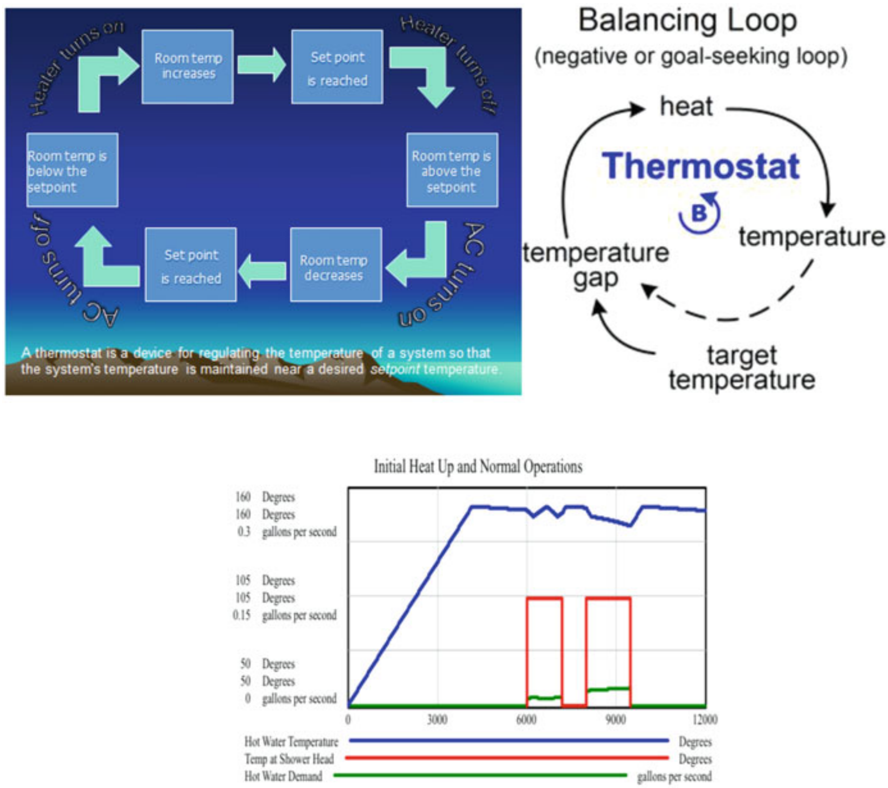


Fig. 1.6 Temperature control system in a room

1.4 Modes of Behaviour of Dynamic Systems

The basic structure of a feedback loop is shown in Fig. 1.7, and it is a closed path in a sequence consisting of a decision that controls action (based on the present state of the system and the desired goal) which results in flow, the stock or level of the system and information about the stock of the system, the latter returning to the decision-making point for further action. The current available information about the level or stock of the system and the goal is basis for current decision that controls action. The action changes the condition of the system. The single feedback loop structure is the simplest form of feedback system.

Feedback loop structure of a system simulates dynamic behaviour, and all the dynamics arises from the interactions of two types of feedback loops: positive feedback loops and negative feedback loops. Positive feedback loop generates growth, i.e. self-reinforcing and the causal loop consisting of population, birth and population in sequence in Fig. 1.8 is a positive feedback loop, and it reinforces population level. Negative feedback loop in Fig. 1.8 consisting of population, death and population is goal seeking. Figure 1.9 shows the dynamic behaviour of the positive and negative feedback systems. Positive feedback system generates exponential growth as shown in Fig. 1.9a, while the negative feedback system is goal seeking as shown in Fig. 1.9b. Figure 1.10 shows the control theory block diagram of a negative feedback system which is analogous to the causal loop diagram in system dynamics, and essentially system dynamics is a control theory for social systems.

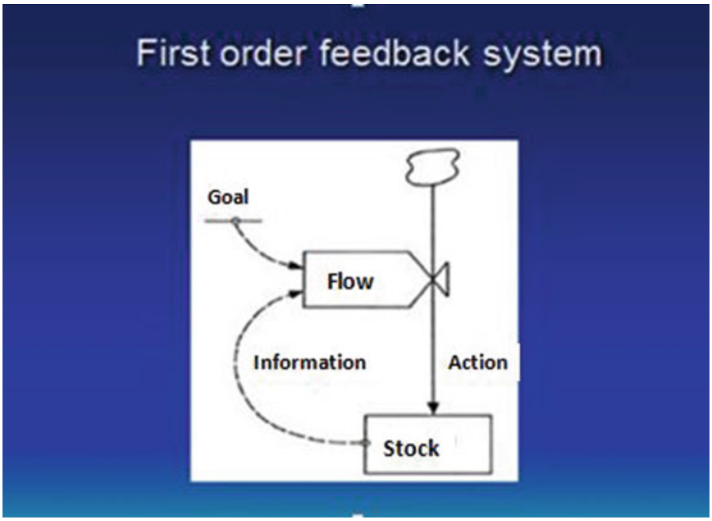


Fig. 1.7 Feedback loop

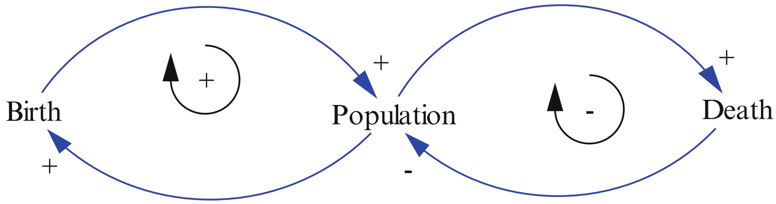


Fig. 1.8 Causal loop

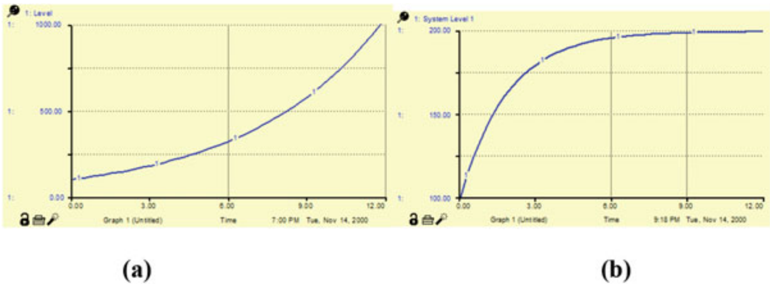


Fig. 1.9 Dynamic behaviour of (**a**) positive feedback and (**b**) negative feedback systems

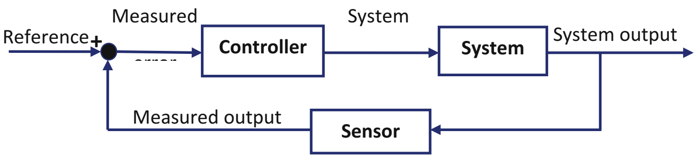


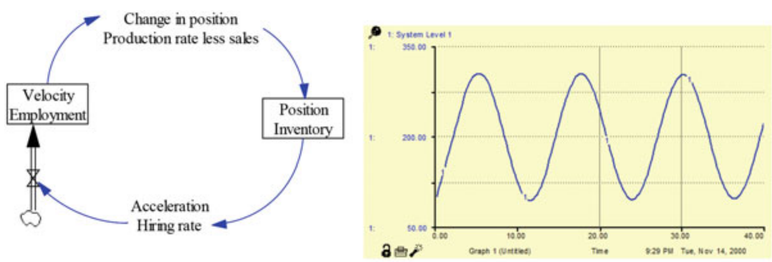
Fig. 1.10 Control theory block diagram of a negative feedback system

Figure 1.11a shows a second order feedback closed loop system characterised by two stocks: employment and inventory, and Fig. 1.11b represents the response of a second order system. The second order feedback loop system generates oscillation.

Figure 1.12 represents the responses of some complex systems. Figure 1.12a shows s-shaped growth, Fig. 1.12b shows s-shaped growth with overshoot and Fig. 1.10c shows overshoot and collapse of complex systems. First order and higher order positive feedback systems generate growth. First order negative feedback system is goal seeking, but the higher order negative system oscillates with a search for goal. Models in practice may contain thousands of interconnected loops with time delay and non-linearities.

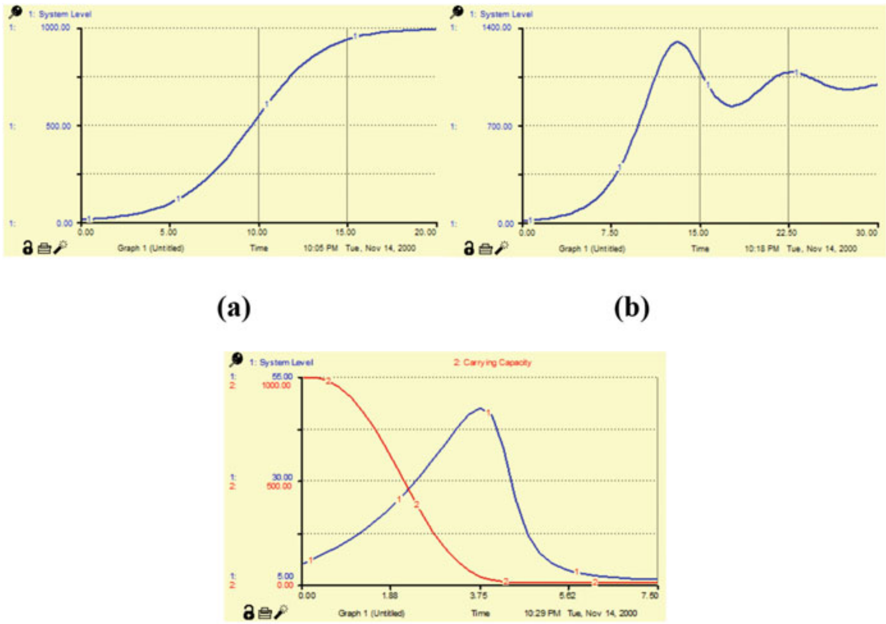
1.5 Models and Simulation

We can study the dynamic behaviour of a physical system by experimentation with the system itself. Sometimes it may be expensive and time consuming. An alternative to this method is to construct a number of prototypes of physical models to



(a) (b)

Fig. 1.11 (**a**) Causal loop diagram of a second order system and (**b**) dynamic behaviour of a second order feedback system



(a) (b)

(c)

Fig. 1.12 Dynamic behaviour of complex systems: (**a**) s-shaped growth, (**b**) s-shaped growth with overshoot and (**c**) overshoot and collapse of complex systems

experiment with it. Sometimes even it may not be possible or practical to experiment with the existing system or construct a physical model for experimentation. Consequently the most inexpensive and less time consuming method is to use a mathematical or computer model.

A model may be defined as a substitute of any object or system. Everyone uses models in their daily life. A mental image used in thinking is a model, and it is not the real system. A written description of a system is a model that presents one aspect of reality. The simulation model is logically complete and describes the dynamic behaviour of the system. Models can be broadly classified as (a) physical models and (b) abstract models as shown in Fig. 1.13. Children's model of car and aeroplane are examples of physical models. Mental models and mathematical models are examples of abstract models.

Mathematical models can be classified as shown in Fig. 1.13 (Bala 1999). A model is a dynamic if it portrays time-varying characteristics; otherwise, the model is static. Steady state and transient characteristics are the properties of the dynamic systems, whereas in static systems, the characteristics do not undergo substantial change in time. In dynamic systems the system states change substantially in time.

It is sometimes possible to solve the mathematical models by analytical methods. But for complex systems, the solution of the mathematical model of the systems by analytical methods is extremely difficult, or it may be beyond the reach of today's mathematics. For such complex systems, only the step-by-step numerical solution is possible. This process of step-by-step numerical solution is called simulation. Simulation models are used in place of real systems. The computer simulation is an inexpensive and rapid method of experimenting with the system to give useful information about the dynamics of the real system. Scenarios based on simulated results can provide guidelines for policy planning and management of complex and dynamic systems.

Forrester's system dynamics methodology provides a foundation for constructing computer models to do what the human mind cannot do—'rationally' analyse the structure, the interactions and mode of behaviour of complex

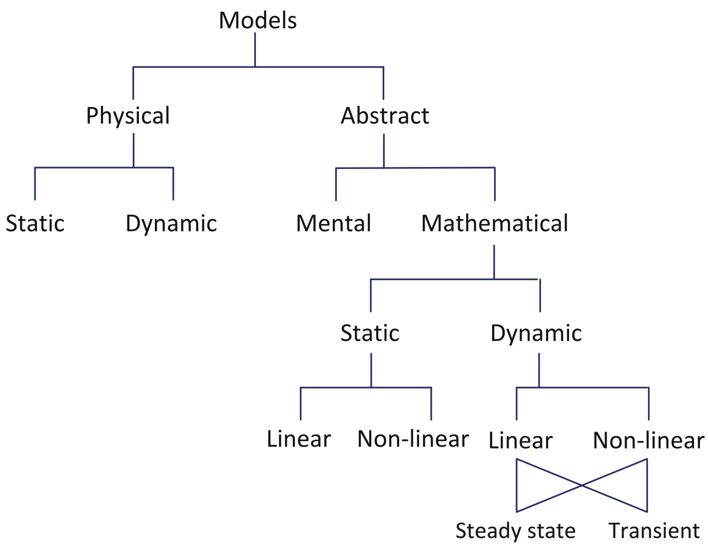


Fig. 1.13 Classification of mathematical models

socio-economic, technological, biological and political systems. The advantages of a computer model over a mental model are (Forrester 1968):

1. It is precise and rigorous instead of ambiguous and unquantified.
2. It is explicit and can be examined by critics for consistency and error.
3. It can contain much more information than any single model.
4. It can proceed from assumption to conclusions in logical error-free manner.
5. It can easily be altered to represent different assumptions or alternate policies.

1.6 Systems Thinking and Modelling

Indeed, we need some structures or guiding principles to model and simulate complex dynamic systems and the systems approach which considers the whole systems rather than in isolation refers to a set of conceptual and analytical methods used for systems thinking and modelling (Cavana and Maani 2000). The general methodological approach towards systems thinking and modelling is discussed here. Many contributions have been reported on systems thinking and system dynamics. The systems thinking and modelling essentially consist of problem statement, causal loop diagram, stock–flow diagram, scenario planning and modelling and implementation and organisation learning. The character of systems thinking makes it extremely effective on the most difficult types of problems to solve: those involving complex issues, those that depend a great deal dependence on the past or on the actions of others and those stemming from ineffective coordination among those involved. The steps for simulating a system dynamics model are summarised below:

- Identify the problem and formulate the mental model in the form of a verbal description (problem identification/conceptualisation) and develop a dynamic hypothesis to account for problematic behaviour in terms of causal loop diagrams and stock and flow structure of the system.
- Create basic structure of the causal diagram from the verbal model.
- Augment causal loop diagrams into system dynamics flow diagrams.
- Translate the system dynamics flow diagrams into STELLA or VENSIM or a set of simultaneous difference equations.
- Estimate the parameters.
- Validate the model, analyse the sensitivity and analyse the policy.
- Application of the model.

1.7 Usefulness of Models

The validity and usefulness of dynamic models should be judged not against imaginary perfection, but in comparison with other mental and descriptive models which are available. The usefulness of a mathematical simulation model should be judged in comparison with the mental image or other models which would be used instead (Forrester 1968). There is nothing in either physical or social science about which we have perfect knowledge and information. We can never say that a model is a perfect representation of the reality. On the other hand, we can say that there is nothing of which we know absolutely nothing. So, models should not be judged on an absolute scale but on relative scale if the models clarify our knowledge and provide insights into systems.

1.8 Structure of the Book

This book is organised into two parts—Part I: Concepts, methodology and techniques and Part II: Case studies. Part I consists of seven chapters, and Part II has five chapters. Chapter 2 provides the over review of systems thinking methodology with an example of systems thinking in action. In Chap. 3 we introduce causal loop diagram, a qualitative methodology with examples, and in Chap. 4, we present stock–flow diagrams, a computer simulation methodology with examples. We discuss parameter estimation and model validation in Chaps. 5 and 6, respectively. Chapter 7 provides scenario development and policy planning. In Part II we present five case studies of systems thinking and modelling, and these are modelling of boom and bust of cocoa production systems in Malaysia in Chap. 8, modelling of hilsa fish in Bangladesh in Chap. 9, modelling of food security in Malaysia in Chap. 10, modelling of supply chain of rice milling systems in Bangladesh in Chap. 11 and modelling of solid waste management in Chap. 12.

Exercises

Exercise 1.1 What is meant by complexity and always at a change of a dynamic system? How such a system can be understood and policy options to manage can be designed?

Exercise 1.2 What is system dynamics? Discuss the potentials of system dynamics methodology to handle complex dynamic socio-economic systems.

Exercise 1.3 Define feedback systems and describe the basic structure of a feedback loop. Discuss the different modes of behaviour of dynamic systems.

Exercise 1.4 What is meant by model? Describe the classification of models. Mention the advantages of a computer model over a mental model. Also discuss the usefulness of models.

Exercise 1.5 What is meant by simulation? What is simulation based on systems thinking and systems approach? Discuss the steps to be followed for simulating a system dynamics model.

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2 Systems Thinking: System Dynamics

The concept of systems thinking was introduced in Chap. 1 and this chapter presents systems thinking based on systems approach. Systems thinking methodology, participatory systems thinking and systems thinking in action are presented to demonstrate the potentiality of systems thinking to study complex and dynamic systems. Participatory systems thinking is highlighted.

2.1 Introduction

Systems thinking is a method of studying the dynamic behaviour of a complex system considering the systems approach, i.e. considering the entire system rather than in isolation, and system dynamics is a tool or a field of knowledge for understanding the change and complexity over time of a dynamic system. In isolation a complex system may give a false impression of the dynamic behaviour which is far from the real behaviour of the actual system. Thus, systems thinking should consider all the interacting components influencing the dynamics of the complex system, and system dynamics methodology based on the feedback concepts of control theory developed by Forrester (1968) is the most appropriate technique to handle such complex systems to enhance systems thinking and systems learning.

2.2 Systems Thinking Methodology

To enhance systems thinking and systems learning, the system must be modelled and simulated. Basically, there are six important steps in building system dynamics model. It starts with the problem identification and definition, followed by system conceptualisation, model formulation, model testing and evaluation, model use, implementation and dissemination and design of learning/strategy/infrastructure. There is a feedback in this step and it is illustrated in Fig. 2.1. Therefore, the steps

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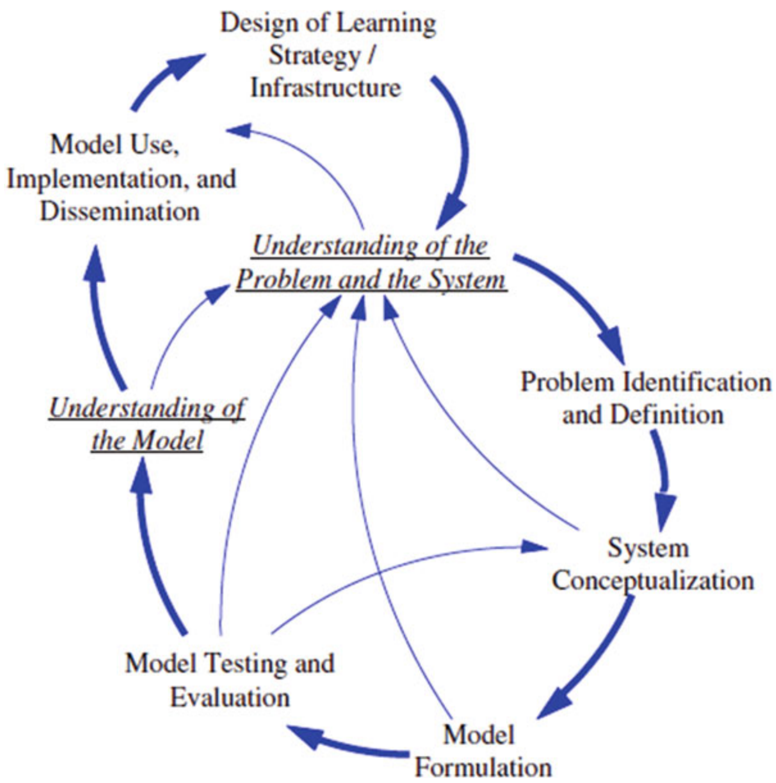

Fig. 2.1 Overview of the system dynamics modelling approach (Source: Martinez-Moyano and Richardson 2013)

needed for modelling and simulating of complex systems based on systems thinking are:

1. Identify the problem.
2. Develop a dynamic hypothesis explaining the cause of the problem.
3. Create a basic structure of a causal graph.
4. Augment the causal graph with more information.
5. Convert the augmented causal graph to a system dynamics flow graph.
6. Translate a system dynamics flow graph into STELLA or VENSIM programs or equations.

These steps of systems thinking are discussed below in detail.

2.2.1 Problem Identification

The first step in the model building is to identify the problem, set its boundary and state the specific objectives. The problem should be clearly identified and it is important for a successful modelling to solve the real problem. Systems thinking should be used for addressing the problem. Neither the whole system nor the part of it should be considered to draw the boundary of the model rather systems approach of considering the entire system that endogenously responsible to cause the problem from the feedback structure of the stated entire system. Therefore, the system boundary should encompass that portion of the whole system which includes all the important and relevant variables to address the problem and the purpose of policy analysis and design. The scope of the study should be clearly stated in order to identify the causes of the problem for clear understanding of the problem and policies for solving the problem in the short run and long run.

To recognise the problem, prepare a detailed description of the system based on available reports and studies, expert opinions and past behaviour of the system and identify the important variables generating the observed dynamic behaviour of the system. The problem of system identification is the problem of system operation. Thus, the problem identification should include clear statement of the problem based on different reports, historical and statistical records and previous studies. The problem statement should clearly describe the major factors influencing the dynamics of the system behaviour with facts and figures. Next, it should include the purpose and clearly defined objectives. Discussion with all the stakeholders such as focus group discussions should be conducted to justify their opinions on the existing problems, their views on the data collected and also their views on the solution of the problems.

The verbal description is the simplest way to communicate with others about the system. The more detailed is the description, the more it becomes easier to model the system. Major subsystems and their relationships within and between the subsystems of the system as a whole should be clearly described. The model should include only the relevant aspects of the study objectives. The verbal description is in practice a qualitative model of the system.

In selecting the variables to be included in the model, all the variables or factors relevant to the study objectives should be included, and unnecessary restrictions must be avoided. The accuracy of the information gathered should be considered. A further factor to be considered is the extent to which the number of individual entities can be grouped together into large entities. The boundary should be such that nothing flows across the boundary except perhaps a disturbance for exciting the system, and the factors needed to address the problem must be included inside the system boundary for the proper comprehensiveness of the model with adequacy. Figure 2.2 illustrates the closed boundary concept. Formulating a model of a system should start with a boundary that encompasses the smallest number of components within which the dynamic behaviour under study is generated.

Often, it may be difficult to comprehend the whole system, especially when it is very large and complex. It is convenient to break up such system into sectors or

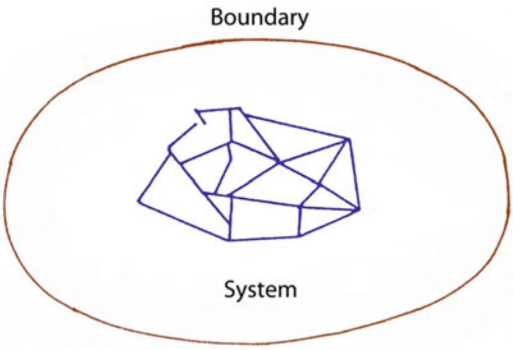

Fig. 2.2 Closed boundary concept

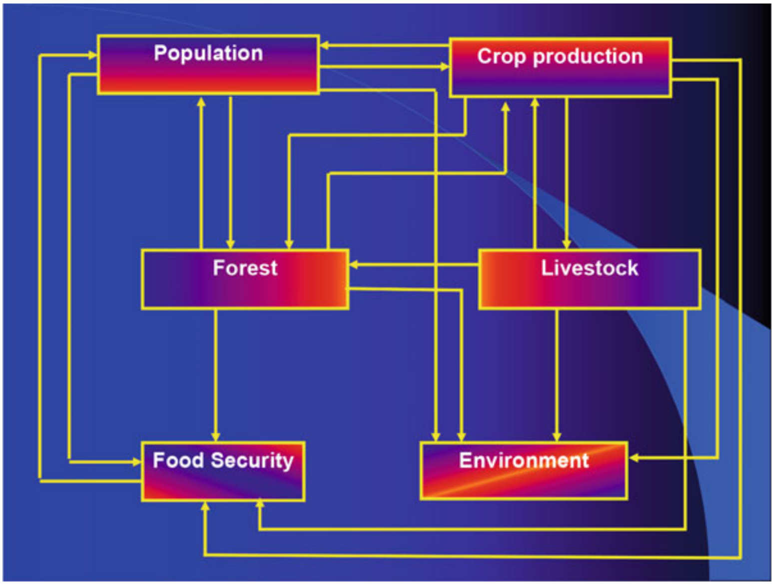

Fig. 2.3 Structure of food, energy and environment model

blocks. The description of the system should be organised in a series of blocks. The aim in constructing the blocks is to simplify the specification of the interactions within the system boundary. Each block describes a part of a system that depends upon a few, preferably one, input variable and results in a few output variables. The system as a whole can be described in terms of interconnections between the blocks. Correspondingly, the system can be represented graphically as a simple block diagram. Figure 2.3 shows the overall structure of food, energy and environment model and it is a typical example of a block or sectorial diagram. The model is about the study of food, energy and CO_2 production in Bangladesh. The six sectors of the model are food, forest, population, cattle population, energy and CO_2. The major influences to a sector from other sectors and its influences on other sectors are shown in the diagram.

System dynamics model of endogenous structure of feedback loops is simulated to generate the problem dynamically, i.e. the observed dynamic behaviour. This pattern of change of the behaviour with time is termed as reference mode behaviour or historical behaviour. We need the observed reference mode behaviour to understand the problem and hence variables are selected accordingly. Figure 2.4a shows the observed reference mode behaviour of crude palm oil (CPO) price and the observed and simulated reference mode behaviours of boom and bust of cocoa production systems in Malaysia. The time horizon of the reference mode and policy are also important and must be sufficient to cover the problem symptoms and policy issues addressed (Fig. 2.4b).

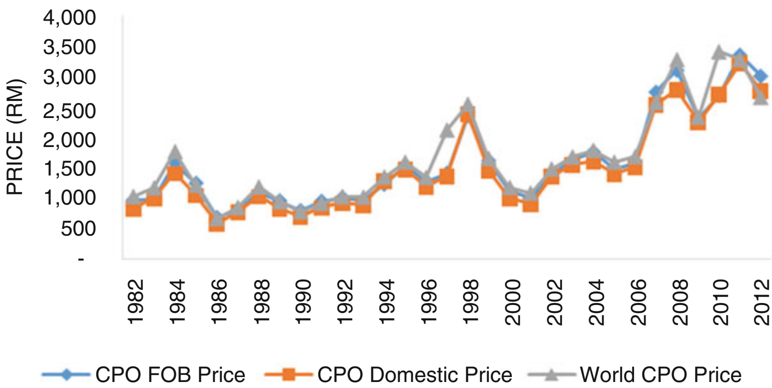

Fig. 2.4a CPO FOB Price, CPO Domestic Price and World CPO Price (1982–2012) (Source: MPOB 2012)

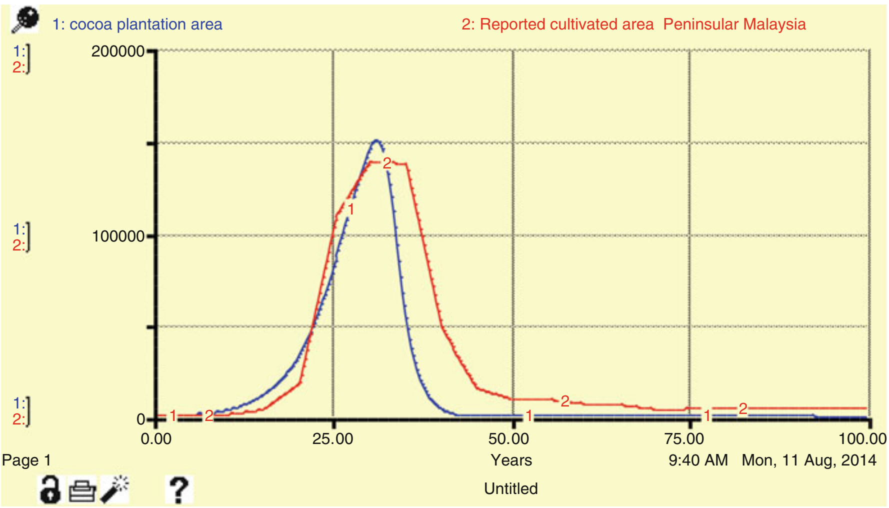

Fig. 2.4b Observed and simulated reference mode behaviour of cocoa production systems in Malaysia (Source: Fatimah et al. 2015)

The following aspects are to be addressed in the development of problem identification:

1. Definition of the problem
2. Purpose of the model
3. Systems approach
4. Reference mode
5. Time horizon

2.2.2 Dynamic Hypothesis

Once the problem is identified, the next step is to develop a theory called dynamic hypothesis based on the reference mode behaviour over a time horizon. The dynamic hypothesis in terms of causal loop diagram and stock–flow diagram of the system can explain the dynamics of the problem. The hypothesis is provisional and is subject to revision and rejection which solely depends on the observed and simulated reference mode of behaviour over a time horizon (Sterman 2000).

The dynamic hypothesis is a conceptual model typically consisting of a causal loop diagram, stock–flow diagram or their combination. The dynamic hypothesis seeks to define the critical feedback loops that drive the system's behaviour. When the model based on feedback concept is simulated, the endogenous structure of the model should generate the reference mode behaviour of the system, and thus, the endogenous structure causes the changes in the dynamic behaviour of the system (Sterman 2000). For example, the boom and bust of shrimp production systems can be represented by causal loop diagram and stock–flow diagram, and the simulation model based on the causal loop diagram and stock–flow diagram can generate dynamic behaviour of the shrimp production systems. The shrimp production systems in the form of causal loop diagram and stock–flow diagram are hypothesised to generate the observed boom and bust of shrimp production systems in the reference mode. In essence the degradation of the soils in the shrimp aquaculture ponds resulting from the large-scale intensification of the shrimp culture caused the boom and bust of shrimp production systems in Thailand. In fact when the shrimp industry is prone to exceed and consume its carrying capacity, the boom and bust type of development results in and this dynamics results from the endogenous consequences of the feedback structure (Arquitt et al. 2005).

The next step in dynamic hypothesis is how to test it. The hypothesis is tested using both the observed and simulated reference mode data. In essence, the goal of dynamic hypothesis is to develop an endogenous explanation of the problematic behaviour. Endogenous explanation is that the endogenous structure, i.e. the interactions of the variables inside the system, causes the problematic behaviour (Sterman 2000).

The following aspects are to be addressed in the development of dynamic hypothesis:

1. Endogenous feedback structure
2. Observed and simulated reference mode behaviour
3. Theory to explain the reference mode behaviour

2.2.3 Causal Loop Diagram

The system boundary covers the key variables inside the boundary and variables crossing the boundary. The variables inside the boundary are endogenous variables and the variables outside the boundary are exogenous variables. The next step in the systems thinking is to search the relationships between the variables and the developments of feedback loops. These feedback structures are represented in the form of causal loop diagrams in system dynamics (Sterman 2000) and in the form of control theory block diagram in systems analysis (Manetsch and Park 1982). Figure 2.5 shows the causal loop diagram of a simple irrigation model. In this simple irrigation model, the major variables are irrigated area, irrigated area increase rate and also irrigation area discard or abandon rate. Irrigated area increase rate decreases with the increase in irrigated area and increase in irrigated area increase increases the irrigated. This forms the negative feedback loop B1. The irrigation area discard rate increases with the increase in irrigated area and in turn this causes to decrease the irrigated area. This forms the negative feedback loop B2. Thus, the irrigated area forms two negative feedback loops. The causal loop diagram represents feedback loop structure of the system and causes the dynamic behaviour of the system. Causal loop diagram represents the feedback structure of systems to capture the hypotheses about the causes of dynamics and the important feedbacks. The causal loop structure generating the reference behaviour of the system is hypothesised to be the dynamic hypothesis. The following steps are followed in the development of causal loop diagram:

1. Define the problem and the objectives.
2. Identify the most important elements of the systems.
3. Identify the secondary important elements of the systems.
4. Identify the tertiary important elements of the systems.
5. Define the cause–effect relationships.

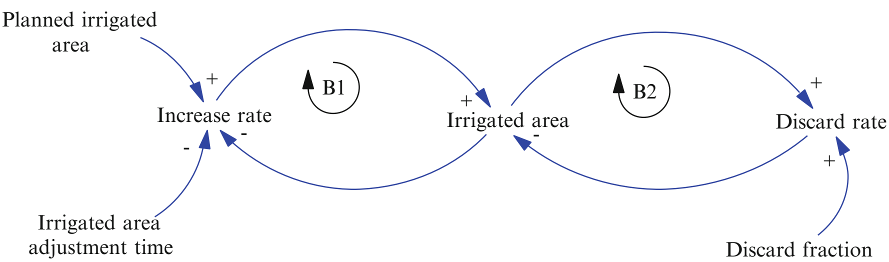

Fig. 2.5 Causal loop diagram of a simple irrigation model

6. Identify the closed loops.
7. Identify the balancing and reinforcing loops.

The details of construction of causal loop diagrams are described in Chap. 3.

2.2.4 Stock–Flow Diagram

The stock–flow diagram is the underlying physical structure of the system in terms of stock and flow. Stock–flow diagram is usually followed after the causal loop diagram. However, the causal loop diagram can follow the stock–flow diagram. The stock represents the state or condition of the system, and the flow is changed by decisions based on the condition of the system. It is essentially the physical structure of the system and can be simulated to generate the dynamic behaviour of the system. The stock–flow diagram represents integral finite difference equations involving the variables of the feedback loop structure of the system and simulates the dynamic behaviour of the system. But differential equations are formulated in systems analysis based on the control theory block diagram (Manetsch and Park 1982). The stock–flow diagram or the system of the differential equations representing the feedback structure of systems captures the hypotheses about the causes of dynamics and the important feedbacks. The stock–flow diagram or the system of the differential equations representing the feedback structure of the system generating the reference behaviour of the system is hypothesised to be the dynamic hypothesis. Figure 2.6 shows the stock–flow diagram of a simple irrigation model. The three main variables are irrigated area, irrigated area increase rate and irrigation area discard rate. Here, we have one stock variable irrigated area stating the condition of irrigation, and it is increased by one inflow-increasing rate and decreased by one outflow discard rate. Also, the irrigated area has the unit of quantity, while the increase rate and discard rate have the unit of quantity per unit time. The following steps are followed in the development of stock–flow diagram:

1. Define the problem and the objectives.
2. Identify the most important variables of the systems.
3. Identify the secondary important variables of the systems.
4. Identify the tertiary important variable of the systems.
5. Identify the variables representing the stocks, i.e. accumulations.
6. Identify the variables representing the flows having a unit of per unit time of the stock.
7. Ensure the inflows entering the stock and outflow leaving the stock.

The details of construction of stock–flow loop diagrams are described in Chap. 4.

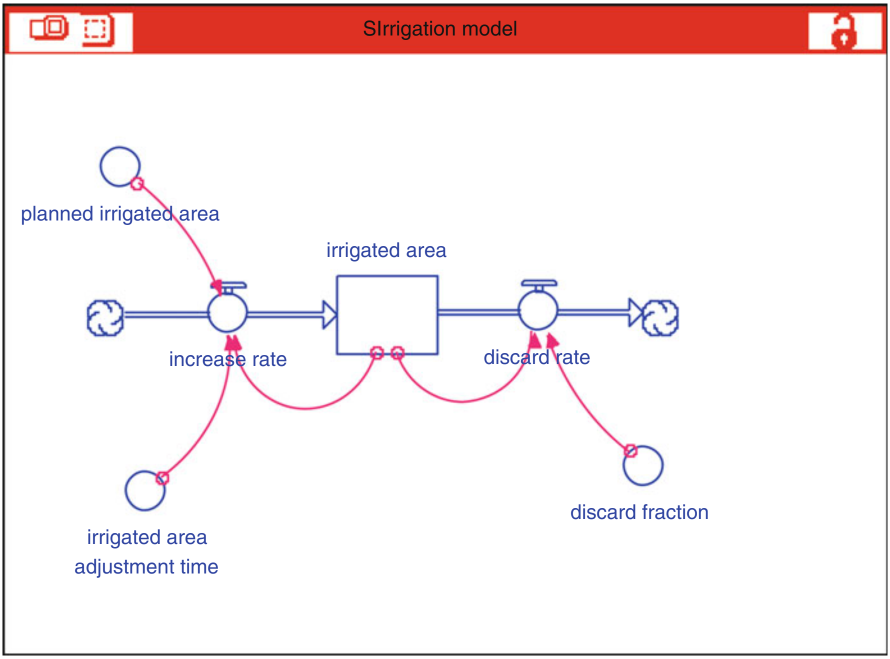

Fig. 2.6 Stock–flow diagram of the irrigation model

2.2.5 Parameter Estimation

Parameter estimation is one of the important steps in system dynamics modelling. Parameter estimation techniques can be classified into three categories: these are (i) estimation from unaggregate data, (ii) estimation from an equation and data at a level of aggregation of model variables and (iii) estimation from the knowledge of the entire model structure and data at a level of aggregation of model variables. The details are described in Chap. 5.

2.2.6 Model Validation, Sensitivity Analysis and Policy Analysis

The tests for building confidence in system dynamics model consist of validation, sensitivity analysis and policy analysis of system dynamics models. The two important notions of the building confidence in system dynamics models are testing and validation. Testing means the comparison of a model to empirical reality for accepting or rejecting the model, and validation means the process of establishing confidence in the soundness and usefulness of the model. The tests for building confidence in system dynamics models may be broadly classified as:

1. Tests for structure
2. Tests for behaviour
3. Tests for policy implication

The detailed tests for building confidence in models are described in Chap. 6.

2.2.7 Application of the Model

Because of the counterintuitive nature of the complex systems, the human mind is not capable of tracing the dynamic behaviour of the systems. System dynamics simulation model can provide better understanding and greater insights of such systems. Examining the alternative policies for the selection of best policy for the improved performance of the system is essential for policy planning. System dynamics simulation model can be used as a computer laboratory for policy analysis, and it can also be used to assist in the management and control policy design. Optimal management and control policy design of the system with regard to certain criterion and constraints is the ultimate goal of the optimisation of the system. A simulation model is essential for such optimisation of the system. Applications of system dynamics models in different areas of agricultural, biological, aquacultural, environmental and socio-economic systems are presented in Part II in Chaps. 8, 9, 10, 11 and 12.

2.3 Critical Aspects of Systems Thinking

The following aspects of systems thinking are very important for studying the dynamic behaviour of the complex system and need attention to develop the model based on systems thinking:

1. Thinking in terms of cause-and-effect relationships
2. Focusing on the feedback linkages among components of a system
3. Determining the appropriate boundaries for defining what is to be included within a system

We are interested to study and examine the dynamic behaviour of systems containing biological, agricultural, aquacultural, environmental, technological and socio-economic components. In formulating a model for this purpose in mind, formulating the model should start from the question 'where is the boundary of the dynamic system?'. In concept the feedback system is a closed system and the dynamic behaviour arises within the system.

2.4 Participatory Systems Thinking

The system dynamics uses simulation models for policy design and policy analysis and it is based on the feedback concepts of control theory. More specifically, the system dynamics uses feedback loops, stock and flow diagrams and non-linear differential equations. Stakeholders form an important part of the system dynamics methodology (Forrester 1961; Gardiner and Ford 1980; Vennix 1996, 1999; Hsiao 1998; Elias et al. 2000 and Maani and Cavana 2000). Group model building is defined as a model-building process which involves the client group deeply in the process of modelling (Vennix 1996, 1999; Andersen and Richardson 1997; Rouwette et al. 2011).

There are many reasons to take stakeholders into account in the model-building process (de Gooyert 2012). And the three distinct types of group model-building interventions are (1) modelling stakeholder behaviour, (2) modelling with stakeholders and (3) modelling stakeholder behaviour with stakeholders. Group model-building intervention needs several iterations. This intervention will support learning for the stakeholders, and learning will change the behaviour and hence the decision. The simulation model should be updated after each iteration to take the new stakeholder behaviour into account

Participatory modelling includes a broad group of stakeholders in the process of formal decision analysis. It is a process of incorporating stakeholders, often the public, and decision-makers into the modelling process (Voinov and Gaddis 2008). Non-scientists are engaged in the scientific process and the stakeholders are involved to a greater or lesser degree in the process. A fully participatory process is one in which participants help identify the problem, describe the system, create an operational computer model of the system, use the model to identify and test policy interventions and choose one or more solutions based on the model analysis. Involving the stakeholders in the model-building process can build trust among stakeholders (Tàbara and Pahl-Wostl 2007).

Participatory system dynamics modelling uses system dynamics perspective in which stakeholders or clients participate to some degree in different stages of the model-building process. Participatory system dynamics modelling is more than simply eliciting knowledge from clients about the problem and the system. It involves building shared ownership of the analysis, problem, system description and solutions or a shared understanding of the tradeoffs among different decisions. In other words, it may be termed as participatory systems thinking. The details of the participatory system dynamics modelling are discussed in Chap. 7.

2.5 Systems Thinking in Action

In the previous sections, the systems thinking methodology has been explained. Here in this section, the focus is on policy simulation and analysis to address how systems thinking-based modelling and simulation can assist in policy simulation and analysis. To achieve this goal, the focus is concentrated on the introduction of system, on differential equation model and stock–flow diagram and more importantly on policy simulation and analysis to demonstrate how systems thinking-based model can address the policy issues. To demonstrate how to apply systems thinking in action, we consider here the dynamics of the mangrove forest in the Sundarbans in Bangladesh as an example.

2.5.1 Introduction

The **Sundarbans** is the largest single block of tidal halophytic mangrove forest in the world located in the southern part of Bangladesh, and the Sundarbans was declared as the world heritage site by UNESCO in 1997. The Sundarbans is intersected by a complex network of tidal waterways, mudflats and small islands of salt-tolerant mangrove forests. The Sundarbans mangrove ecoregion is the world's largest mangrove ecosystem. The Sundarbans flora is characterised by the abundance of Sundari (*Heritiera fomes*), Gewa (*Excoecaria agallocha*) and Keora (*Sonneratia apetala*). Figure 2.7 shows a pictorial of Sundari, Gewa and Keora trees in the Sundarbans. The number of tree species in the mangrove forest of Sundarbans is very large (a total of 245 genera and 334 plant species). Based on their growth characteristics, tree species can be classified into three functional groups, and Keora, Gewa and Sundari are identified to represent these functional groups and the growth dynamics of the mangrove forest.

For proper management and understanding of the forest ecosystem, it must be modelled and simulated. Growth models of forests can assist in many ways. Some important uses of growth models are its ability to predict the future yields; it provides an efficient way to resource forecasts; and it can be used to prepare harvesting schedules for sustainable development. It can also provide a better understanding and greater insights into forest dynamics. The model presented here focuses on these three functional groups: pioneer (Keora), intermediate (Gewa) and climax (Sundari).

(a) (b) (c)

Fig. 2.7 (a) Sundari, (b) Gewa and (c) Keora trees of the Sundarbans

2.5.2 Differential Equation Model and Stock–Flow Diagram

In this example we demonstrate systems analysis approach of using differential equations and also the system dynamics approach of stock–flow diagram which essentially represents the integral finite difference equations. The model is based on a system of three coupled differential equations, which describe stem volume changes of the succession groups for every time steps. The equations are converted into stock–flow diagram of STELLA and solved by the Runge–Kutta fourth-order method.

The volume change for pioneer tree species turns out to be fundamentally different from that of the two other species. After a clear cut, pioneer tree species grows at the fastest pace at the beginning of the regrowth process, which can be described by the Michaelis–Menten kinetics (Haefner 1996). In contrast intermediate and climax tree species initially show a much slower growth and have their maximal volume increment when they have reached half of the volume they would have in a mature forest. This kind of dynamics can be described by logistic growth (Bossel 1994). Both approaches are consistent with the observation that on a scale of several hectares of the forest dynamics lead to a steady state, in which no changes occur any more over time, except from stochastic processes. Additionally, for each tree species group, competition exists within and between groups.

The following assumptions are made for the mangrove forest growth model:

1. Stand growth was considered in the model.
2. Aggregated growth of Sundari, Gewa and Keora is considered in the model.
3. Competition among these species exists.
4. The tree species are pioneer (Keora), intermediate (Gewa) and climax (Sundari).

Pioneer Tree Species

According to the Michaelis–Menten equation, the volume of pioneer tree species V_{P} at time t is calculated from the maximal volume $V_{\mathrm{mat,P}}$, time t and constant K_{M}. This constant describes the time it takes to reach half of the maximal volume $V_{\mathrm{mat,P}}$:

$$V_{\mathrm{P}}(t) = \frac{V_{\mathrm{mat,P}}t}{K_{\mathrm{M}} + t} \tag{2.1}$$

The equation can be rewritten as a differential equation where only the first term is dependent on the volume. The first term can be interpreted as a growth term, and the second one as a constant input rate:

$$\frac{dV_{\mathrm{P}}}{dt} = \frac{1}{K_{\mathrm{M}}} V_{\mathrm{P}} \left(\frac{V_{\mathrm{P}}}{V_{\mathrm{mat,P}}} - 2 \right) + \frac{V_{\mathrm{mat,P}}}{K_{\mathrm{M}}} \tag{2.2}$$

The growth of pioneer tree species is inhibited by trees of other successional groups. Tietjen and Huth (2006) reported that only the second term is affected by other species groups. Therefore, a competition factor C_P that reduces the constant input is introduced:

$$\frac{dV_P}{dt} = \frac{1}{K_M} V_P \left(\frac{V_P}{V_{mat,P}} - 2 \right) + \frac{V_{mat,P}}{K_M} C_P \tag{2.3}$$

with

$$C_P = 1 - \frac{\omega_{IP}}{\omega_{IP} + \omega_{CP}} \frac{V_I}{V_{mat,I}} - \frac{\omega_{CP}}{\omega_{IP} + \omega_{CP}} \frac{V_C}{V_{mat,C}}$$

where V_I and V_C describe the current volumes of intermediate and climax tree species, respectively, and $V_{mat,I}$ and $V_{mat,C}$ denote the corresponding volumes in a mature forest. The additional factors ω_{IP} and ω_{CP} weigh the influence of the particular competition and add up to 1. If the volume of intermediate and climax trees species is zero, then the competition factor equals one, and the growth of the pioneer trees is not inhibited. On the other hand, if both tree species groups reach the volume of a mature forest, the competition factor becomes zero and the constant input disappears.

Intermediate and Climax Tree Species

Both successional groups are described by logistic growth. The specific growth rates for intermediate and climax tree species are g_I and g_C, respectively. Competition within one group and in between the two groups is considered, and as before it is weighed by competition factors adding up to 1. An additional constant a_{input} is added to the equations of both groups to avert extinction. This constant is chosen small enough not to affect the main dynamics and can be interpreted as constant seedling input:

$$\frac{dV_I}{dt} = \left(a_{input} + g_I V_I \right) \times \left(1 - \frac{\mathrm{II}}{\omega_{II} + \omega_{CI}} \frac{V_I}{V_{mat,I}} - \frac{\omega_{CI}}{\omega_{II} + \omega_{CI}} \frac{V_C}{V_{mat,C}} \right) \tag{2.4}$$

$$\frac{dV_C}{dt} = \left(a_{input} + g_C V_C \right) \times \left(1 - \frac{\omega_{IC}}{\omega_{IC} + \omega_{CC}} \frac{V_I}{V_{mat,I}} - \frac{\omega_{CC}}{\omega_{IC} + \omega_{CC}} \frac{V_C}{V_{mat,C}} \right) \tag{2.5}$$

The total harvestable volume $V_{harv,total}$ is determined by adding the difference between current and remaining volume of both successional groups: climax and intermediate:

$$V_{harv,total} = V_{harv,I} + V_{harv,C} \tag{2.6}$$

$$V_{harv,X} = V_X - V_{rem,X}, \quad X = I, C \tag{2.7}$$

The stock–flow diagrams of the mangrove forest growth models are shown in Figs. 2.8 and 2.9 for undisturbed forest growth and forest growth with logging scenarios, respectively.

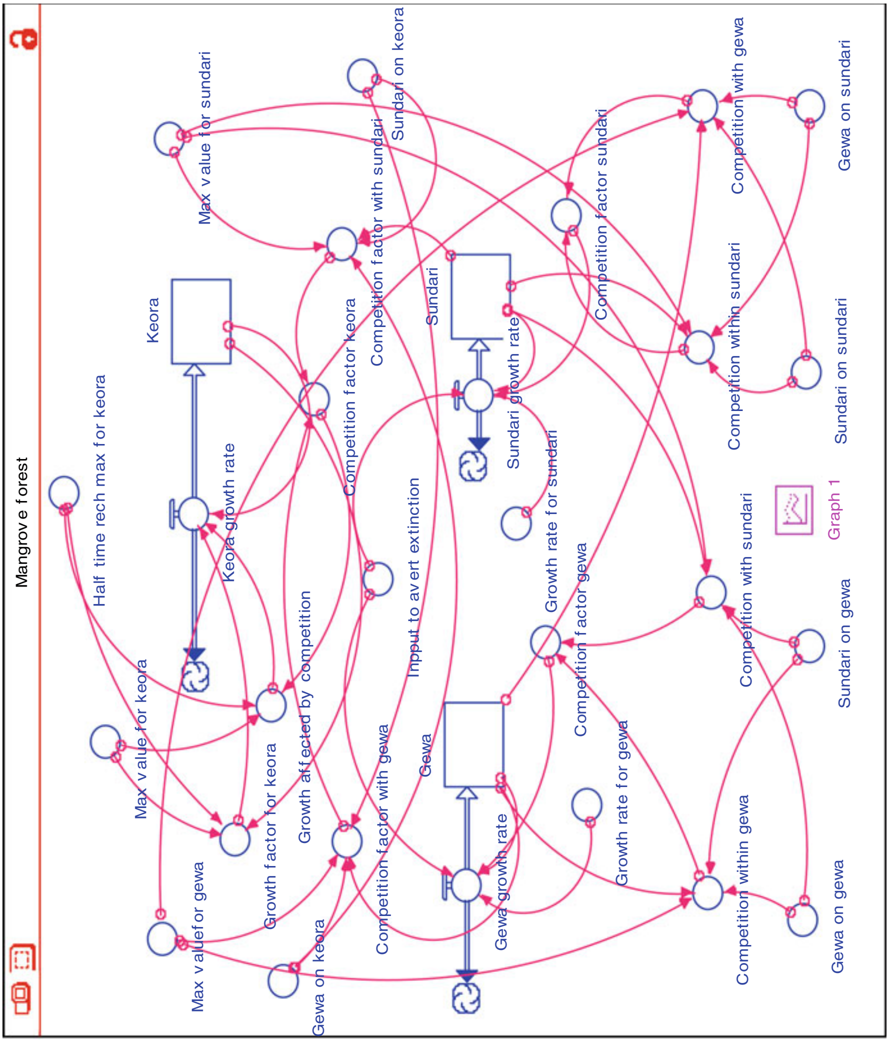

Fig. 2.8 Stock–flow diagram for undisturbed mangrove forest model

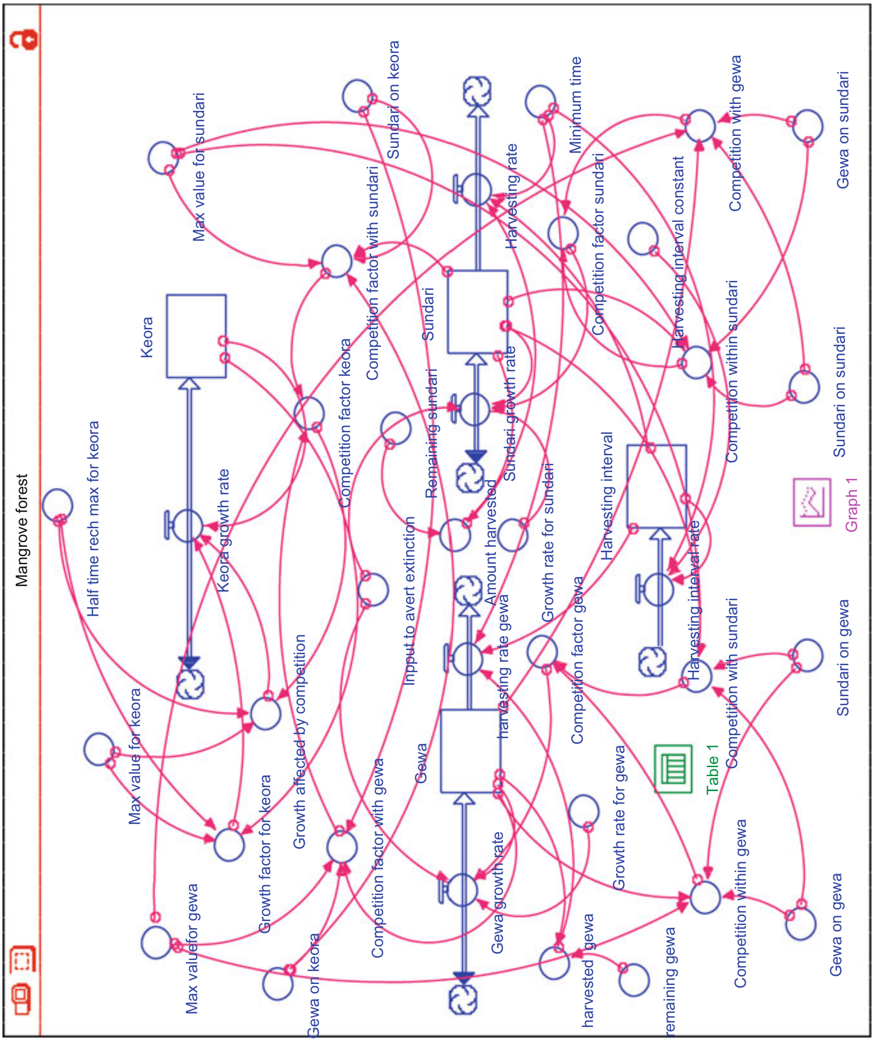

Fig. 2.9 Stock–flow diagram for mangrove forest model with logging operations

Table 2.1 Parameter values of the model

Parameter description	Values
Competition factor Gewa	Gewa on Gewa = 0.32
	Gewa on Keora = 0.32
	Gewa on Sundari = 0.01
Competition factor Sundari	Sundari on Gewa = 0.68
	Sundari on Keora = 0.68
	Sundari on Sundari = 0.99
Half-time reach maximum for Keora	3.65
Input to avert extinction	0.01
Maximum value for Gewa	80.0
Maximum value for Keora	196.11
Maximum value for Sundari	320.0

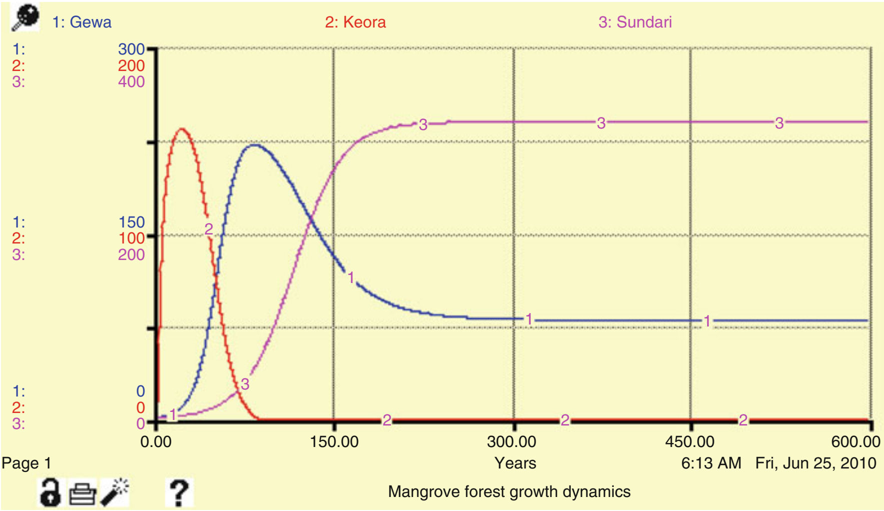

Fig. 2.10 Simulated volume for undisturbed mangrove forest (Keora, pioneer; Gewa, intermediate; Sundari, climax)

2.5.3 Simulation and Policy Analysis

The parameters of the model were collected from secondary sources such as reports, journal publications and personal communication with experts. The important parameter values are given in Table. 2.1. The models were assessed for structural consistency and both the model generate plausible behaviours.

The model was simulated to predict the forest stand of three major mangrove species Sundari, Gewa and Keora of the mangrove forest in the Sundarbans. Simulated total bole volumes of pioneer, intermediate and climax tree species for undisturbed forest growth with time are shown in Fig. 2.10. Pioneer tree species

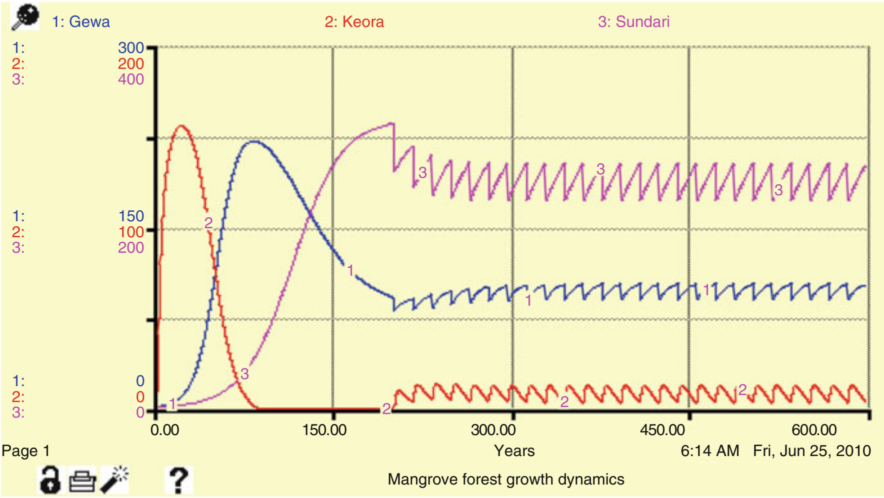

Fig. 2.11 Simulated volume of mangrove forest for 16 years logging cycle (Keora, pioneer; Gewa, intermediate; Sundari, climax)

(Keora) grows fast until a maximum volume of 160 m^3/ha is reached at 25 years. Because of light competition, these are suppressed by intermediate and climax tree species and disappear after 80 years; by this time, the intermediate tree species (Gewa) reach their maximum volume of 225 m^3/ha. This is now inhibited by the increasing appearance of climax tree species (Sundari) and decline until the forest reaches a steady state after another 190 years. Here, the volumes of intermediate and climax tree species are 80 and 320 m^3/ha, respectively.

Simulated total bole volumes of pioneer, intermediate and climax tree species for a logging cycle of 16 years are shown in Fig. 2.11. The first logging is practised after the forest reached a steady-state condition. For the undisturbed forest growth model, the pioneer tree species (Keora) disappears after a certain period due to competition with climax and intermediate tree species (Fig. 2.10), but after a logging operation, it reappears and if the logging operation continues at a certain interval, the pioneer species never disappear (Fig. 2.11). The maximum volume of the climax tree species for undisturbed model is 320 m^3/ha, but for 16 years logging cycle, it can't reaches this maximum volume, rather than volume changes in cyclical manner with a mean volume of 195 m^3/ha with a maximum volume is 275 m^3/ha.

When the logging cycle of 50 years is selected, the climax tree species reaches its maximum volume, that is, the forest reaches to its steady-state condition before each logging operation. Figure 2.12 shows simulated effects of 50 years logging cycle. The volume of the pioneer tree species changes in cyclic manner with a mean value of 10 m^3/ha.

Figure 2.13 simulates the effect of 100 years logging cycle. It shows similar effects of 50 years logging cycle. In both cases pioneer species develops a maximum volume of 15 m^3/ha and then it disappears and reappears in a cyclic manner. The changes in cyclic manner of intermediate tree species are small and remain almost same for both 50 and 100 years logging cycle.

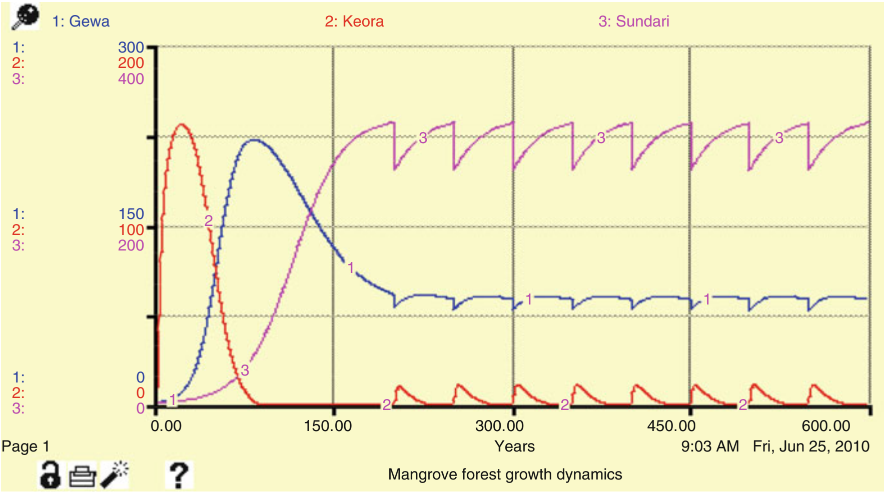

Fig. 2.12 Simulated volume of mangrove forest for 50 years logging cycle (Keora, pioneer; Gewa, intermediate; Sundari, climax)

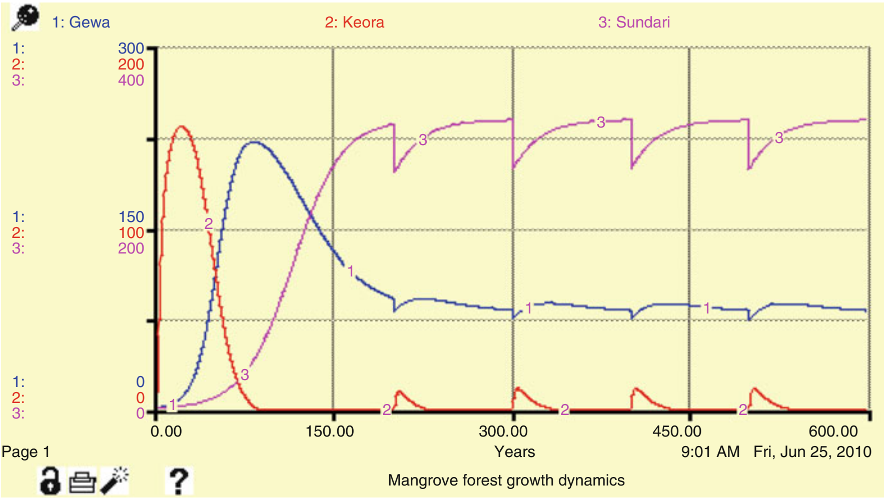

Fig. 2.13 Simulated volume of mangrove forest for 100 years logging cycle (Keora, pioneer; Gewa, intermediate; Sundari, climax)

Here, simulated harvesting strategies are presented using system dynamics model based on systems thinking. Simulated results show plausible behaviour, and this model is able to reproduce the volume dynamics of succession groups of the mangrove forest of the Sundarbans in Bangladesh. Simulated results for different logging strategies show that short logging cycles affect the forest more heavily in terms of damage and the ability to regrow to a mature stand. So, longer logging cycles are preferable to protect the mangrove forest. However, the maximum total yield is achieved if medium logging cycles are applied, and this suggests that medium cycle logging should be considered for economic and ecological benefits. The simulated scenarios for different logging strategies demonstrate the potentiality of the model for policy simulation and analysis.

Exercises

Exercise 2.1 What is meant by systems thinking? Describe the steps needed for modelling and simulation of a dynamic complex system based on systems thinking.

Exercise 2.2 What is problem identification? What are the steps to be addressed in problem identification for developing a simulation model for policy analysis and design?

Exercise 2.3 What is meant by dynamic hypothesis? What are the steps to be taken into account to develop a dynamic hypothesis?

Exercise 2.4 What is causal loop diagram? What are the purposes of drawing causal diagrams of a complex dynamics systems? Describe the steps to be followed to develop the causal loop diagrams.

Exercise 2.5 What is stock–flow diagram? What is the basic difference between a differential equation model and stock–flow model of a system? What are the steps to be followed to develop the stock–flow diagrams?

Exercise 2.6 What are participatory systems thinking? What are the critical aspects of systems thinking?

Exercise 2.7 Describe how participatory systems approach can be included in the modelling and simulation in the example of the systems thinking in action.

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Causal Loop Diagrams 3

The concept of causal loop diagram was introduced in Chap. 2, and this chapter presents concepts, methodology and techniques of causal loop diagrams. The cause–effect relationships and reinforcing and balancing loops are highlighted with examples. Steps to construct causal loop diagrams are provided. A good number of worked out examples are included to illustrate the techniques of constructing causal loop diagrams for dynamic systems.

3.1 Introduction

System dynamics methodology is based on feedback concepts of control theory, and causal loop is a convenient way to represent the feedback loop structure of systems. Causal loop diagram is used to represent the feedback loop systems diagrammatically, and it is a communication tool of feedback structure representing the principal feedback loops of the systems which generate the reference dynamic behaviour of the systems.

3.2 Causal Loop Diagrams

Causal loop diagrams identify the principal feedback loops of the systems. The causal loop diagrams are used to describe basic causal mechanisms hypothesised to generate the reference mode of behaviour of the system over time. A feedback loop contains two or more casualty related variables that close back on themselves. The relationship between one variable and next in the loop can be either positive or negative. A positive relationship means that if one variable increases, the other also increases. For example, in Fig. 3.1 the arrow from A to B means that an increase in A causes an increase in B. It can also mean if A decreases, B will also decrease. The arrow starting from A and terminating at B with a (+) sign at the end of the arrow means the cause–effect relationship is positive. In a negative relationship, the two

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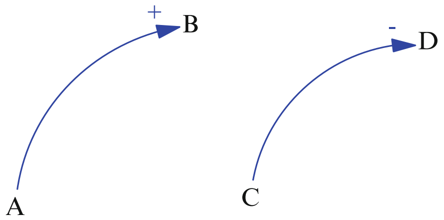

Fig. 3.1 Cause and effect relationships

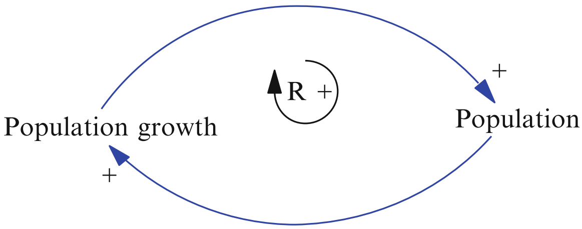

Fig. 3.2 Positive feedback loop

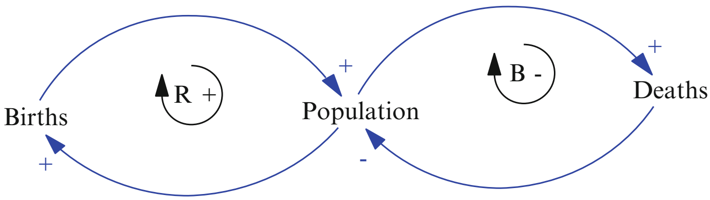

Fig. 3.3 Positive and negative feedback loops

variables change inversely. For example, in Fig. 3.1 the arrow in the direction of C to D means that if C increases, D will decrease. It can also mean if C decreases, D will also increase. The arrow starting from C and terminating at D with a (−) sign at the end of the arrow means the cause–effect relationship is negative.

Figure 3.2 shows an example of causal loop diagram with notation. This simple causal loop diagram of population consists of two variables, population growth and population. This figure illustrates a simple positive feedback loop consisting of two cause–effect relationships. In this example an increase in population will cause an increase in population growth. The cause–effect relationship is positive, and it is indicated by an arrow with a (+) sign starting at population and terminating at population growth. The cause–effect relationship between population growth and population is also positive. An increase in the population growth will cause an increase in population. This is indicated by an arrow with (+) sign staring at population growth and terminating at population. The loop formed from population to population growth and back to population is reinforcing loop and it is indicated by a (+) sign with an arrow inside the causal loop diagram. Figure 3.3 illustrates two feedback loops. In loop 1 the number of births increases with the population, and the births in turn increases population. These are positive relationships and

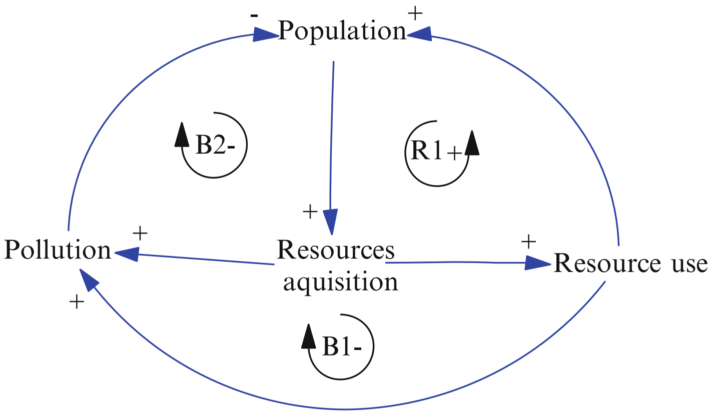

Fig. 3.4 Coupled feedback loops

represented by arrows with a (+) sign. In loop 1 there are two positive relationships. Hence, it is a positive and reinforcing loop. In loop 2 the number of deaths increases with population and the population decreases as the death increases. In loop 2 the first relationship is positive, and it is represented by an arrow (+) sign, while the second relationship is negative, and it is represented by an arrow with (−) sign. One can easily determine if a loop is positive or negative by counting the number of negative relationships in a loop. If there are an even numbers of negative relationships in total in a feedback loop, then the loop is positive; if there are odd numbers of negative relationships, the loop is negative. In fact, positive feedback loops generate growth, i.e. the loop is reinforcing and negative feedback loops are goal seeking. In loop 2 number of negative relationships is odd, i.e. 1. Hence, this loop is negative and goal seeking.

Let us now consider a coupled feedback loop of population, resource use and pollution as shown in Fig. 3.4. Loop at the right corner is positive, i.e. reinforcing, while the loops at the bottom and left corner are negative, i.e. balancing loop. In the positive loop, all the cause–effect relationships are positive, while in negative feedback loops, the number of (−) relationships is 1, i.e. an odd number.

3.3 Steps in Causal Loop Diagram

We must consider the description of the system and dynamic behaviour of the reference modes to construct the causal loop diagram, and these can aid in developing dynamic hypothesis. The following steps are to be followed for developing causal loop diagrams.

1. *Define the problem and the objectives.*

We must first of all study the system based on information collected through interview, focus group discussion, research report and case study. We must describe the system and define the problem with the reference mode of the behaviour of the system.

2. *Identify the most important elements of the systems.*

We should identify the key variables affecting the behaviour of the system, and it should be a good starting point to develop the causal loop diagram. Other variables can be added during later stages of causal loop development.

3. *Identify the secondary important elements of the systems.*

Secondary variables within the system boundary should be added after careful identification of the most important variables. This would provide an opportunity to consider the secondary variables of the system of importance in the causal loop diagram.

4. *Identify the tertiary important elements of the systems.*

Tertiary variables within the system boundary should be added after careful identification of the secondary variables. However, tertiary variables of little importance can be omitted in the later stages once it is established by simulated studies.

5. *Define the cause–effect relationships.*

Find the cause–effect relationships using arrows with polarity for the primary variables first, then for the secondary and tertiary variables.

6. *Identify the closed loops.*

Trace closed loops formed by cause–effect relationships for the variables describing the system.

7. *Identify the balancing and reinforcing loops.*

Identify the number of negative cause–effect relationships in each of the closed loops. The closed loops with odd number of negative relationships are negative, i.e. balancing loops, and the others are positive, i.e. reinforcing loops.

3.4 Examples

3.4.1 Population

Population has been growing exponentially throughout the history. Population increases by a fixed percentage per year, and also it decreases by a fixed percentage per year because of the fact that the human has a limited life. Draw the causal loop diagram of the simple population model.

Solution
Three key variables are population, birth rate and death rate. Birth rate increases with population, and also birth rate adds to population. These two are positive cause–effect relationships. Death rate increases with the increase in population, and it is a positive cause–effect relationship, but population decreases with the increase in death rate, and it is a negative cause–effect relationship. Hence, the model consists of two fundamental loops. The regenerating loop R generates new birth and adds it to population. The balancing loop B creates the death and depletes it from the population. The birth creates a positive loop since all the cause–effect relationships within this loop are positive, while there is an odd number of negative relationships within the balancing loop, and hence it a negative feedback loop. Figure 3.5 shows causal loop diagrams of a simple population model.

3.4.2 Carbon Metabolism in Green Plant

Carbon enters the plant by diffusion as carbon dioxide and is fixed. A labile pool of carbohydrate is produced. The entry and fixation rate is controlled by photosynthetic tissue represented chiefly by the leaves. The carbohydrate from the pool is allocated to the photosynthetic and non-photosynthetic parts of the plant body. Net loss of plant weight from the photosynthetic and non-photosynthetic parts is due to respiration. Draw the causal loop diagram for the description of carbon metabolism in green plant.

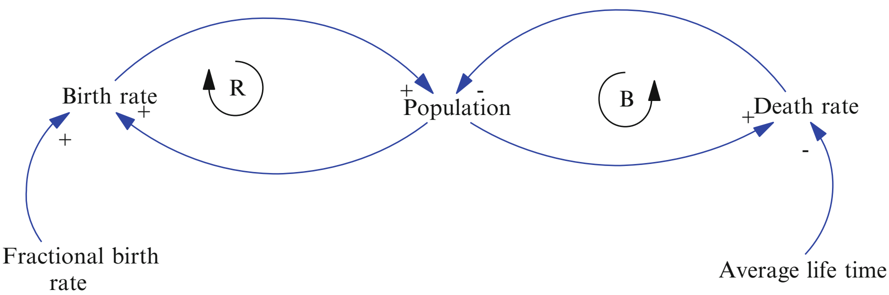

Fig. 3.5 Causal loop diagram of a simple population model

Solution

The carbon enters the plant in the form of carbon dioxide, and the rate of photosynthesis depends on solar radiation, temperature, weight of photosynthetic organs and photosynthetic area. The rate of photosynthesis increases with the increase of the weight of photosynthetic organs. The carbohydrate produced increases with the increase of photosynthesis rate and is translocated to the photosynthetic and non-photosynthetic organs. The carbohydrate pool, weight of photosynthetic organs and photosynthesis rate form a positive feedback loop (R1).

Again, respiration rate increases with carbohydrate in photosynthetic organs. The weight of the organs is decreased by respiration. The photosynthetic organs and respiration rate form a negative feedback loop (B1). Similarly the weight of non-photosynthetic organ and respiration form another negative feedback loop (B2). The resulting causal loop diagram of the carbon metabolism in green plant is shown in Fig. 3.6.

3.4.3 Food Security

Food security is a worldwide problem that has called the attention to governments and the scientific community. It particularly affects developing countries. The scientific community has had increasing concerns for strategic understanding and implementation of food security policies in developing countries, especially since the food crisis in the 1970s and 2009. The process of decision-making is becoming increasingly complex due to the interaction of multiple dimensions related to food

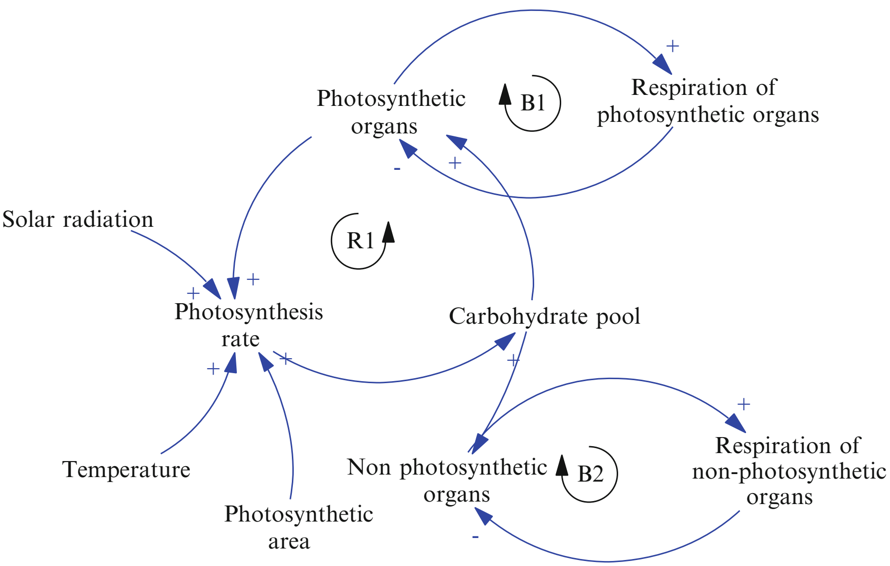

Fig. 3.6 Causal loop diagram of carbon metabolism in green plant

security (Giraldo et al. 2008). There is a need for models to examine the dynamics of this complex food security issues and design policies for sustainable development.

Food security is a situation in which people do not live in hunger or fear of starvation. FAO (1996a, b) defined the objective of food security as assuring to all human beings the physical and economic access to the basic food they need. This implies three different aspects: availability, affordability and access. Food security exists when all people at all times have access to sufficient, safe and nutritional food to meet their dietary needs and food preferences for an active and healthy life (FAO 2002). Draw the causal loop diagram of the food security model.

Solution

Food production depends on area cultivated and yield of the crop. Food production increases food availability. And also food production increases per capita income and hence food affordability. Food availability and food affordability would enhance the food access. Food security would depend on food availability, food affordability and food access.

As mentioned earlier the increased food production increases food availability, per capita food availability and hence food self-sufficiency. The increased food self-sufficiency would reduce the food price. The higher price would motivate the farmers to produce more food. This forms the negative feedback loop B1. Again, increased food self-sufficiency would reduce the deaths, and the increased deaths would reduce the population level. The increased population would reduce per capita food availability, and the increased per capita food availability would increase the food self-sufficiency. This forms the negative loop B2. Population forms one positive feedback loop R1 resulting from births and one negative feedback loop B3 resulting from deaths. The resulting causal loop diagram of the food security model is shown in Fig. 3.7.

3.4.4 Price Determination of a Commodity

Agricultural commodities are sold in highly competitive markets whose prices change yearly, daily, hourly and even by the minute. Farmers are affected by fluctuations of price—good times bring him an increase in income, and depression causes his cash income to drop away to very little. The price received by the farmers is important not only to him; the rate of production depends on it to a large extent. In addition, pigs, and to some extent cattle and chickens show fluctuations in price and supply of a persistent nature at a frequency consistent over long periods of time (Meadows 1970).

Most of the poorer nations are dependent upon the export of primary agricultural commodities as a source of foreign exchange, and the pronounced fluctuations in

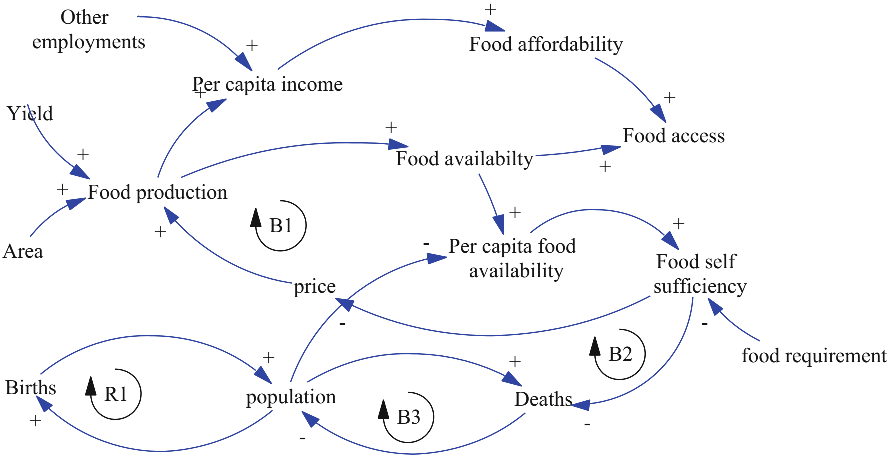

Fig. 3.7 Causal loop diagram of food security

price and supply have aroused much concern. Inflation, disruption of development programmes, loss of investor's confidence and political unrest are only a few of the results of the fluctuations in price and supply. Even developed countries find their economies affected.

Price determination is one of the most difficult challenges in economic modelling. Nerlove (1958) has given an excellent mathematical interpretation, and according to Nerlove farmers revise their previous expectations of normal price in each period in proportion to the difference between actual and what was previously considered normal. Sterman (2000) further modified this model, and according to Sterman the traders revise their expectations based on expectation adjustment and price adjustment. Draw the causal loop diagram of price determination based on the modifications suggested by Sterman.

Solution

The causal loop diagram of price determination of an agricultural commodity is shown in Fig. 3.8. The trader price is settled by price adjustment and expectation adjustment, and these form one positive feedback loop R1 and one negative feedback loop B1. The price depends on relative inventory coverage and trader price and the increase in price would reduce the consumption and thereby forms the negative feedback loop B2. On the production side, price, profitability and production also form a negative feedback loop B3. Also inputs, yield and production form a negative feedback loop B4. R & D, yield and production rate form a positive feedback loop (R2). The increase in population would increase the consumption rate and the population consists of one positive feedback loop R3 and one negative feedback loop B5.

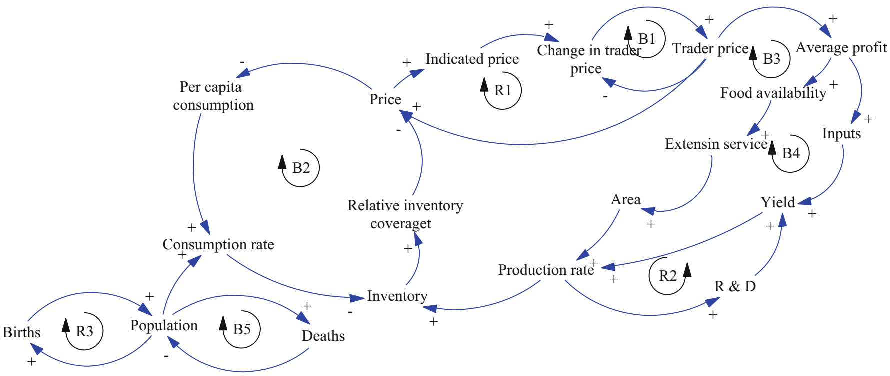

Fig. 3.8 Causal loop diagram of price determination of a commodity

3.4.5 Fishery Dynamics

Many fish stocks are in decline worldwide. Overfishing has led to the complete collapse of numerous fisheries including those for important and well-publicised species. In addition, over-exploitation of fisheries has led to reductions in biodiversity and modified ecosystem functioning. Despite management attempts to reduce overfishing, little progress has been made due to a general inability to endure the short-term economic and social costs of reduced fishing. Indeed, historical analysis reveals that resources are consistently and inevitably over-exploited. There is a need for models to examine the dynamics of this complex fishery issues and design policies for sustainable fishery development (Dudley 2008).

The model developed here is based on the biomass dynamic model (Graham 1935; Schaefer 1954, 1957), in which the population biomass increased due to both growth and the addition of new fish and decreases due to natural mortality and catch. Growth is equal to biomass fractional growth times existing biomass, and the natural decrease is growth multiplied by the ratio of biomass population to maximum biomass population possible. Catch depends on the current level of population biomass, number of gear units and fishing gear efficiency. The fleet entering or leaving depends on catch per unit effort and vessel replacement. In some fisheries, fishing activity decreases ecosystem carrying capacity. Draw the causal loop diagram of the fishery management system.

Solution

The causal loop diagram of fishery dynamics is shown in Fig. 3.9. Fish biomass increases by regeneration and decreases by catch and deaths. The regeneration forms a positive feedback loop (R1) with fish biomass, and the catch and deaths form negative feedback loops (B1 and B2) with fish biomass. Effect of relative fish biomass and deaths has a negative effect on fish biomass (B3). Fish catch, CPUE, fishing unit entry and units of fishing gear form a positive feedback loop (R2). Units

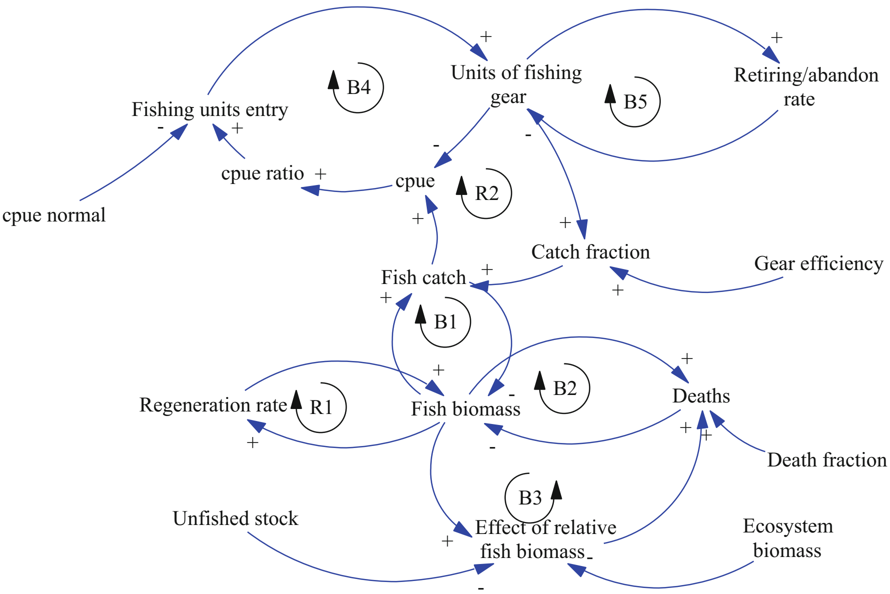

Fig. 3.9 Causal loop diagram of fishery dynamics

of fishing gear form two negative feedback loops with fishing unit entry and retiring/abandon rate (B4 and B5).

3.4.6 Forest Dynamics

Industrialisation, population growth and depletion of natural resources are threatening ecosystems all over the world. Climate change is one of the results of this development. But forests can play an important role in maintaining the global system in balance, and these forests are also the largest carbon sink above the soil. Furthermore, about 70–90 % of the global biodiversity are found in this ecosystem.

Over the last few decades, due to the increasing environmental awareness, the importance of the forest ecosystem has been acknowledged at the global level, which in turn enabled it to become a topic of relevance to the general public. Sustainable forest management, that is, the achievement of long-term economic, social and environmental goals has thus become the basic forestry principle. Forest management is a problem of increasing controversy and difficulty (Rosser Jr 2003).

Forest provides timber and fuel wood. Forest is also a renewable resource and is the largest carbon sink on the earth. Plantation of forest is motivated by profitability and demand for fuel wood and timber, and the harvesting of the mature forest for timbers is triggered by the demand. The saw mills demand logs from harvesting of

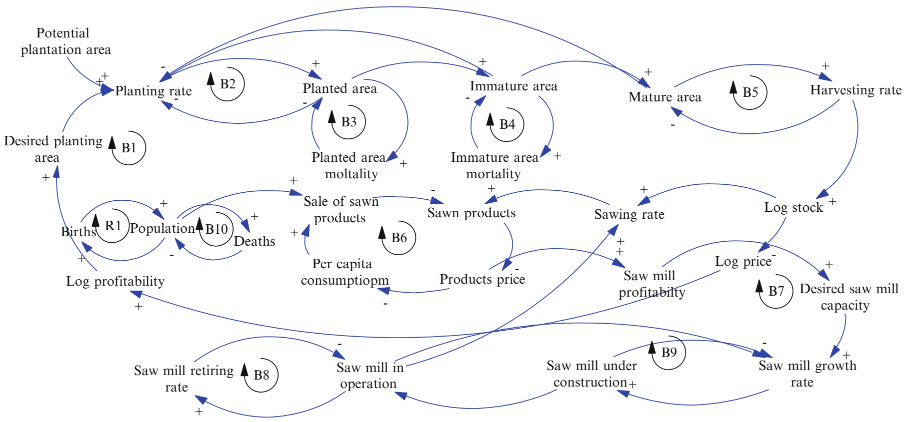

Fig. 3.10 Causal loop diagram of forest dynamics

timbers, and the expansion of the saw mills depends on profitability. Draw a causal loop diagram of the forest dynamics and management.

Solution

The causal loop diagram of forest dynamics is shown in Fig. 3.10. Planting rate increases planting and mature area and higher harvesting rate. The higher log stock would cause to lower the log price and the higher price resulting higher profitability would motivate to increase the planting area. This forms a negative feedback loop B1. The planting area forms negative feedback loop with planting rate (B2). Planted area and immature area are decreased by mortality, and the mature area is decreased by harvesting rate (B3, B4 and B5). Sawn products, products price and sales of sawn products form a negative feedback loop (B6). Increase in saw mill under construction would ultimately increase the saw mill under operation which results in higher sawing rate. This in turn would reduce product price, and the higher product price would result in higher profitability and saw mill growth rate. This forms a negative feedback loop B7. Saw mill under construction with saw mill growth rate and saw under operation with retiring rating rate balance the saw mill under construction and saw mill under operation, respectively (B8 and B9). Sales of sawn products increase with population and population comprises of one reinforcing loop (R1) and one balancing loop (B10).

3.4.7 Electricity Supply

Energy is needed for economic and social development (Bala 1997a, b, 1998). Per capita consumption of energy is a measure of physical quality of life (Bala 1998). Also per capita consumption of electrical energy is a measure of physical quality of life. Energy demands are increasing rapidly. Investments for power plants are triggered by the power supply gap, price and public pressure. Indicated price

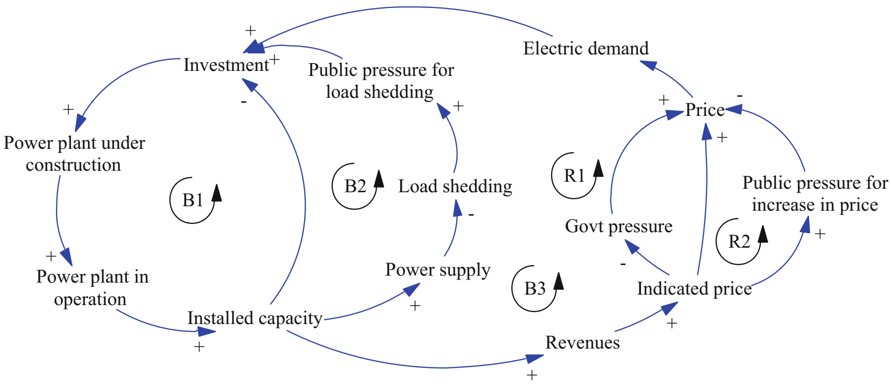

Fig. 3.11 Causal loop diagram of electricity supply system

depends on revenue received which creates govt pressure to increase the price as the indicated price increases while the public pressure for increase in price creates pressure to decrease the price. A power plant under construction becomes operational after some time delay and adds to the installed capacity to supply electricity and hence reduces the pressure on new investments. Draw the causal loop diagram of the simple electric supply system.

Solution
The causal loop diagram of the simple electricity supply system is shown in Fig. 3.11. Investment increases the installed capacity which in turn would invite less investment. This forms a negative feedback loop B1. The increase in installed capacity would increase power supply, and the increased power supply would reduce the load shedding. The load shedding increases public pressure which would increase the investment. The increased investment would result in increased installed capacity. This forms the negative feedback loop B2. Revenues, indicated price, government pressure, public pressure for increase in price, electric demand, investment and installed capacity form two positive feedback loops, and these are indicated R1 and R2.

3.4.8 Global Warming

Global warming refers to an increase in the average temperature of the atmospheric temperature resulting from greenhouse effect, and it is a prime concern in many developing countries. Earth's surface average temperature is increased by emissions of greenhouse gases and incoming solar radiation. The emissions are reduced by carbon sink of plant kingdom and algae in the sea. The water vapour increases the absorbed radiation. Draw the causal loop diagram of this simple global warming model.

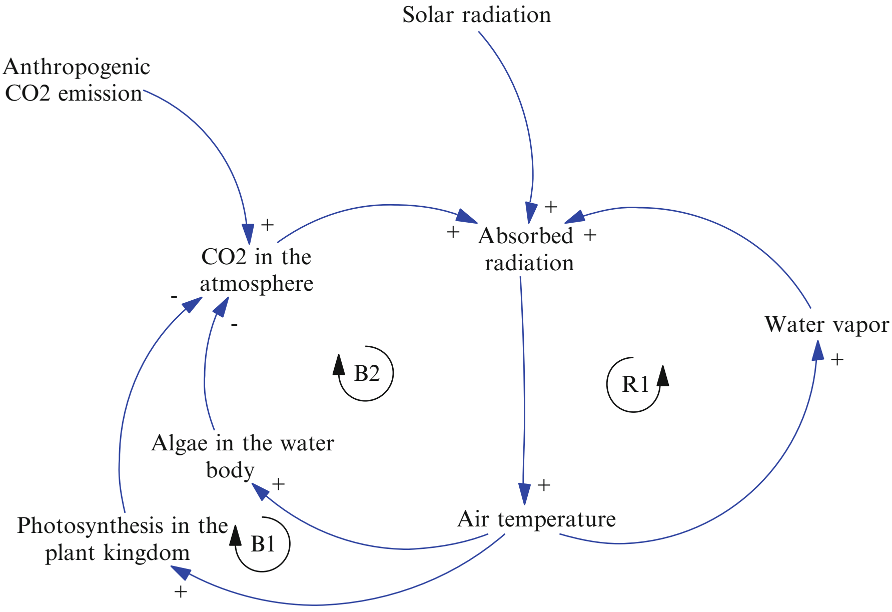

Fig. 3.12 Causal loop diagram of global warming

Solution

The causal loop diagram of the simple global warming model system is shown in Fig. 3.12. Absorbed radiation is increased by solar radiation and CO_2 in the atmosphere and water vapour. The increase in air temperature causes increase in photosynthesis in the plant kingdom and algae in the water body which decrease the CO_2 in the atmosphere (B1 and B2). Air temperature increases water vapour which increases the absorbed radiation. This forms a positive feedback loop (R1). Thus, there are one reinforcing loop and two distinct balancing feedback loops B1 and B2.

Exercises

Exercise 3.1 Rural and urban population

Population is divided into rural and urban. Population increases by birth rate and decreases by death rate. Both the rates are considered to be influenced by the availability of food, crowding and earning. Draw the causal loop diagram for the description of rural and urban population.

Exercise 3.2 Fish pond ecosystem

Fish pond ecosystem can be divided into two parts known as the biotic (living) and abiotic (nonliving) components. The abiotic substances are the water, the nutrients, oxygen, carbon dioxide, etc. The producers in the ecosystems are the large rated plants and the free-floating plants, usually algae, called phytoplankton. These store energy and liberate oxygen. The primary consumers are benthos or bottom form and zooplankton with little or no swimming ability. The phytoplanktons are consumed by zooplankton, which are in turn eaten by large aquatic life such as fish. Other consumers are the insects, frogs, man, etc., and a category called detritivores which live on the organic wastes. All of these forms produce organic waste and dead organisms. The decomposers, bacteria and fungi, utilise the organic carbon and generate CO_2 which in turn is used by the algae. Additional CO_2 is provided from the atmosphere and through the respiration of fish. In a healthy system, the availability of the nutrients, carbon, phosphorus and nitrogen is sufficiently small so as to limit the production of algae. Draw the causal loop diagram for fish pond ecosystem.

Exercise 3.3 Prawn production system
The prawn production system consists of two components: biological component and economic component. The biological component is a dynamic population model. Population of either sex at any time is determined from death rate, population level and harvest size. The number of deaths increases with an increase in population, and again the increase in number of deaths decreases the population. We can divide the population by length and size. Draw the causal loop diagram for prawn production system.

Exercise 3.4 Price forecasting of palm oil
Palm oil production is a highly complex system starting from plantation to export of palm oil. Our starting hypothesis about the market of palm oil should be something to do with the balance of supply and demand as in case with other agricultural commodities. The change in the palm oil price is a result of two major adjustments; change in palm oil price due to expectation adjustment and price adjustment. Short-term pressures arising from imbalance of supply and demand, changes in costs or competitors' prices will cause the traders to bid prices up or down relative to their expectation about equilibrium price. Other factors are such as substitutes, trade liberalisation and export restriction. Our initial dynamic hypothesis of palm oil market structure is based on standard assumptions how commodity markets typically work. If our hypothesis is correct, the model will be able to reproduce the general historical pattern followed by the palm oil price. Draw the causal loop diagram of price forecasting model of palm oil.

Exercise 3.5 Biofuel Promotion
Biofuel inventory and food inventory are key factors which regulate the prices and the profitability for farmers. The inventories act as buffers between production and supply and absorb variations on both sides. An increase in biofuel demand depletes biofuel inventory and causes biofuel price to increase and subsequently biofuel crop land to increase. This increase in land is at the expense of food crop land. The need for cultivable land is reinforced by the simultaneous increase in population. Government policies are represented through the variables such as incentives for biofuels and biofuel technology and management capabilities. The former is a

direct policy instrument, whereas the latter is an indirect one resulting in the funding of related R&D projects. These two instruments are competing for resources and have contrasting effects, as incentives increase land use, whereas technology increases the yield of the existing land. Draw causal the loop diagram.

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Stock and Flow Diagram

4

The concept of stock–flow diagram was introduced in Chap. 2, and this chapter presents concepts, methodology and techniques of constructing stock–flow diagrams. The basic building blocks of the system structure: stock and flow are explained. Delays and graphical functions are highlighted. Function with and without integrations are presented. A good number of examples are included to demonstrate the techniques of constructing the system structures in terms of stock–flow diagrams and simulation using the software STELLA.

4.1 Introduction

One approach to study a system is verbal description, and another approach is causal loop diagram. Causal loops are wonderful to tell the story of the dynamic behaviour of complex and dynamic systems to others and represent the verbal and mental model more clearly using cause and effect relationships. But to show the relationship and to accentuate the loop structure of a system, the flow diagram is the best since causal loops suffer from their inability to capture the stock and flow of the systems. Essentially stock and flow represent systems of first-order difference equation central to the system dynamics theory.

Feedback loop is the basic structural element within the system boundary. The boundary separates the system from the surrounding environment. Dynamic behaviour is simulated by the feedback loops. The feedback loop is a path coupling decision, action, level (or condition) and information with the path returning to the decision point (Fig. 4.1). The decision process is one that controls action. It can be the governing process in biological development, or it may be the valve and actuator in a chemical plant. Whatever may be the decision process, it is embedded in a feedback loop. The decision is based on the available information; the decision controls an action that influences a system level and new information arises to modify the decision stream. A system may be a single loop or interconnected loops.

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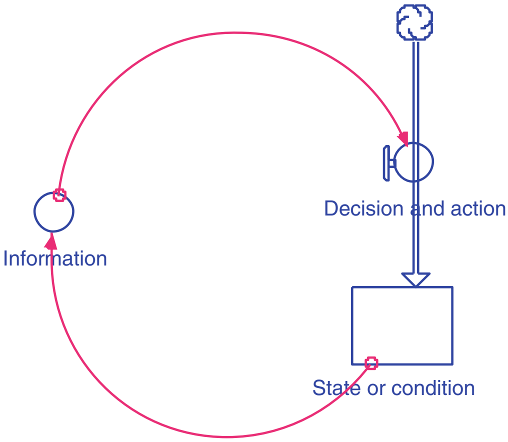
Fig. 4.1 Feedback loop



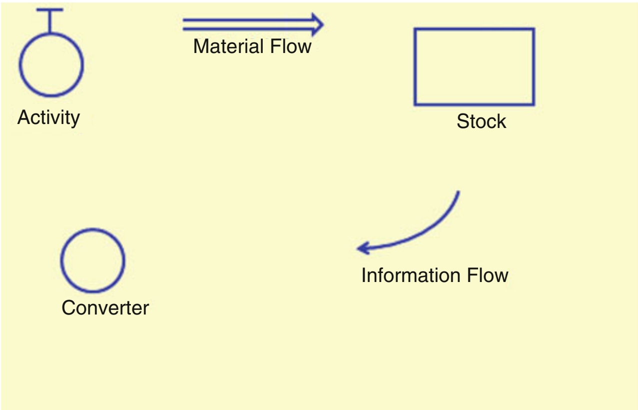


Fig. 4.2 Symbols of STELLA flow diagrams

The stocks and flows are two basic building blocks in system dynamics modelling. The equations of a system focus on the composition of each stock and flows. The stock–flow diagram should show how stocks and flows are interconnected to produce the feedback loops and how the feedback loops interlink to create the system. The symbols used in STELLA stock–flow diagrams are shown in Fig. 4.2. Stock–flow diagram with reference to STELLA stock–flow diagrams are described in the following subsections.

4.2 Stock

The first basic building block in system dynamics modelling is the stock, and this variable describes the condition or state of the system at any particular time. These variables are accumulations in the system. Examples of these variables are

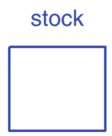


Fig. 4.3 Symbol of stock

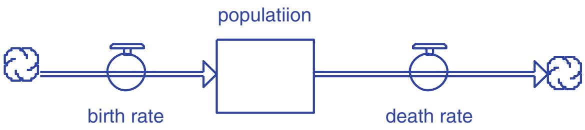


Fig. 4.4 Flow diagram of a stock of population

population or water in a reservoir. These are physical accumulations, while the examples of non-physical accumulations are public pressure, skill and knowledge.

All stock equations and any special function that represents integration are represented by a rectangle (Fig. 4.3). A simple single stock model of population in STELLA is shown in Fig. 4.4. Flow into the system is birth rate, and flow out of the system is death rate. The accumulation of the population is the stock of the model.

Stocks integrate flows into and out of the stock, and the net flow into the stock is the rate of change of the stock. The stock which is represented by a first-order integral equation is

Stock

$$\text{population}(t) = \text{population}(t - dt) + (\text{birth\_rate} - \text{death\_rate})*dt \tag{4.1}$$

Equation (4.1) is in the form of first-order finite difference equation. The simple population model shows that population increases by birth rate and decreases by death rate.

4.3 Flow

The second building block is the flow, and these variables tell how fast the stocks are changing. The flows are represented by valve symbols (Fig. 4.5). The examples of these variables are inflow (birth rate) and outflow (death rate to the stock of population), and these are shown in Fig. 4.6. The birth rate depends on the population size and birth fraction, while death rate depends on the population size and death fraction.

The inflow and outflow equations are

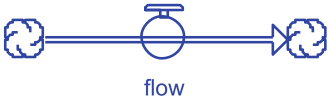


Fig. 4.5 Symbol of flow

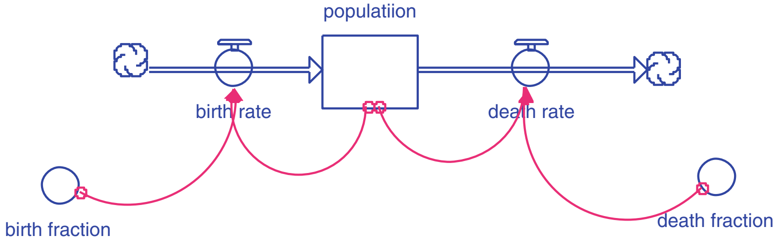
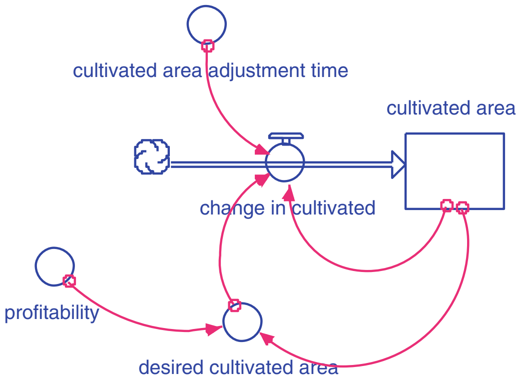


Fig. 4.6 Flow diagram showing flows to stock of population

Fig. 4.7 Flow diagram illustrating converter



Inflow

$$\text{birth rate} = \text{population} * \text{birth fraction} \tag{4.2}$$

Outflow

$$\text{death rate} = \text{population} * \text{death fraction} \tag{4.3}$$

4.4 Converter

In STELLA the converter serves utilitarian role in the software. It holds the values for constants, defines external inputs to the model, calculates algebraic relationships and serves as the repository for graphical functions. In general, it converts inputs into outputs. Hence, the name is ‘converter’. In Fig. 4.7 desired cultivated area, profitability and cultivated area adjustment time are converters.

4.5 Delays

It's the time between the action and the result (consequence) of this action. Delay is a commonly observed phenomenon in material and information flow, and it takes time for the material to flow and information to process. Time delay is defined as the time required for the flow of material or information, and more precisely it is the time by which the output lags behind the input. Thus, the delay may be material delay or information delay. The material delay causes the delay in the supply of the material, and the information delay is the delay in processing the information.

In pipeline delay the delay time is constant, and the order of output is precisely same as the order of entry. The delay may be first order, second order, third order and even higher order. In first-order delay, the outflow is always proportional to the stock of the material in transit. The second-order delay consists of two first-order delays in series, with each of time delay of half of the original time delay, while a third-order delay consists of three first-order delays in series with each of the time delay of one third of the original time delay. Also higher-order delays approach the pipeline delay. Figure 4.8 shows the responses of different types of delay functions.

Delays

```
first_order_delay = SMTH1(input,2,0)
input = STEP(100,2)
pipeline_delay = DELAY(input,2,0)
third_order_delay = SMTH3(input,2,0)
```

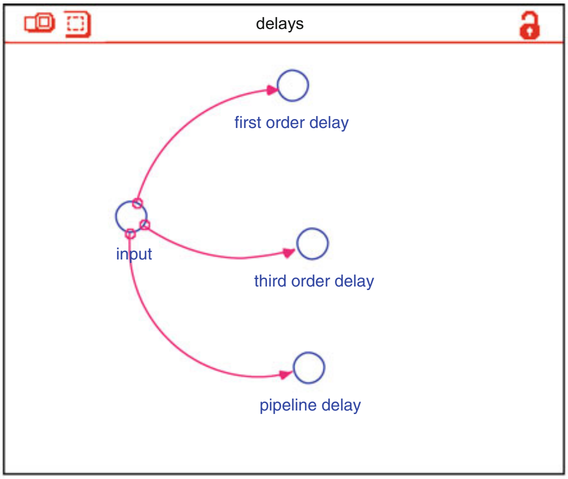
4.5.1 Role of Delay

Delay plays an important role in information and material flow and hence the behavioural performance of the system and the key points which deserve special attentions are:

(a) Acknowledge delay as a *factor* in decision-making.
(b) Respect delay as an *element* to understand success or failure.
(c) Regard delay as a *force* in determining value of change.

4.5.2 Choice of Delay Function

The choice of delay function is quite important when inputs of sharp variations such as STEP function are used. The difference in the response of third- and higher-order delays is not quite large. For practical purposes three main possibilities are



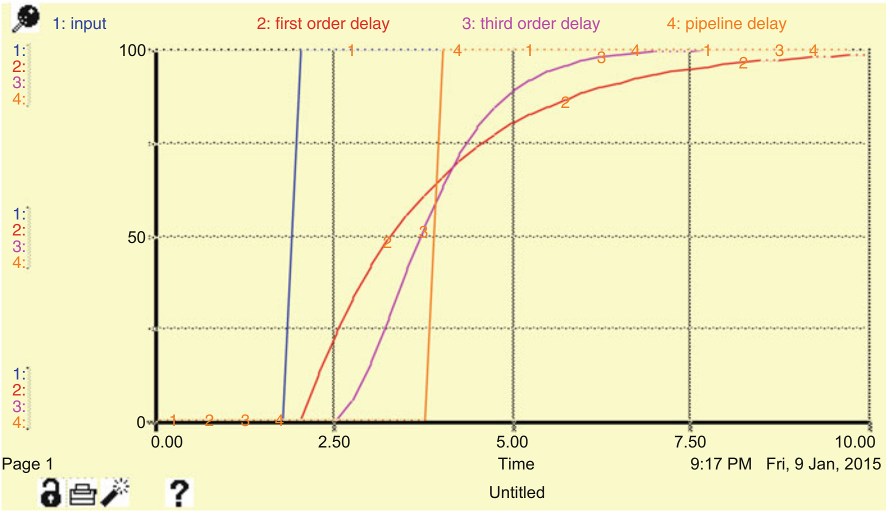


Fig. 4.8 STEP response of first-, third-order and pipeline delay

first-order delay, third-order delay and pure or pipeline delay. When the input has an immediate effect and then long tail, first-order delay is recommended. But when the output is the exact copy of the input, pipeline delay is appropriate. In intermediate case where the input has a delayed response and a spread of inflow, third-order delay is recommended. Third-order delay is usually a good compromise well within accuracy of the commonly available data, and that is why it is commonly used in system dynamics modelling.

4.6 Identification of Stock and Flow

In control theory stocks are known as state variable and flows are known as derivatives, while in system dynamics, these are also known as levels and rates, respectively. In system dynamics modelling first of all, the variables within the system boundary must be identified. Then identify which variables are affected or influenced by other variable and the affected variables which represent state of the system, i.e. quantities of material or other materials are stocks. The others having the unit per unit time of the unit of the stock variables are flows. It should be remembered that stocks are quantity and flows are quantity per unit time. The stocks are only changed by flows and the contents of stocks, and flow networks are conserved. Also converters (auxiliaries) are elaboration of flows, and hence these are affected by stocks and constants. For example, in a simple population model, the variables are birth rate, death rate and population. The population has a unit of quantity, while birth rate and death rate have a unit of quantity per unit time. Also population level is changed by birth rate and death as inflow and outflow, respectively. Hence, the population is a stock variable, and birth rate and death rate are flow variables.

4.7 Mathematical Representation of Stock and Flow

Integration or accumulation creates the dynamic behaviour of the systems, and integration occurs naturally both in physical and biological systems. Stock equation can be represented by first-order finite difference equation, and it can be expressed as

$$\text{stock}(t) = \text{stock}(t_0) + \int_{t_0}^{t} (\text{inflow}(t) - \text{outflow}(t))dt \tag{4.4}$$

And this integration equation in the differential equation form is

$$\frac{d(\text{stock})}{dt} = \text{inflow}(t) - \text{outflow}(t) \tag{4.5}$$

Equation (4.5) is an initial value problem and several methods are available to solve this problem. STELLA provides three methods of solution of this initial value problem. These methods are (i) Euler's method, (ii) second-order Runge–Kutta method and (iii) fourth-order Runge–Kutta method. The numerical solution procedure of these methods is summarised below:

(i) Euler's Method
Denote the first-order problem in Eq. (4.5) as

$$\frac{d(\text{stock})}{dt} = \frac{dy}{dt} = y' = f(t, y), \qquad y(t_0) = y_0 \tag{4.6}$$

The derivative of y at i, $f(t,y) = f_{\rm i}$ can be evaluated using Eq. (4.6) as soon as $y_{\rm i}$ is known. Once $f_{\rm i}$ is known, the approximate integration formula gives

$$\Delta y_{\rm i} = y_{\rm i+1} - y_{\rm i} = \int_{t_{\rm i}}^{t_{\rm i+1}} f(t, y)\, dt = (t_{\rm i+1} - t_{\rm i})f_{\rm i} \tag{4.7}$$

And solving for $y_{\rm i+1}$

$$y_{\rm i+1} = y_{\rm i} + (t_{\rm i+1} - t_{\rm i})f_{\rm i} \tag{4.8}$$

Equation (4.8) is known as Euler's formula, and it has a truncation error of order h^2.

(ii) Second-Order Runge–Kutta Method
Given the equation

$$\frac{dy}{dt} = y' = f(t, y), \tag{4.9}$$

the Runge–Kutta forward integration formulae are derived by determining a point

$$\bar{t} = t_{\rm i} + \alpha h, \quad \bar{y} = y_{\rm i} + \beta h, \quad (h = t_{\rm i+1} - t_{\rm i}) \tag{4.10}$$

and the increment is computed by the one-term formula as given by Eq. (4.11):

$$\overline{\Delta} y_{\rm i} = y_{\rm i+1} - y_{\rm i} = f(\bar{t}, \bar{y})h \tag{4.11}$$

The increment in Eq. (4.11) is identical with the increment computed by means of a predetermined number of terms of the Taylor series expansion in Eq. (4.12):

$$\Delta y_{\rm i} = y'_{\rm i}\, h + y''_{\rm i}\, \frac{h^2}{2} + y'''\frac{h^3}{6} + \cdots\cdots \tag{4.12}$$

The second-order Runge–Kutta formula is obtained by setting increment in Eq. (4.11) equal to the first two terms of the Eq. (4.12), and it is given by

$$f(\bar{t}, \bar{y}) = f(t_{\rm i} + \alpha h, y_{\rm i} + \beta h) = y'_{\rm i} + y''_{\rm i}\frac{h}{2} + \ldots\ldots\ldots\ldots \tag{4.13}$$

When $f(\bar{t}, \bar{y})$ in Eq. (4.13) is expanded into a double Taylor series about (t, y) truncated after the first derivate terms, it can expressed as

$$f(t_\mathrm{i} + \alpha h, y_\mathrm{i} + \beta h) = f_\mathrm{i} + \alpha h f_{\mathrm{t,i}} + \beta h f_{\mathrm{y,i}} \tag{4.14}$$

By Eq. (4.9), the right-hand side of Eq. (4.13) becomes

$$y'_\mathrm{i} + y''_\mathrm{i}\mathrm{i}\frac{h}{2} = \left[f + \frac{h}{2}\frac{df}{dt}\right]_{t=t_\mathrm{i}} \tag{4.15}$$

where $f(t,y)$ is to be considered a function of t only, through substitution of $y(t)$ for y. Hence, the derivative of $f(t, y)$ with respect to t can be expressed as

$$\frac{df(t,y)}{dt} = \frac{\delta f}{\delta t} + \frac{\delta f}{\delta y}\frac{dy}{dt} = f_t + f_y f, \tag{4.16}$$

Substituting Eq. (4.16) into Eq. (4.15) can expressed as

$$y'_\mathrm{i} + y''_\mathrm{i}\frac{h}{2} = f_\mathrm{i} + \frac{h}{2}\left(f_{\mathrm{t,i}} + f_{\mathrm{y,i}} f_\mathrm{i}\right) \tag{4.17}$$

Substitution of Eq. (4.14) and Eq. (4.17) into Eq. (4.13) gives

$$f_\mathrm{i} + \alpha h f_{\mathrm{t,i}} + \beta h f_{\mathrm{y,i}} = f_\mathrm{i} + \frac{h}{2} f_{\mathrm{t,i}} + \frac{h}{2} f_{\mathrm{y,i}} \tag{4.18}$$

Equation (4.18) gives

$$\alpha = \frac{1}{2}, \quad \beta = \frac{1}{2} f_\mathrm{i}, \quad \bar{t} = t + \frac{h}{2}, \quad y = y_\mathrm{i} + \frac{h}{2} f_\mathrm{i} \tag{4.19}$$

The evaluation of $y_{\mathrm{i}+1}$ by second-order Runge–Kutta formula requires the following three steps:

$$\Delta' y_\mathrm{i} = h f_\mathrm{i} = h f(t_\mathrm{i}, y_\mathrm{i})$$

$$\overline{\Delta} y_\mathrm{i} = h f(\bar{t}, \bar{y}) = h f\left(t_\mathrm{i} + \frac{h}{2}, y_\mathrm{i} + \Delta' y_\mathrm{i}\right)$$

$$y_{\mathrm{i}+1} = y_\mathrm{i} + h f\left(t_\mathrm{i} + \frac{h}{2}, y_\mathrm{i} + \Delta' y_\mathrm{i}\right) \tag{4.20}$$

Equation (4.20) is known as second-order Runge–Kutta formula, and it has truncation error of order h^3.

(iii) Fourth-Order Runge–Kutta Method

To obtain the fourth-order Runge–Kutta formula with error of order h^5, the following successive values of must be evaluated:

$$\Delta' y_i = hf(t_i, y_i)$$

$$\Delta'' y_i = hf\left(t_i + \frac{h}{2}, y_i + \frac{1}{2}\Delta' y_i\right)$$

$$\Delta''' y_i = hf(t_i + h, y_i + 2\Delta'' y_i - \Delta' y_i)$$

$$\overline{\Delta} y_i = \frac{1}{6}(\Delta' y_i + 4\Delta'' y_i + \Delta''' y_i)$$

$$y_{i+1} = y_i + \frac{1}{6}(\Delta' y_i + 4\Delta'' y_i + \Delta''' y_i) \tag{4.21}$$

Equation (4.21) is known as fourth-order Runge–Kutta formula, and it has truncation error of order h^5. Thus, for better prediction of the model the Runge–Kutta fourth-order method is recommended.

4.8 Solution Interval

The proper length of the solution interval is related to the shortest delays that are represented in the model. If the solution interval is too long, instability is generated which arises from the computing process, not from any inherent dynamic characteristic of the system itself. If the solution interval is too short, the equation will be evaluated unnecessarily often using extra computer time. As a practical rule of thumb, the solution interval should be half or less of the shortest first-order delay in the system.

A model should be always tested for sensitivity to step size. The model should be first run for full length of simulation. Some variables should be plotted and printed. Next, the step size should be cut half, and the simulation should be repeated. This process should be continued until the improvements in results become negligible.

4.9 Functions Without Integration

There are several types of special function having the nature of flows (rates) or converter (auxiliary). These are special computation procedures, table interpolation, test inputs, randomness and logical choices. These functions can be imposed in any flow channel, and they would not introduce any time delay or periodicity in the system. They alter only the instantaneous amplitude of the signals.

The group of special computation procedures includes the square root, exponential and logarithmic functions. In STELLA there is no special symbol for each of these functions. These functions in STELLA are represented by converters.

SQRT(<expression>)
The SQRT function gives the square root of *expression*. *Expression* can be variable or constant. For meaningful results, expression must be greater than or equal to 0.

Examples:
SQRT(400) returns 20

EXP(<expression>)
The EXP function gives e raised to the power of *expression*. *Expression* can be variable or constant. The base of the natural logarithm, e, is also known as Euler's number. e is equal to 2.7182818.... EXP is the inverse of the LOGN function (natural logarithm). To calculate powers of other bases, use the exponentiation operator (^).

Examples:
EXP(1) equals 2.7182818 (the value of Euler's constant)
EXP(LOGN(3)) equals 3

LOGN(<expression>)
The LOGN function calculates the natural logarithm of *expression*. *Expression* can be variable or constant. Natural logarithms use Euler's constant e, 2.7182818..., as a base. For LOGN to have meaningful results, expression must be positive. LOGN is the inverse of the EXP function, e raised to the power of *expression*.

Examples:
LOGN(2.7182818) equals 1
LOGN(EXP(3)) equals 3
LOGN(−10) returns ? (undefined for non-positive numbers)

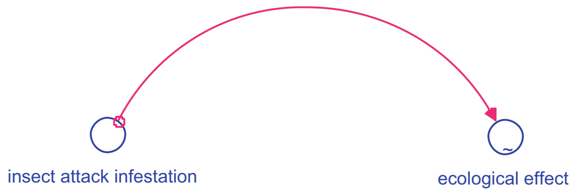
LOG10(<expression>)
The LOG10 function gives the base 10 logarithm of *expression*. *Expression* can be variable or constant. For LOG10 to be meaningful, *expression* must evaluate to a positive value. LOG10 is the inverse of the letter E in scientific notation, or base 10 exponentiation (10 raised to the power of *expression*).

Examples:
LOG10(10) equals 1
LOG10(1E5) equals 5
LOG10(−10) returns ? (undefined for non-positive numbers)

Graphical Function
Second class of functions provides for interpolation in a table. Non-linear relationships appear repeatedly in system dynamics. Table functions locate by linear interpolation, the values intermediate between the points entered in a table. These functions in STELLA are represented by converters with a small shadow inside the converters, and the flow diagram symbol of graphical functions is shown in Fig. 4.9.

In STELLA graphical function is essentially a sketch that relates between some input and output. This can be represented as

Fig. 4.9 Graphical function



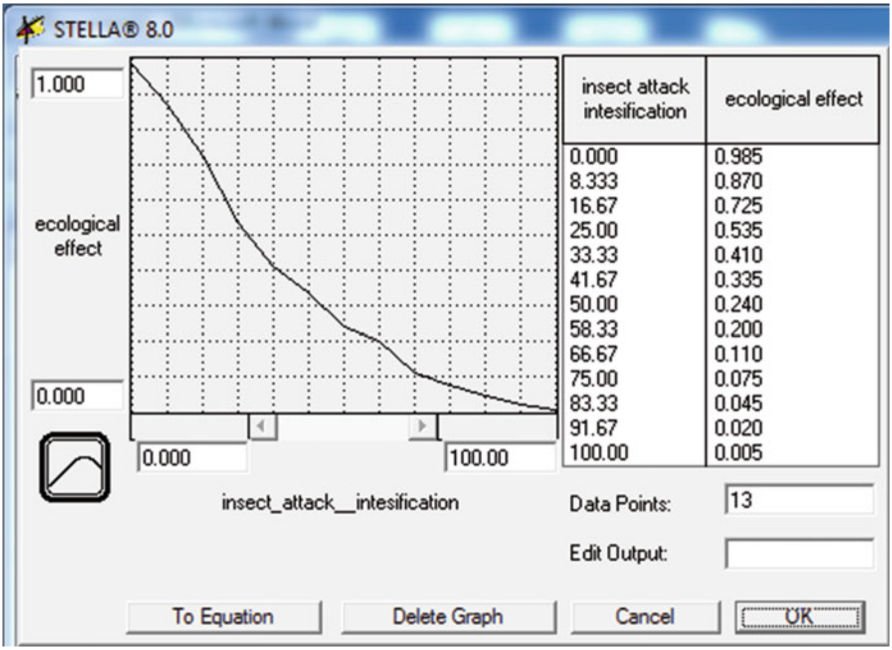


Fig. 4.10 Illustration of graphical function

Graphical_function_name GRAPH (input_ variable_ name) (x_1,y_1), (x_2, y_2), (x_3, y_3)……… (x_n, y_n)
where

graphical_function_name is name of the graphical function.
Input_variable_name is the input variable for which corresponding graphical/table entry is made.

(x_1,y_1) is first graphical point with input variable x_1, and output variable y_1. (x_2,y_2) is the second graphical point with input variable x_2 and output variable y_2. Similarly (x_n,y_n) is the nth graphical point. n is the number of points in the graphical function. Figure 4.10 illustrates the graphical function of ecological effect as a function of insect attack infestation. We need to provide data on minimum and maximum values of the *X*-axis and *Y*-axis, number of data points and *x* values as well as *y* values of each point for the graphical function.

Test Input Functions

A group of function consisting of STEP, RAMP, SIN and COS are primarily used as test inputs.

STEP(<height>,<time>)

STEP function produces a specified constant height starting at a specified time, and it is frequently used as a shock excitation to determine the dynamics of the system recovery.

RAMP(<slope> [,<time>])

The RAMP function generates a linearly increasing or decreasing input over time with a specified slope (*slope*). Optionally, you may set the time at which the ramp begins. Slope and time can be either variable or constant.

PULSE(<volume> [,<first pulse>,<interval>])

The PULSE function generates a pulse input of a specified size (*volume*). In using the PULSE function, you have the option of setting the time at which the PULSE will first fire (*first pulse*), as well as the interval between subsequent PULSEs (*interval*). Each time that it fires a pulse, the software pulses the specified volume over a period of one time step (DT). Thus, the instantaneous value taken on by the PULSE function is volume/DT. Volume can be either variable or constant. First pulse and interval should be specified as constants.

SIN(<radians>)

SIN generates a sinusoidal fluctuation having a unit amplitude and specified period. The SIN function gives the sine of *radians*, where *radians* is an angle in radians. To convert measurement between degrees and radians, use the identity: pi (radians) = 180 (degrees). *Radians* can be constant or variable.

COS(<radians>)

COS in a similar fashion generates a cosine function of unit amplitude and specified period. The COS function gives the cosine of *radians*, where *radians* is an angle in radians. To convert measurement between degrees and radians, use the identity: pi (radians) = 180 (degrees). *Radians* can be constant or variable.

RANDOM(<min>,<max>, [<seed>])

The RANDOM function generates a series of uniformly distributed random numbers between *min* and *max*. RANDOM samples a new random number in each iteration of a model run. If you wish to replicate the stream of random numbers, specify *seed* as an integer between 1 and 32,767. To replicate a simulation, all variables that use statistical functions must have seeds specified. Each variable using a statistical function should use a separate seed value.

MAX(<expression>,<expression>,. . .)
The MAX function gives the maximum value among the expressions contained within parentheses.

MIN(<expression>,<expression>,. . .)
The MIN function gives the minimum value among the expressions contained within parentheses.

SWITCH(<Input1>,<Input2>)
The SWITCH function is equivalent to the following logic:
If *Input1* > *Input2* then 1 else 0.

Logical Function
The logical functions – IF, THEN, ELSE, AND, OR, NOT – are used to create expressions, and then give values based upon whether the resulting expressions are TRUE or FALSE. When you have multiple conditions, the expressions to be evaluated must be enclosed in parentheses ().

In STELLA the logical functions – IF, THEN, ELSE, AND, OR, NOT – are used to create expressions and give values based upon whether the resulting expressions are TRUE or FALSE. An example of bonus payments logic given below is essentially a logical function:

```
bonus_payments = 1F(TIME = 5) OR (sales > 5000) THEN Bonus ELSE 0
```

This statement sets bonus payments to the value of bonus at simulated time 5, or whenever the value of sales is greater than 5000. When neither condition is met, the statement gives the value, 0.

4.10 Functions Containing Integration

The functions SMOOTH, information delay and material delay contain integration. These are normally inserted in the flow channel or information channel in a model. Since these functions include stock, they change the time shape quantities moving between their inputs and outputs. These functions are assemblies of elementary stock and flow equations.

4.10.1 Smooth

SMOOTH produces first-order exponential average of a physical flow, and it is represented as shown in Fig. 4.11. Internally, the following equations will be generated and executed:

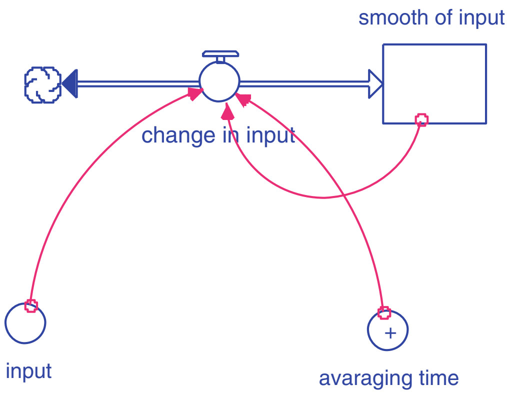


Fig. 4.11 Flow diagram of SMOOTH

```
smooth_of_input(t) = smooth_of_input(t - dt) + (change_in_input) * dt
INIT smooth_of_input = { Place initial value here... }
```

INFLOWS:

```
change_in_input = { Place right hand side of equation here... }
averaging_time = { Place right hand side of equation here... }
input = { Place right hand side of equation here... }
```

4.10.2 Information Delay

First-Order Information Delay

First-order information delay is used in the information channel to produce a first-order exponential delay. It represents the process of gradual, delayed adjustment of recognised information moving towards a value being supplied by a source. It is used to generate a delayed awareness of a changing situation. The flow diagram for first-order information delay is shown in Fig. 4.12. Internally, the following equations will be generated and executed. This function being first-order negative loop has a simple exponential response to the changes in its input:

```
output_with_information_delay1(t) = output_with_information_delay1
(t - dt) + (change_in_output) * dt
INIT output_with_information_delay1 = 0
```

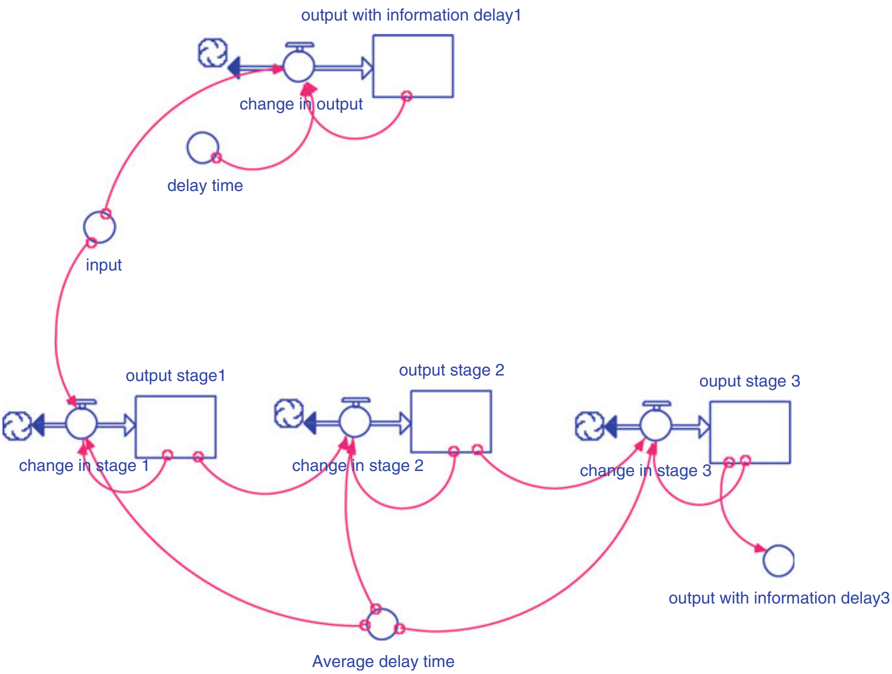


Fig. 4.12 Flow diagram of information delay

INFLOWS:

```
change_in_output = (input-output_with_information_delay1)/delay_time
delay_time = 2
input = STEP(100,2)
```

Third-Order Information Delay

Third-order information delay is a cascade of three first-order information delays as shown in Fig. 4.12. The equations and flow diagram show three sections like that for first-order information delay except in each section the delay is one third of the total. The following equations produce the third-order information delay in the information stream:

```
ouput_stage_3(t) = ouput_stage_3(t - dt) + (change_in_stage_3) * dt
INIT ouput_stage_3 = 0
```

INFLOWS:

```
change_in_stage_3 = (output_stage_2-ouput_stage_3)/
Average_delay_time
```

```
output_stage_2(t) = output_stage_2(t - dt) + (change_in_stage_2) * dt
INIT output_stage_2 = 0
```

INFLOWS:

```
change_in_stage_2 = (output_stage1-output_stage_2)/
Average_delay_time
```

```
output_stage1(t) = output_stage1(t - dt) + (change_in_stage_1) * dt
INIT output_stage1 = 0
```

INFLOWS:

```
change_in_stage_1 = (input-output_stage1)/Average_delay_time
Average_delay_time = 2/3
output_with_information_delay3 = ouput_stage_3
input = STEP(100,2)
```

The delay may be first order, second order, third order and even higher order. Third-order and first-order information delays are placed in the information channel. But third-order information delay produces a different time shape in output. Figure 4.13 shows the step responses of first-order and third-order information delay.

4.10.3 Material Delay

The outflow from a first-order material delay is always proportional to the stock of material in transit, and the flow diagram of a first-order material delay is shown in Fig. 4.14. Third-order material delay is similar to third-order information delay, and it is also the three cascaded first-order exponential loops. Therefore, it has the same response. It differs from third-order information delay being placed in flow channel and creates a delay in the transmission of quantity from the input to the output. Internally the following equations will be generated and executed. Figure 4.15 shows STEP responses of first- and third-order material delay.

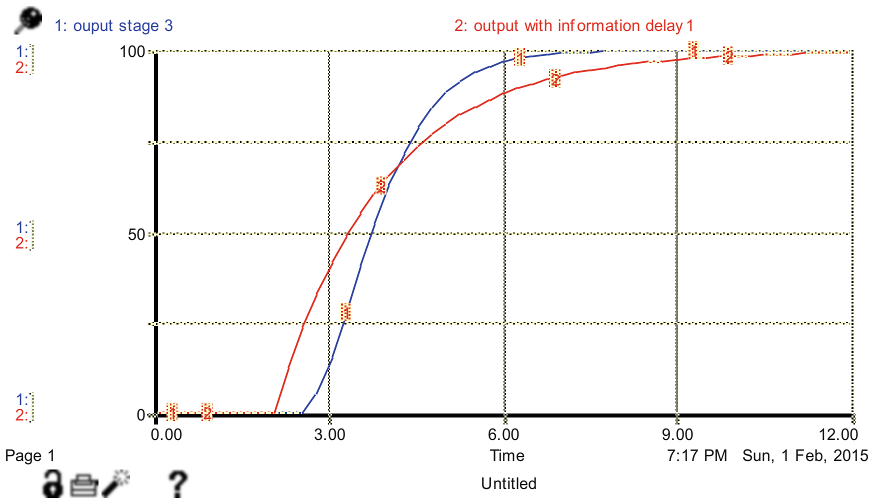


Fig. 4.13 STEP response of first-order information delay (output with information delay 1) and third-order information delay (output stage 3)

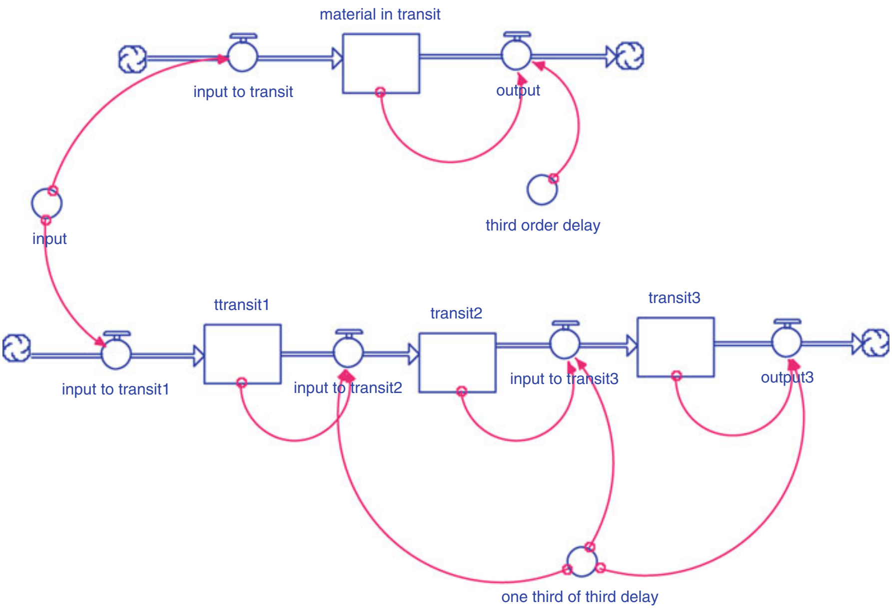


Fig. 4.14 Flow diagram of material delay

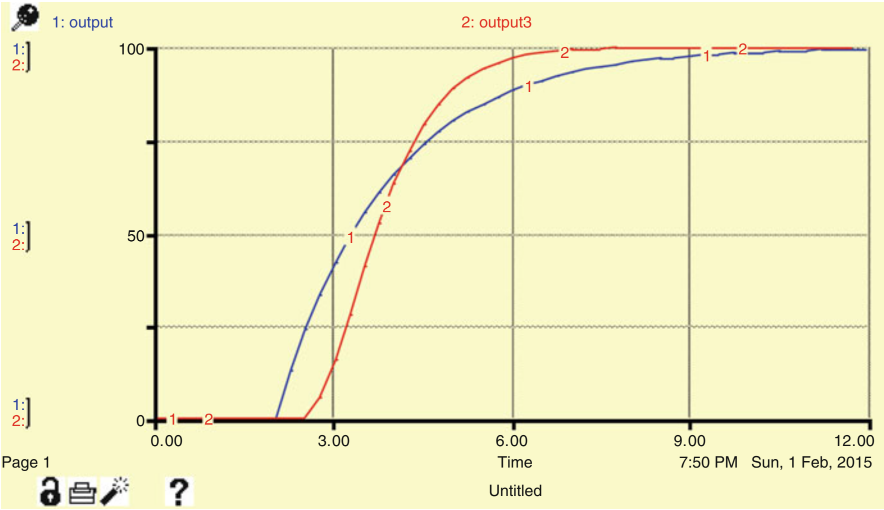


Fig. 4.15 STEP response of first-order material delay (output) and third-order material delay (output 3)

First-Order Material Delay

```
material_in_transit(t) = material_in_transit(t - dt) + (input_to_transit
 - output) * dt
INIT material_in_transit = 0
```

INFLOWS:

```
input_to_transit = input
```

OUTFLOWS:

```
output = material_in_transit/third_order_delay
third_order_delay = 2
```

Third-Order Material Delay

```
transit2(t) = transit2(t - dt) + (input_to_transit2 - input_to_
transit3) * dt
INIT transit2 = 0
```

INFLOWS:

```
input_to_transit2 = ttransit1/one_third_of_third_delay
```

OUTFLOWS:

```
input_to_transit3 = transit2/one_third_of_third_delay
```

```
transit3(t) = transit3(t - dt) + (input_to_transit3 - output3) * dt
INIT transit3 = 0
```

INFLOWS:

```
input_to_transit3 = transit2/one_third_of_third_delay
```

OUTFLOWS:

```
output3 = transit3/one_third_of_third_delay
```

```
ttransit1(t) = ttransit1(t - dt) + (input_to_transit1 - input_to_
transit2) * dt
INIT ttransit1 = 0
```

INFLOWS:

```
input_to_transit1 = input
```

OUTFLOWS:

```
input_to_transit2 = ttransit1/one_third_of_third_delay
one_third_of_third_delay = 2/3.
input = STEP(100,2)
```

4.11 Examples

4.11.1 Population Model

In this example the stock–flow diagram of population model is derived from the causal loop diagram of population model in example 3.4.1 in Chap. 3. In the causal loop diagram, population is a state variable (population level), and it is represented by a stock. The birth rate is an inflow (population/year) into the stock population, and the death rate is an outflow into stock population. The stock–flow diagram of a

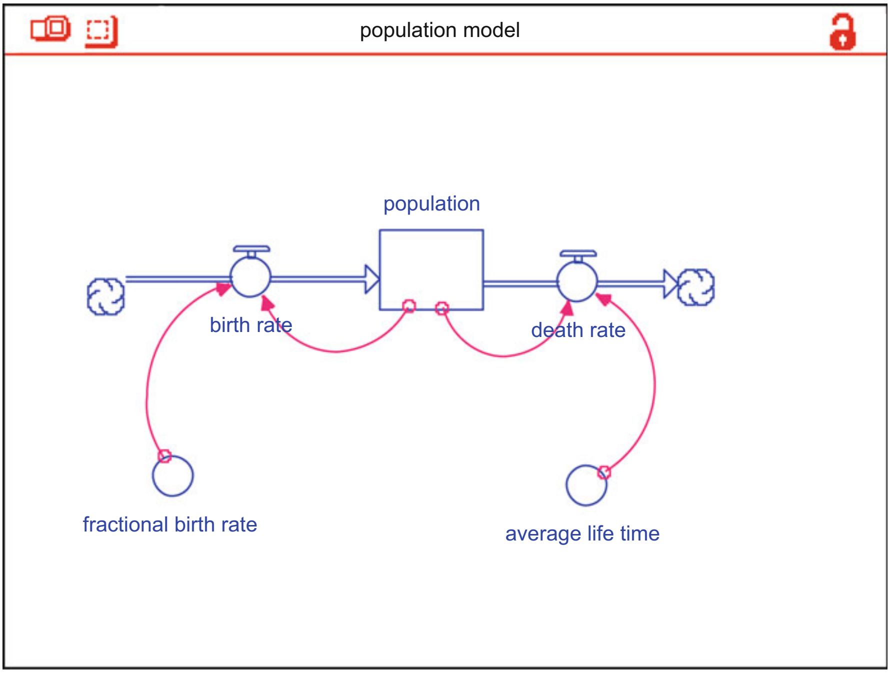


Fig. 4.16 Stock–flow diagram of a simple population model

simple population model derived from the causal loop diagram in example 3.4.1 in Chap. 3 is shown in Fig. 4.16, and the model consists of two feedback loops. The positive feedback loop consisting of population and birth generates population growth, and the negative loop consisting of population and death decreases the population.

Population is increased by births and decreased by deaths, and it is expressed as

```
population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 100
```

The birth is computed as a fixed percentage of population.

```
birth_rate = population*fractional_birth_rate
fractional_birth_rate = 0.03
```

The death is computed from population and average lifetime.

```
death_rate = population/average_life_time
average_life_time = 70
```

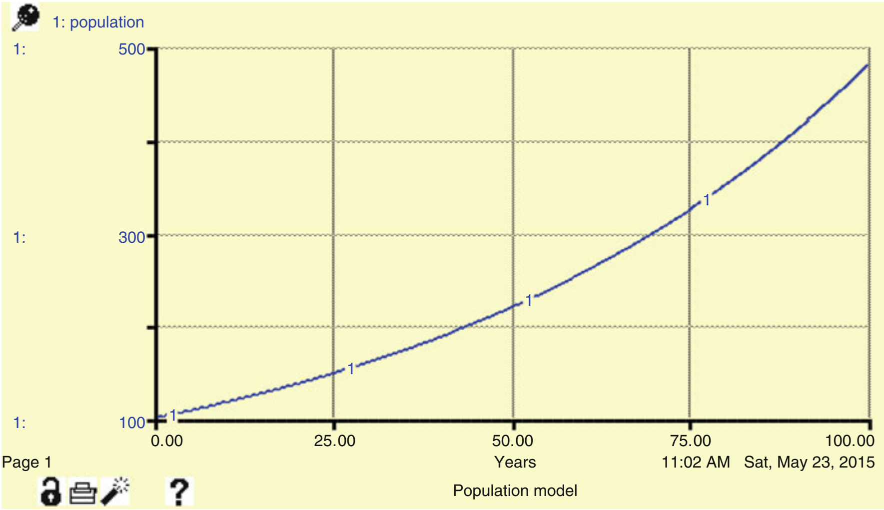


Fig. 4.17 Simulated population for a period of 100 years

Simulated population is shown in Fig. 4.17, and population grows by a fixed percentage exhibiting exponential growth. However, in practice the exponential growth cannot continue indefinitely. When the ultimate limit is approached, the negative loop becomes dominant.

STELLA model of the population is given below:

Population Model

```
population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 100
```

INFLOWS:

```
birth_rate = population*fractional_birth_rate
```

OUTFLOWS:

```
death_rate = population/average_life_time
average_life_time = 70
fractional_birth_rate = 0.03
```

4.11.2 Grain Storage System

Grains are basically stored to maintaining the quality for planting as a seed, continuity of supply and higher price. Here we consider the storage for grains at the retailer to iron out the price variations and provide consumer's welfare. The stock–flow diagram of simple grain storage system is shown in Fig. 4.18, and it consists of grain stock for consumers and grain on order to maintain desired supply of grain on order.

Grain stock is increased by receiving rate from grain on order and decreased by release rate from the grain stock.

```
grain_stock(t) = grain_stock(t - dt) + (receiving_rate - release_rate)
* dt
INIT grain_stock = 1000
```

Release rate depends on grain stock and release fraction.

```
release_rate = grain_stock*release_fraction
release_fraction = 0.025
```

Receiving rate depends on grain on order and receiving delay.

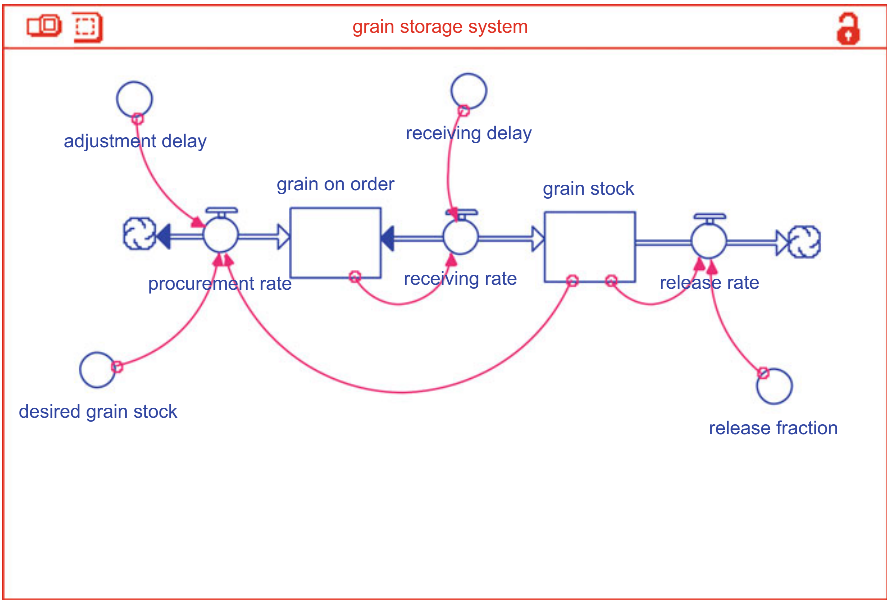


Fig. 4.18 Stock–flow diagram of grain storage system

```
receiving_rate = grain_on_order/receiving_delay
receiving_delay = 10
```

Grain on order is increased by procurement rate and decreased by receiving rate in the grain stock.

```
grain_on_order(t) = grain_on_order(t - dt) + (procurement_rate -
receiving_rate) * dt
INIT grain_on_order = 10000
```

The procurement rate depends on the difference between desired stock and current stock and procurement adjustment delay.

```
procurement_rate = (desired_grain_stock-grain_stock)/
adjustment_delay
adjustment_delay = 5
```

This model was simulated to see what happens to grain stock, receiving rate and procurement over time. Figure 4.19 shows the simulated grain stock, receiving rate and procurement over time. The grain stock, receiving rate and procurement rate oscillate over time due to addition of delay created by the supply line as represented by the grain on order and receiving rate.

STELLA model of the grain storage system is given below:

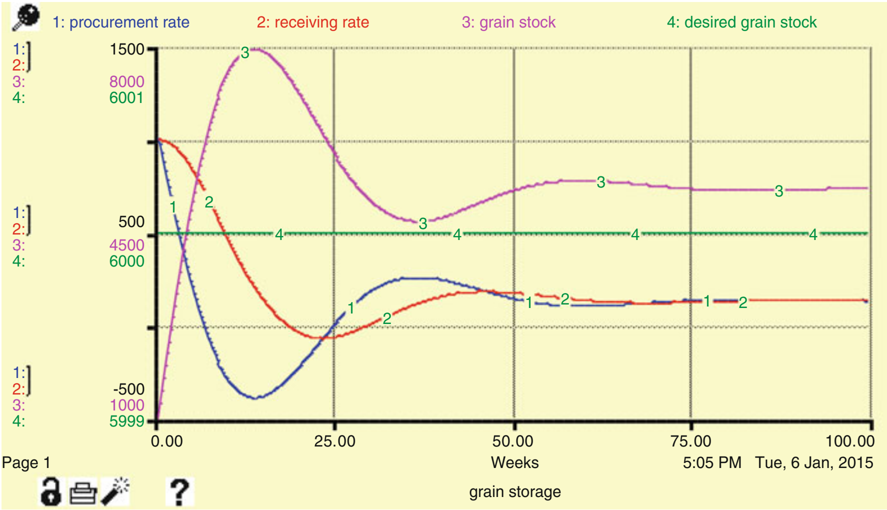


Fig. 4.19 Simulated grain stock, receiving rate and procurement over time

Grain Storage System

```
grain_on_order(t) = grain_on_order(t - dt) + (procurement_rate -
receiving_rate) * dt
INIT grain_on_order = 10000
```

INFLOWS:

```
procurement_rate = (desired_grain_stock-grain_stock)/
adjustment_delay
```

OUTFLOWS:

```
receiving_rate = grain_on_order/receiving_delay

grain_stock(t) = grain_stock(t - dt) + (receiving_rate - release_rate)
* dt
INIT grain_stock = 1000
```

INFLOWS:

```
receiving_rate = grain_on_order/receiving_delay
```

OUTFLOWS:

```
release_rate = grain_stock*release_fraction

adjustment_delay = 5
desired_grain_stock = 6000
receiving_delay = 10
release_fraction = 0.025
```

4.11.3 Food Security Model

Food security is a worldwide problem that has called the attention to governments and the scientific community. It particularly affects developing countries. The scientific community has had increasing concerns for strategic understanding and implementation of food security policies in developing countries, especially since the food crisis in the 1970s. The process of decision-making is becoming increasingly complex due to the interaction of multiple dimensions related to food security (Giraldo et al. 2008).

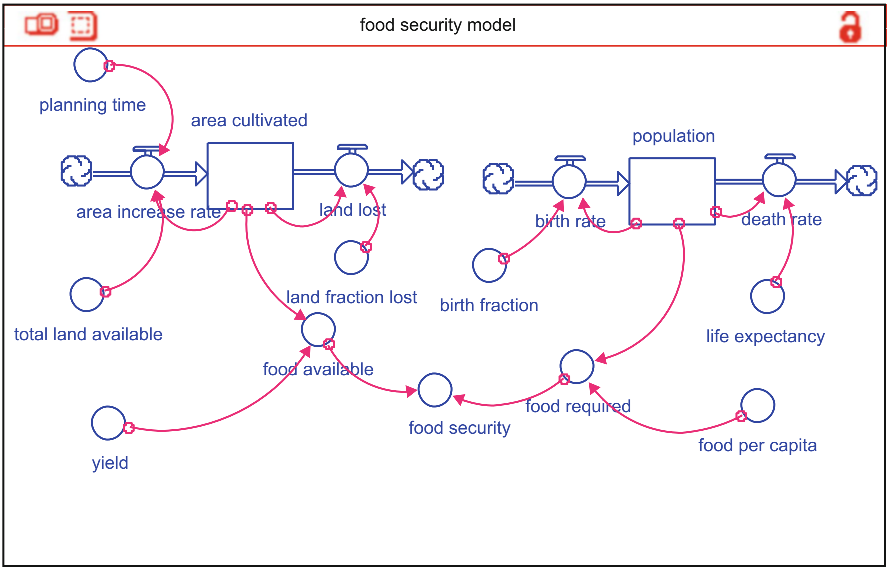


Fig. 4.20 Stock–flow diagram of food security model

In this model land suitable for rice production is a limited resource and the available land area suitable for rice production is converted into rice area. The rice area is also converted into industrial areas. The rice available is computed from area cultivated and yield. Population increases by birth and decreases by death. Food security defined as a ratio of rice available per capita and changes with both changes in food available and population. Figure 4.20 shows the stock–flow diagram of rice food security model.

Area cultivated is increased by transfer of land suitable for rice cultivation based on development policy of covering the land suitable for rice cultivation, and also the area cultivated is decreased by a discard rate of a fraction of rice area for housing, roads and highways and industries.

```
area_cultivated(t) = area_cultivated(t - dt) + (area_increase_rate - land_lost) * dt
INIT area_cultivated = 68000
```

Area increase rate is computed from land available for cultivation and planning time horizon.

```
area_increase_rate = MAX((total_land_available-area_cultivated)/planning_time,0)
total_land_available = 120000
planning_time = 15
```

Area lost rate is computed from area cultivated and lost fraction.

```
land_lost = area_cultivated*land_fraction_lost
land_fraction_lost = 0.00085
```

Food available depends on the yield of the crop rice (tons/ha) and area under rice cultivation.

```
food_available = area_cultivated*yield
yield = 3.2
```

Population level at any time t is computed from the population growth rate, and it is given by

```
population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 2800000
```

In this simple model, the birth rate is computed from population and birth fraction.

```
birth_rate = population*birth_fraction
birth_fraction = 0.025
```

And death rate is computed from population and life expectancy.

```
death_rate = population/life_expectancy
life_expectancy = 65
```

Food requirement depends on the per capita consumption of rice and population level, and it is computed as

```
food_required = population*food_per_capita
food_per_capita = 180/1000
```

Food security is defined as the ratio of rice production to rice requirement:

```
food_security = food_available/food_required
```

Food security level 1 means surplus food and less than 1 means shortage in food supply to lead healthy life.

Figure 4.21 shows the simulated area cultivated, area increase rate, land lost, population and food security in rice production for a simulation period of 100 years. The rice area initially increases till about 50 years and reaches the upper limit of available land suitable for rice and remains constant. The food security in rice increases till 25 years and then decreases due to increase in the population.

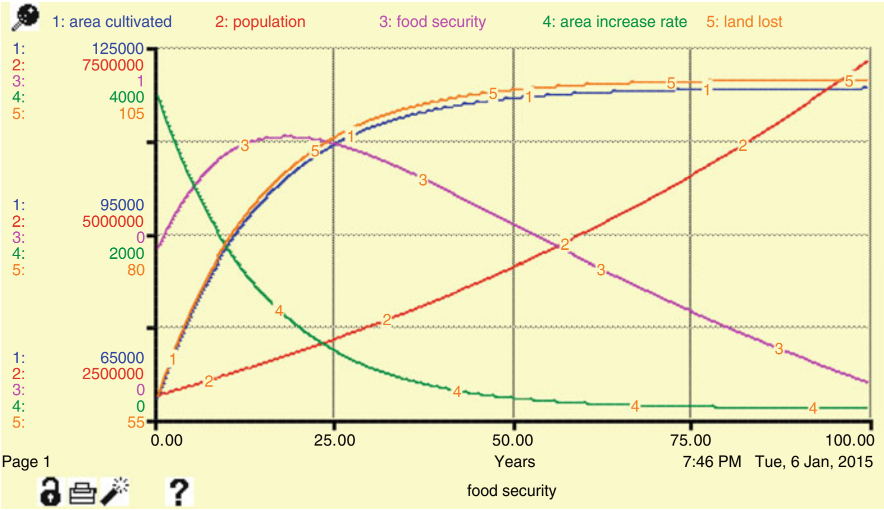


Fig. 4.21 Simulated area cultivated, area increase rate, land lost, population and food security

STELLA model of food security is given below:

Food Security Model

```
area_cultivated(t) = area_cultivated(t - dt) + (area_increase_rate -
land_lost) * dt
INIT area_cultivated = 68000
```

INFLOWS:

```
area_increase_rate = MAX((total_land_available-area_cultivated)/
planning_time,0)
```

OUTFLOWS:

```
land_lost = area_cultivated*land_fraction_lost
```

```
population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 2800000
```

INFLOWS:

```
birth_rate = population*birth_fraction
```

OUTFLOWS:

```
death_rate = population/life_expectancy

birth_fraction = 0.025
food_available = area_cultivated*yield
food_per_capita = 180/1000
food_required = population*food_per_capita
food_security = food_available/food_required
land_fraction_lost = 0.00085
life_expectancy = 65
planning_time = 15
total_land_available = 120000
yield = 3.2
```

4.11.4 Commodity Production Cycle Model

Agricultural commodities are sold in highly competitive markets whose prices change yearly, daily, hourly and even by the minute. Farmers are affected by fluctuations of price – good times bring him an increase in income, and depression causes his cash income to drop away to very little. The price received by the farmers is important not only to him; the rate of production depends on it to a large extent. In addition, pigs, and to some extent cattle and chickens, show fluctuations in price and supply of a persistent nature at a frequency consistent over long periods of time (Meadows 1970).

We formulate here a commodity production cycle model based on two feedback loops, a production and a consumption loop each trying to adjust inventory coverage to the desired level. Price links the supply and demand. Nerlove's formulation of expected price is incorporated (Nerlove 1958). If the price is high, this tends to reduce the consumption and increase the production after some time delay. This in turn, increases the inventory level, the price would fall. Similarly, if the price is too low, the consumption would increase to raise it back to the equilibrium. The stock–flow diagram of the commodity production cycle model is shown in Fig. 4.22.

In every commodity there will be stocks of products in physical forms and in many locations, and only production and consumption determine the inventory level.

```
distributor_inventory(t) = distributor_inventory(t - dt) + (supply_
rate - consumption_rate) * dt
INIT distributor_inventory = 6000
```

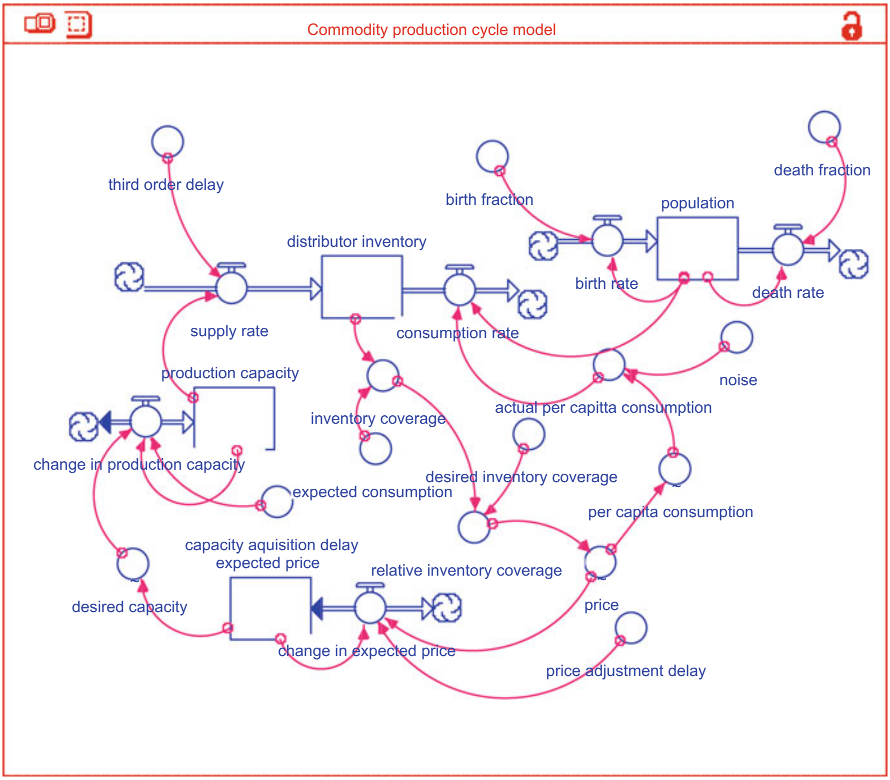


Fig. 4.22 Stock–flow diagram of the commodity production cycle model

The holdings of the inventory stocks of the commodity are concerned with length of time current inventory satisfy anticipated demand. The inventory coverage is simply the ratio of distributor inventory to expected consumption.

```
inventory_coverage = distributor_inventory/expected_consumption
```

Actual coverage is compared with desired coverage to determine the relative coverage as the ratio of inventory coverage to desired inventory coverage.

```
relative_inventory_coverage = inventory_coverage/
desired_inventory_coverage
desired_inventory_coverage = 1
```

When the relative inventory coverage increases, the price will fall, and conversely if the relative inventory coverage decreases, the price would increase. The relationship between price and relative inventory coverage is non-linear, and it is expressed by a graphical function.

```
price = GRAPH(relative_inventory_coverage)
(0.00, 100), (0.4, 94.0), (0.8, 80.0), (1.20, 50.0), (1.60, 20.0),
(2.00, 10.0)
```

We adopt the model of producer expectations as proposed by Nerlove (1958). The current rate of change in the expected price is proportional to the difference between recent expected price and recent actual price.

```
expected_price(t) = expected_price(t - dt) + (- change_in_expected_
price) * dt
INIT expected_price = 70

change_in_expected_price = (expected_price-price)/price_adjustment_
delay
```

Desired capacity is non-linearly related to expected price, and it is represented by a graphical function.

```
desired_capacity = GRAPH(expected_price)
(0.00, 0.00), (20.0, 40.0), (40.0, 200), (60.0, 1000), (80.0, 1200),
(100, 1280)
```

Production capacity is influenced by change in production capacity, and it is computed as

```
production_capacity(t) = production_capacity(t - dt) + (change_in_
production_capacity) * dt
INIT production_capacity = 600
```

Change in production capacity depends on desired capacity, present level of production capacity and capacity acquisition delay, and it is expressed as

```
change_in_production_capacity = (desired_capacity-production_
capacity)/capacity_aquisition_delay
capacity_aquisition_delay = 4
```

The model acknowledges a third-order delay due to biological, physical and meteorological factors in the supply of the commodity from initiation to final availability.

```
supply_rate = SMTH3(production_capacity,third_order_delay)
third_order_delay = 12
```

Consumption rate is the product of per capita consumption and population of consumers.

```
consumption_rate = population*actual_per_capita_consumption
```

Per capita consumption depends on the price, and it is non-linearly related to price. This relationship is given by graphical function.

```
per_capita_consumption = GRAPH(price)
(0.00, 7.00), (20.0, 6.00), (40.0, 4.00), (60.0, 2.00), (80.0, 1.00),
(100, 0.00)
```

Population is increased by birth and decreased by death:

```
population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 200
birth_rate = population*birth_fraction
death_rate = population*death_fraction

birth_fraction = 0.025/12
death_fraction = 0.008/12
```

The model was simulated to a step change in consumption with noise to address the stability of commodity production systems. Figure 4.23 shows the simulated production of price, supply rate and distributor inventory of the commodity

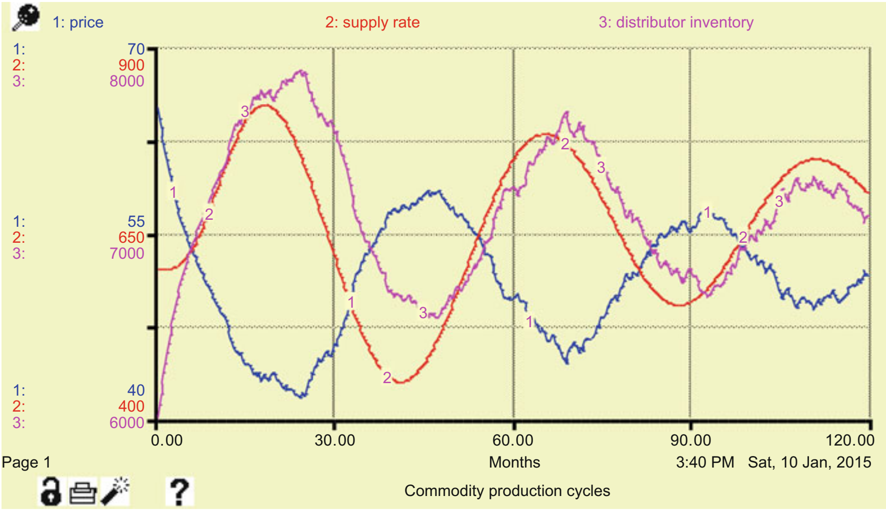


Fig. 4.23 Simulated price, supply rate and distributor inventory of the commodity production cycle model

production cycle model, and the simulated results exhibit periodicity and qualitatively reflect real-world behaviour.

STELLA model of the commodity production cycle model is given below:

Commodity Cycles

```
distributor_inventory(t) = distributor_inventory(t - dt) + (supply_
rate - consumption_rate) * dt
INIT distributor_inventory = 6000
```

INFLOWS:

```
supply_rate = SMTH3(production_capacity,third_order_delay)
```

OUTFLOWS:

```
consumption_rate = population*actual_per_capita_consumption

expected_price(t) = expected_price(t - dt) + (- change_in_expected_
price) * dt
INIT expected_price = 70
```

OUTFLOWS:

```
change_in_expected_price = (expected_price-price)/price_adjustment_
delay

population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 200
```

INFLOWS:

```
birth_rate = population*birth_fraction
```

OUTFLOWS:

```
death_rate = population*death_fraction

production_capacity(t) = production_capacity(t - dt) + (change_in_
production_capacity) * dt
INIT production_capacity = 600
```

INFLOWS:

```
change_in_production_capacity = (desired_capacity-
production_capacity)/capacity_aquisition_delay


actual_per_capita_consumption = per_capita_consumption*(1 + noise)
birth_fraction = 0.025/12
capacity_aquisition_delay = 4
death_fraction = 0.008/12
desired_inventory_coverage = 1
expected_consumption = 6000
inventory_coverage = distributor_inventory/expected_consumption
noise = RANDOM(−0.5,0.5,2374)*STEP(0.5,10)
price_adjustment_delay = 5
relative_inventory_coverage = inventory_coverage/
desired_inventory_coverage
third_order_delay = 12


desired_capacity = GRAPH(expected_price)
(0.00, 0.00), (20.0, 40.0), (40.0, 200), (60.0, 1000), (80.0, 1200),
(100, 1280)


per_capita_consumption = GRAPH(price)
(0.00, 7.00), (20.0, 6.00), (40.0, 4.00), (60.0, 2.00), (80.0, 1.00),
(100, 0.00)


price = GRAPH(relative_inventory_coverage)
(0.00, 100), (0.4, 94.0), (0.8, 80.0), (1.20, 50.0), (1.60, 20.0),
(2.00, 10.0)
```

4.11.5 Food Relief Model

Food relief is provided for humanitarian ground. This model examines what will happen if suddenly food relief of a poor country having shortage of food and relying greatly on food relief is cut off. Stock–flow diagram of the food relief model is shown in Fig. 4.24.

Population is increased by birth rate and decreased by death rate.

```
population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 100E06
```

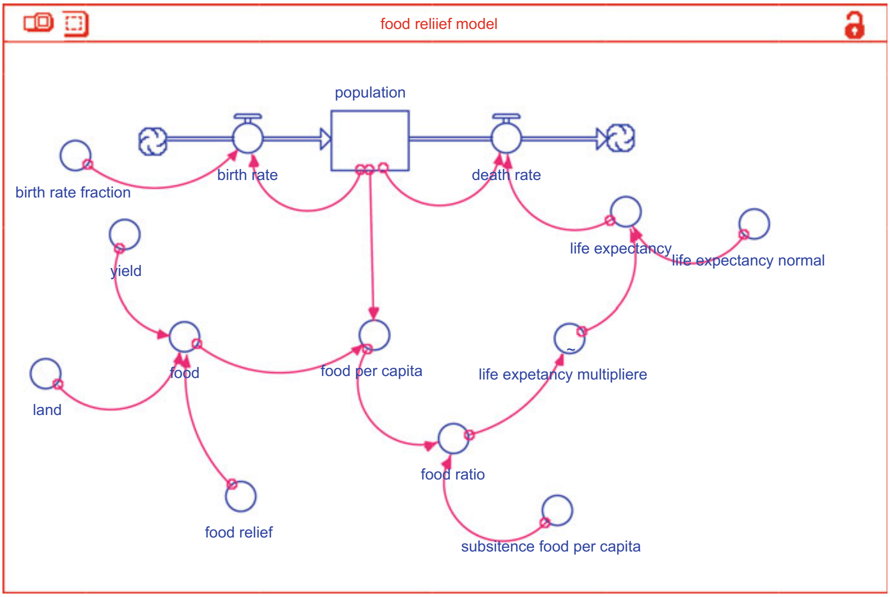


Fig. 4.24 Stock–flow diagram of the food relief model

Birth rate is assumed to depend on population and birth rate normal.

```
birth_rate=population*birth_rate_fraction
birth_rate_fraction=0.045
```

Death rate depends on population level, reference life expectancy and life expectancy multiplier.

```
death_rate=population/life_expectancy
```

Life expectancy is affected by food, and it is expressed in terms of life expectancy normal and life expectancy multiplier from food.

```
life_expectancy=life_expectancy_normal*life_expetancy_multipliere
life_expectancy_normal=45
```

Life expectancy multiplier is non-linearly related to food ratio, and it is expressed by graphical function.

```
life_expetancy_multiplier = GRAPH(food_ratio)
(0.00, 0.033), (0.313, 0.25), (0.625, 0.5), (0.938, 0.825), (1.25,
1.02), (1.56, 1.18), (1.88, 1.25), (2.19, 1.25), (2.50, 1.25)
```

Food ratio is defined as the ratio of food per capita to subsistence food per capita.

```
food_ratio = food_per_capita/subsitence_food_per_capita
subsitence_food_per_capita = 180
```

Food per capita is defined as the ratio of total food available to population.

```
food_per_capita = food/population
```

Food is the most crucial regulator of life expectancy, and it depends on total production of food and food relief available:

```
food = land*yield + food_relief
land = 7.4E06
yield = 2200
```

Food relief for humanitarian ground is considered to increase at the rate of 5000E5 kg/year, and it is interrupted after 50 years of continuous supply.

```
food_relief = IF(TIME) >= (50)THEN(0)ELSE(RAMP(5000E5,0))
```

RAMP function is used to provide continuous supply of relief.

Simulated population, birth rate, death rate and food per capita for continuous food relief for 50 years at a constant rate of 500E6 and then its interruption are shown in Fig. 4.25.

STELLA model of food relief is given below:

Food Relief Model

```
population(t) = population(t - dt) + (birth_rate - death_rate) * dt
INIT population = 100E06
```

INFLOWS:

```
birth_rate = population*birth_rate_fraction
```

OUTFLOWS:

```
death_rate = population/life_expectancy
```

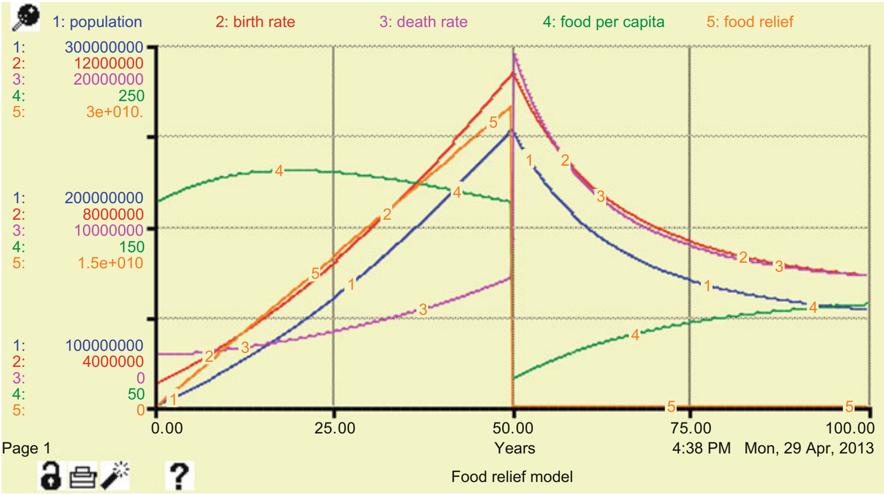


Fig. 4.25 Simulated population, birth rate, death rate and food per capita for continuous food relief for 50 years at a constant rate of 500E6 and then its interruption

```
birth_rate_fraction = 0.045
food = land*yield + food_relief
food_per_capita = food/population
food_ratio = food_per_capita/subsitence_food_per_capita
food_relief = IF(TIME)>=(50)THEN(0)ELSE(RAMP(5000E5,0))
land = 7.4E06
life_expectancy = life_expectancy_normal*life_expetancy_multipliere
life_expectancy_normal = 45
subsitence_food_per_capita = 180
yield = 2200


life_expetancy_multiplier = GRAPH(food_ratio)
(0.00, 0.033), (0.313, 0.25), (0.625, 0.5), (0.938, 0.825), (1.25, 1.02),
(1.56, 1.18), (1.88, 1.25), (2.19, 1.25), (2.50, 1.25)
```

4.11.6 Crop Livestock Model

Crop-based agriculture is the main source of livelihoods in low-income countries. When crop-based agriculture cannot support livelihoods, it is for the farmers to look for additional income-generating opportunities. In order to create livelihood, they must combine the capital endowments that they have access to and control, and livestock production is an important source of income in such situation to create livelihoods. The stock–flow diagram of the crop livestock model is shown in

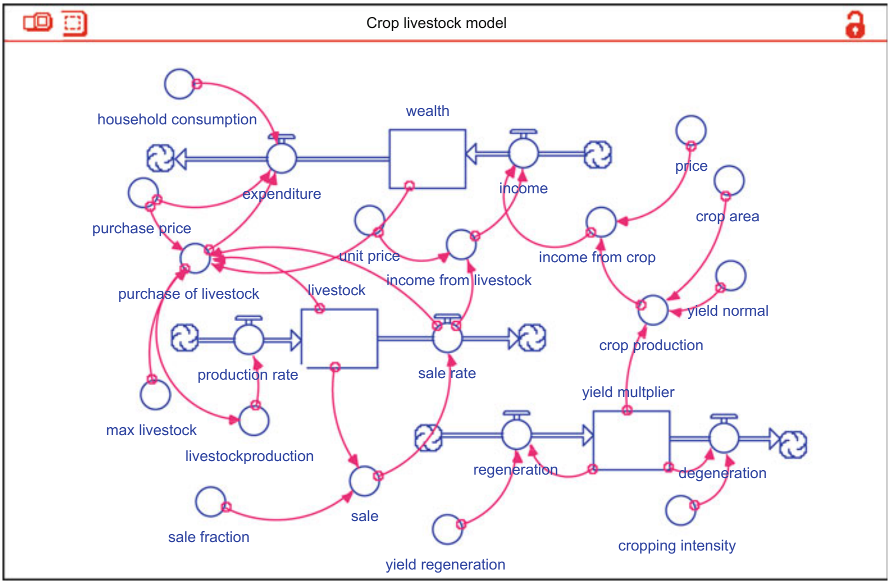


Fig. 4.26 The stock–flow diagram of the crop livestock model

Fig. 4.26. The model consists of a fixed amount of crop area and fixed number of family members for rearing livestock provided the family has some wealth as grant or bank loan to start the livestock husbandry.

As the crop area is limited, the crop production depends on the yield, and the crop production is computed from crop area, yield normal and yield multiplier. The effect of cropping intensity on yield, i.e. the effect of degeneration, and regeneration effect are assumed to be zero.

```
crop_production = crop_area*yield_normal*yield_multplier
crop_area = 0.5
yield_normal = 3.2
```

The wealth of the family increases from the income from crop production and also from the income from livestock and decreases by the expenditure on household consumption and the expenditure on purchase of livestock.

```
wealth(t) = wealth(t - dt) + (income - expenditure) * dt
INIT wealth = 10000
```

The income is derived from crop and from sale of livestock.

```
income = income_from_crop + income_from_livestock
income_from_crop = crop_production*price
income_from_livestock = sale_rate*unit_price
```

The expenditure comes from household consumption and from the purchase of livestock. The purchase of livestock is considered when it is less than maximum capacity of rearing the livestock.

```
expenditure = purchase_of_livestock*purchase_price
+ household_consumption
purchase_of_livestock = IF(INT(wealth/purchase_price))<=
(max_livestock + sale_rate-livestock)THEN(INT(wealth/
purchase_price))ELSE(0)
purchase_price = 15000
household_consumption = 75000
```

The number of livestock is increased after certain maturation delay by addition from purchase and decreased from sale of the matured livestock.

```
livestock(t) = livestock(t - dt) + (production_rate - sale_rate) * dt
INIT livestock = 4
```

The model was simulated to see what happens to the wealth of the household when some livestock is provided to a small marginal farming family. Simulated wealth, livestock, crop production, income from crop production and income from livestock are shown in Fig. 4.27. The household can increase his income from livestock considerably, but it is after some time delay.

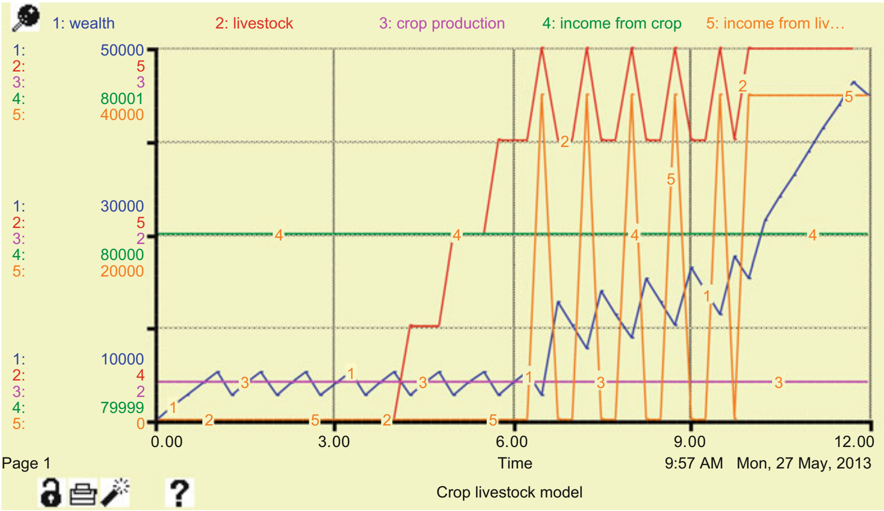


Fig. 4.27 Simulated wealth, livestock, crop production, income from crop production and income from livestock

STELLA model of the crop livestock system is given below:

Crop Livestock Model

```
livestock(t) = livestock(t - dt) + (production_rate - sale_rate) * dt
INIT livestock = 4
```

INFLOWS:

```
production_rate = livestockproduction
```

OUTFLOWS:

```
sale_rate = sale
```

```
wealth(t) = wealth(t - dt) + (income - expenditure) * dt
INIT wealth = 10000
```

INFLOWS:

```
income = income_from_crop + income_from_livestock
```

OUTFLOWS:

```
expenditure = purchase_of_livestock*purchase_price
+ household_consumption
```

```
yield_multplier(t) = yield_multplier(t - dt) + (regeneration - degener-
ation) * dt
INIT yield_multplier = 1
```

INFLOWS:

```
regeneration = yield_multplier*yield_regeneration
```

OUTFLOWS:

```
degeneration = yield_multplier*cropping_intensity
```

```
cropping_intensity = 0
crop_area = 0.5
```

```
crop_production = crop_area*yield_normal*yield_multplier
household_consumption = 75000
income_from_crop = crop_production*price
income_from_livestock = sale_rate*unit_price
livestockproduction = DELAY(purchase_of_livestock,3)
max_livestock = 8
price = 50000
purchase_of_livestock = IF(INT(wealth/purchase_price)) <=
(max_livestock + sale_rate-livestock)THEN(INT(wealth/
purchase_price))ELSE(0)
purchase_price = 15000
sale = INT(livestock*sale_fraction)
sale_fraction = 0.2
unit_price = 35000
yield_normal = 3.2
yield_regeneration = 0
```

4.11.7 Penaeid Shrimp Model

Shrimp farming plays a significant role in the economy of many developing countries in Asia. Due to the economic importance of penaeid shrimp worldwide, particularly in aquaculture, a great effort to understand the growth biology of *Penaeus* spp. has been made in recent years. This includes studies on the influence of environmental factors such as temperature (Wyban et al. 1995; Miao and Tu 1996; Ye et al. 2003; López-Martínez et al. 2003), salinity (Lemos et al. 2001) and lunar cycles (Griffith and Wigglesworth 1993) on shrimp growth. These valuable information may be synthesised and integrated into general models in order to simulate the growth of *Penaeus* individuals. Growth simulations for penaeid shrimp are based on single-equation models such as the von Bertalanffy (Wang 1998; Xiao 1999) and Gompertz growth equations (Jackson and Wang 1998; Xiao 1999), bioenergetic models (Mishra et al.2002) or the Fuzzy Inductive Reasoning (FIR) approach (Carvajal and Nebot 1998). This example presents a system dynamics computer model of penaeid shrimp in STELLA adapted from a computer model developed by Franco et al. (2006).

An individual-based model is presented to simulate the growth of a penaeid shrimp from the juvenile stage to the end of the life cycle. Shrimp larval stages (nauplius, zoea and mysis) have a very short duration (less than 3 weeks) (Haywood et al. 1995) and are not included in the model. The growth model includes five physiological processes, ingestion, assimilation, elimination, respiration and female reproduction, and is forced by water temperature and food availability. The stock–flow diagram of the model is shown in Fig. 4.28.

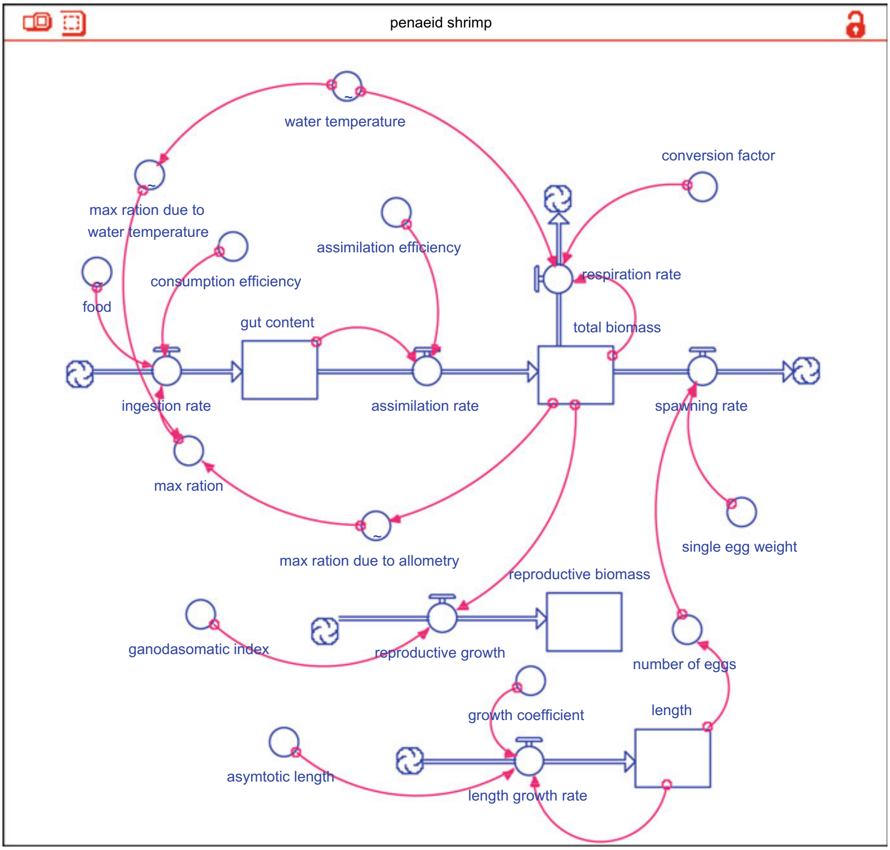


Fig. 4.28 Stock–flow diagram of the penaeid shrimp model

Ingestion

Daily ingestion is simulated after Ivlev (1945) (Eq. (4.23)). In this equation the quantity of food ingested by shrimp increases with the concentration of food available (expresses as dry weight: DW), up to a maximum ration, $R_{\max}$.

$$I = R_{\max}\left(1 - e^{-kF}\right) \tag{4.23}$$

where

$I =$ Ingestion (gDW day^{-1})
$R_{\max} =$ Maximum ration (gDW day^{-1})
$k =$ Consumption efficiency (mgDW^{-1} m^{2})
$F =$ Food (mgDW m^{-2})

The food intake as a function of time is expressed as

```
food = GRAPH(TIME)
(0.00, 695), (29.2, 750), (58.3, 750), (87.5, 730), (117, 720),
(146, 710), (175, 710), (204, 735), (233, 685), (263, 630), (292, 665),
(321, 720), (350, 710)
```

R_{max} is a function of both allometry and water temperature (Eq. (4.24)):

$$R_{max} = f(B_t)f(T) \tag{4.24}$$

where

B_t = Total biomass (gDW)
T = Temperature (°C)
R_{max} is computed from both allometry and water temperature as

```
max_ration = max_ration_due_to_allometry*max_ration_due_to_water_
temperature*2.5
```

Water temperature varies with time and these variations with time are expressed as

```
water_temperature = GRAPH(TIME)
(0.00, 27.3), (29.2, 29.5), (58.3, 30.5), (87.5, 26.5), (117, 27.3),
(146, 28.8), (175, 31.5), (204, 29.5), (233, 25.8), (263, 27.5),
(292, 27.8), (321, 29.5), (350, 29.8)
```

The maximum ration due to allometry was calculated using Eq. (4.24), obtained for *P. subtilis* (Nunes and Parsons 2000):

$$f(B_t) = 0.09(\Phi B_t)^{0.62} \tag{4.25}$$

where

Φ = Conversion factor from dry weight to fresh weight (dimensionless)

The relationship in Eq. (4.25) is simplified, and the maximum ration due to allometry expressed is as a function of total biomass.

```
max_ration_due_to_allometry = GRAPH(total_biomass)
(1.00, 0.15), (1.90, 0.243), (2.80, 0.327), (3.70, 0.393), (4.60, 0.474),
(5.50, 0.543), (6.40, 0.615), (7.30, 0.663), (8.20, 0.708), (9.10, 0.735),
(10.0, 0.75)
```

The effect of water temperature on food consumption was simulated as a positive relationship over a given temperature range, followed by a decrease of food intake beyond the optimal temperature (Niu et al. 2003; Wasielesky et al. 2003; Kumlu and Kir 2005). Wasielesky et al. (2003) found that food consumption increased with temperature but stabilised from 26 °C to 32 °C. Additionally, Hewitt and Duncan (2001) observed that the mean daily consumption of *P. japonicus* was highest at 32 °C (range 28–36 °C). A second-order polynomial was used to describe this relationship in the model, based on data from Wyban et al. (1995) and on the assumption that the shrimp ration is maximal at 32 °C:

$$f(T) = \frac{-0.02T^2 + 1.44T - 17.41}{R_{32}} \tag{4.26}$$

where

R_{32} = Ration at 32 °C

The relationship in Eq. (4.24) is as a function of water temperature.

```
max_ration_due_to_water_temperature = GRAPH(water_temperature)
(25.0, 0.902), (25.7, 0.92), (26.4, 0.951), (27.1, 0.99), (27.8, 1.02),
(28.5, 1.06), (29.2, 1.08), (29.9, 1.08), (30.6, 1.09), (31.3, 1.10),
(32.0, 1.10)
```

Several authors refer that larger sizes and faster growth rates are observed in females (Dredge 1990; Chow and Sandifer 1991; Buckworth 1992); therefore, the model also takes sexual dimorphism into account. This difference was represented as a lower food intake for males than females (Hansford and Hewitt 1994). Growth of male animals (expressed as carapace length) was estimated using the von Bertalanffy equation, parameterised from Le Reste and Marcille (1976):

$$L_t = L_\infty \left[1 - e^{K(t-t_0)}\right] \tag{4.27}$$

where

L_{t} = Carapace length at time t (mm)
L_∞ = Asymptotic carapace length (mm)
K = Growth coefficient (day^{-1})
t = Age (day)
t_0 = Starting age (day)

The Eq. (4.27) can be expressed in the form of differentia equation as

$$\frac{dL_{\mathrm{t}}}{dt} = K(L_\alpha - L_{\mathrm{t}}) \tag{4.28}$$

In STELLA this equation is

```
length(t) = length(t - dt) + (length_growth_rate) * dt
INIT length = 0.0
```

And length growth rate is expressed as

```
length_growth_rate = MAX(0,(growth_coefficient*(asymptotic_length-
length)))
asymptotic_length = 29.9
growth_coefficient = 0.013
```

The growth curve expressed as carapace length was converted to fresh weight and used to parameterise the maximum ration equation for male penaeids by tuning the coefficients to optimally correlate model biomass outputs to the growth curve:

$$f(B_{\mathrm{t}}) = 0.06(\Phi B_{\mathrm{t}})^{0.68} \tag{4.29}$$

Assimilation/Faeces Production

Part of the food ingested is assimilated in the gut, and the remaining fraction is eliminated as faeces. The amount of food assimilated is dependent on the gut content and assimilation efficiency (Eq. 4.30).

$$A = GA_{\mathrm{e}} \tag{4.30}$$

where

A = Assimilation (g DW day^{-1})
G = Gut content (g DW)
A_{e} = Assimilation efficiency (day^{-1})

Respiration

Shrimp metabolic losses are assumed to be due to oxygen consumption (respiration) and dependent on the individual biomass and temperature. Respiration was simulated following the equation derived by Dall (1986) for *P. esculentus* (Eq. 4.31), which gives the weight-specific respiration rate:

$$M_{\mathrm{w}} = 0.05e^{0.07T}(\Phi B_{\mathrm{t}})^{-.0.185} \tag{4.31}$$

where

M_{w} = Weight-specific oxygen consumption (day^{-1})

The weight-specific respiration was then multiplied by the dry weight of the animal to give the total respiration, M, expressed as g DW day^{-1}.

Gut Content and Total Biomass

The balance between ingestion and assimilation determines the gut content (Eq. 4.32.):

$$\frac{dG}{dt} = R_{\max}\left(1 - e^{-kF}\right) - GA_{\mathrm{e}} \tag{4.32}$$

where the first term on the right-hand side corresponds to the ingestion and the second to the assimilation.

Equation (4.32) in STELLA is

```
gut_content(t) = gut_content(t - dt) + (ingestion_rate - assimilation_
rate) * dt
INIT gut_content = 0.5
The ingestion rate is
ingestion_rate = max_ration*(1.0-EXP
(−consumption_efficiency*food))
consumption_efficiency = 0.12
```

The assimilate rate is

```
assimilation_rate = gut_content*assimilation_efficiency
assimilation_efficiency = 0.8
```

The change in total individual biomass (Eq. 4.33) is thus

$$\frac{dB_{\mathrm{t}}}{dt} = GA_{\mathrm{e}} - M - WS \tag{4.33}$$

where

M = Respiration (gDW day^{-1})
S = Spawning (gDW day^{-1})

Equation (4.33) in STELLA is

```
total_biomass(t) = total_biomass(t - dt) + (assimilation_rate - respiration_
rate - spawning_rate) * dt
INIT total_biomass = 1
```

The respiration rate is

```
respiration_rate = 0.05*EXP(0.07*water_temperature)*
((total_biomass*conversion_factor)^(−0.185))*total_biomass
```

The spawning rate is

```
spawning_rate = number_of_eggs*single_egg_weight
single_egg_weight = 2.0E-6
```

Reproduction and Non-somatic Biomass

To describe female reproduction, two processes were considered: maturation and spawning. The gonadosomatic index is employed to simulate gonad growth as it is widely used to assess the maturation state in these animals (Cha et al. 2002). A constant rate of gonad growth over the maturation period was considered. The non-somatic biomass may be described according to Eq. (4.34):

$$\frac{dB_g}{dt} = B_t G_{SI} \tag{4.34}$$

where

B_g = Reproductive (non-somatic) biomass (gDW)
G_{SI} = Gonadosomatic index (day^{-1})

Equation (4.34) in integral form in STELLA is

```
reproductive_biomass(t) = reproductive_biomass(t - dt) + (reproductive_
growth) * dt
INIT reproductive_biomass = .0001
```

The reproductive growth is

```
reproductive_growth = total_biomass*ganodasomatic_index
ganodasomatic_index = .05
```

The somatic tissue biomass B_s may then be calculated as $B_t - B_g$. The loss of biomass due to spawning (S) was calculated by multiplying the number of eggs produced by the mean weight of a single egg (Eq. 4.35):

$$N = 9.3{C_L}^{2.8} \tag{4.35}$$

where

N = Number of eggs produced (day^{-1})
C_L = Carapace length (mm)

This relation (4.35) in STELLA is
number_of_eggs = 9.3*(length^2.8)

$$S = NE_w$$

where

E_w = Single egg weight (gDW)

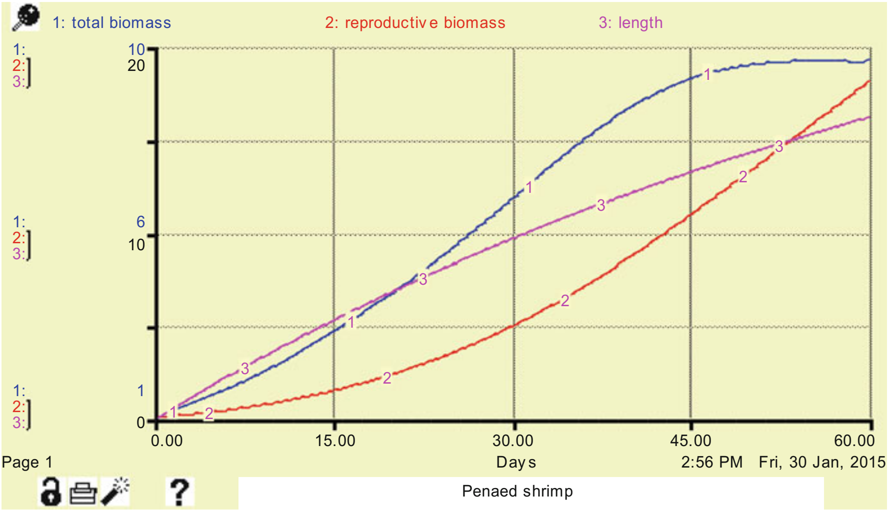


Fig. 4.29 Simulated total biomass, reproductive biomass and length of penaeid shrimp

Figure 4.29 shows the simulated shrimp growth curve, expressed as fresh weight. The model reproduces the typical pattern of growth of a penaeid shrimp, characterised by a rapid weight gain during the juvenile stage followed by the achievement of asymptotic length of adults (Dall et al. 1990). The individual reaches an asymptotic length after 6–8 months, which is in accordance with data from Rothlisberg (1998).The sexual dimorphism is confirmed by a larger size and a faster growth rate of females than males.

STELLA model of the penaeid shrimp growth is given below:

Penaeid Shrimp

```
gut_content(t) = gut_content(t - dt) + (ingestion_rate - assimilation_
rate) * dt
INIT gut_content = 0.5
```

INFLOWS:

```
ingestion_rate = max_ration*(1.0-EXP(−consumption_efficiency*food))
```

OUTFLOWS:

```
assimilation_rate = gut_content*assimilation_efficiency
```

```
length(t) = length(t - dt) + (length_growth_rate) * dt
INIT length = 0.0
```

INFLOWS:

```
length_growth_rate = MAX(0,(growth_coefficient*(asymptotic_length-
length)))

reproductive_biomass(t) = reproductive_biomass(t - dt) + (reproductive_
growth) * dt
INIT reproductive_biomass = .0001
```

INFLOWS:

```
reproductive_growth = total_biomass*ganodasomatic_index

total_biomass(t) = total_biomass(t - dt) + (assimilation_rate -
respiration_rate - spawning_rate) * dt
INIT total_biomass = 1
```

INFLOWS:

```
assimilation_rate = gut_content*assimilation_efficiency
```

OUTFLOWS:

```
respiration_rate = 0.05*EXP(0.07*water_temperature)*
((total_biomass*conversion_factor)^(−0.185))*total_biomass
spawning_rate = number_of_eggs*single_egg_weight

assimilation_efficiency = 0.8
asymptotic_length = 29.9
consumption_efficiency = 0.12
conversion_factor = 5
ganodasomatic_index = .05
growth_coefficient = 0.013
max_ration = max_ration_due_to_allometry*max_ration_due_to_water_
temperature*2.5
number_of_eggs = 9.3*(length^2.8)
single_egg_weight = 2.0E-6

food = GRAPH(TIME)
(0.00, 695), (29.2, 750), (58.3, 750), (87.5, 730), (117, 720),
(146, 710), (175, 710), (204, 735), (233, 685), (263, 630), (292, 665),
(321, 720), (350, 710)
```

```
max_ration_due_to_allometry = GRAPH(total_biomass)
(1.00, 0.15), (1.90, 0.243), (2.80, 0.327), (3.70, 0.393), (4.60, 0.474),
(5.50, 0.543), (6.40, 0.615), (7.30, 0.663), (8.20, 0.708), (9.10, 0.735),
(10.0, 0.75)

max_ration_due_to_water_temperature = GRAPH(water_temperature)
(25.0, 0.902), (25.7, 0.92), (26.4, 0.951), (27.1, 0.99), (27.8, 1.02),
(28.5, 1.06), (29.2, 1.08), (29.9, 1.08), (30.6, 1.09), (31.3, 1.10),
(32.0, 1.10)

water_temperature = GRAPH(TIME)
(0.00, 27.3), (29.2, 29.5), (58.3, 30.5), (87.5, 26.5), (117, 27.3),
(146, 28.8), (175, 31.5), (204, 29.5), (233, 25.8), (263, 27.5),
(292, 27.8), (321, 29.5), (350, 29.8)
```

4.11.8 Crop Irrigation Model

Planning and management of crop irrigation systems require development of analytical models in order to facilitate analysis. The problem is a complex bioeconomic system. System dynamics model of crop irrigation system can be used to determine the quantity and timing of irrigation water supply. Figure 4.30 shows the stock–flow diagram of a simple crop irrigation model. This model provides a framework in which demand and benefits of irrigation may be quantified to aid in irrigation policy planning. Any plant simulation model should include (1) a method of estimating evapotranspiration, (2) a method of estimating soil moisture levels in the root zone and (3) a provision of a means of relating crop growth in each time period to the incidence and severity of moisture stress in that period.

The variations of the reference evaporation with development stage of the crop are a non-linear relationship, and it is expressed by a graphical function.

```
evaporation = GRAPH(TIME)
(0.00, 3.80), (11.0, 4.20), (22.0, 4.60), (33.0, 1.10), (44.0, 2.40),
(55.0, 2.30), (66.0, 2.10), (77.0, 2.30), (88.0, 2.70), (99.0, 3.40),
(110, 3.00), (121, 3.20)
```

Potential evapotranspiration is computed from reference evaporation and crop factor.

```
potential_evapotranspiration = evaporation*crop_factor
```

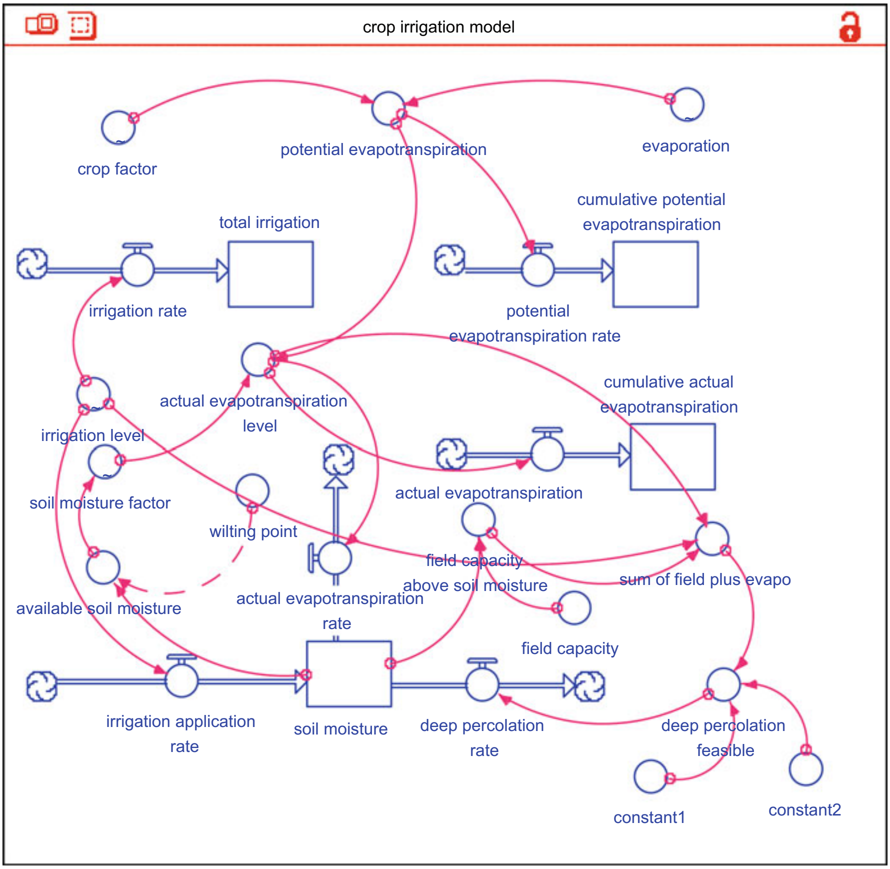


Fig. 4.30 Stock–flow diagram of crop irrigation model

The crop factor with the development stage of the crop is a non-linear relationship, and it is expressed by a graphical function.

```
crop_factor = GRAPH(TIME)
(0.00, 0.3), (12.7, 0.35), (25.5, 0.4), (38.2, 0.55), (50.9, 0.65),
(63.6, 0.85), (76.4, 1.10), (89.1, 1.20), (102, 1.10), (115, 1.05),
(127, 0.9), (140, 0.75)
```

Cumulative potential evapotranspiration is the accumulation of the potential evapotranspiration during the crop production period.

```
cumulative_potential_evapotranspiration(t) =
cumulative_potential_evapotranspiration(t - dt) + (potential_
evapotranspiration_rate) * dt
INIT cumulative_potential_evapotranspiration = 0.0
```

Actual evapotranspiration is evaluated from potential evapotranspiration and soil moisture factor.

```
actual_evapotranspiration = actual_evapotranspiration__level
actual_evapotranspiration__level = potential_evapotranspiration*
soil_moisture_factor
```

Cumulative actual evapotranspiration is the accumulation of the actual evapotranspiration during the crop production period.

```
cumulative_actual_evapotranspiration(t) =
cumulative_actual_evapotranspiration(t - dt)
+ (actual_evapotranspiration) * dt
INIT cumulative_actual_evapotranspiration = 0.0
```

The soil moisture factor is computed from the relation between soil moisture factor and available soil moisture, and it is expressed by a graphical function.

```
soil_moisture_factor = GRAPH(available_soil_moisture)
(0.00, 0.00), (9.00, 0.03), (18.0, 0.06), (27.0, 0.09), (36.0, 0.12),
(45.0, 0.16), (54.0, 0.19), (63.0, 0.23), (72.0, 0.26), (81.0, 0.32),
(90.0, 0.38), (99.0, 0.45), (108, 0.53), (117, 0.62), (126, 0.72),
(135, 0.86), (144, 0.95), (153, 1.00), (162, 1.00), (171, 1.00),
(180, 1.00)
```

The irrigation provided during the development stage of the crop is expressed by a graphical function.

```
irrigation_level = GRAPH(TIME)
(7.00, 0.00), (8.00, 26.8), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00),
(12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 27.0), (16.0, 0.00),
(17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00),
(22.0, 27.4), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00),
(27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 13.8),
(32.0, 0.00)
```

Total irrigation is the accumulation of the irrigation during the crop production period.

```
total_irrigation(t) = total_irrigation(t - dt) + (irrigation_rate) * dt
INIT total_irrigation = 0.0
```

The deep percolation is computed from the consideration that depletion must not take place in unfeasible values, and this is implemented using logical function.

```
deep_percolation__feasible = IF(sum_of_field_plus_evapo = constant2)
THEN(constant1)ELSE(−sum_of_field_plus_evapo)
```

```
sum_of_field_plus_evapo = field_capacity_above_soil_moisture
+ actual_evapotranspiration__level-irrigation_level
field_capacity_above_soil_moisture = field_capacity-soil_moisture
field_capacity = 260
constant1 = 0.0
constant2 = 0.0
```

Soil moisture level at any time is computed from the soil moisture level at previous time, plus irrigation and minus actual evapotranspiration and deep percolation

```
soil_moisture(t) = soil_moisture(t - dt) + (irrigation_application__
rate - actual_evapotranspiration__rate - deep_percolation__rate) * dt
INIT soil_moisture = 240
```

Simulated soil moisture and cumulative actual evapotranspiration are shown in Fig. 4.31. The data and parameters of this model were adopted from Bala et al. (1988). Simulated soil moisture and cumulative actual evapotranspiration agree well with the values of the field level study reported by Bala et al. (1988).

STELLA model of the crop irrigation model is given below:

Crop Irrigation Model

```
cumulative_actual_evapotranspiration(t) = cumulative_actual_
evapotranspiration(t - dt) + (actual_evapotranspiration) * dt
INIT cumulative_actual_evapotranspiration = 0.0
```

INFLOWS:

```
actual_evapotranspiration = actual_evapotranspiration__level
```

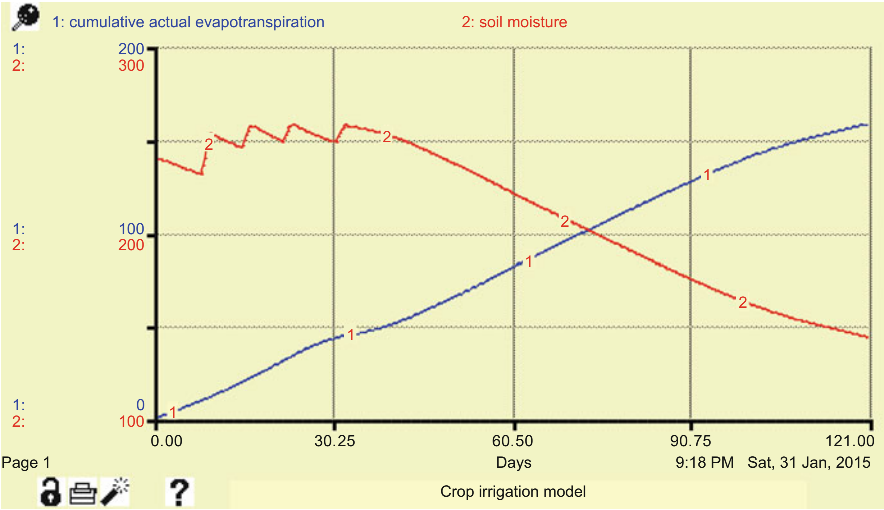


Fig. 4.31 Simulated soil moisture and cumulative actual evapotranspiration

```
cumulative_potential_evapotranspiration(t) =
cumulative_potential_evapotranspiration(t - dt) + (potential_
evapotranspiration_rate) * dt
INIT cumulative_potential_evapotranspiration = 0.0
```

INFLOWS:

```
potential_evapotranspiration_rate = potential_evapotranspiration
```

```
soil_moisture(t) = soil_moisture(t - dt) + (irrigation_application__
rate - actual_evapotranspiration__rate - deep_percolation__rate) * dt
INIT soil_moisture = 240
```

INFLOWS:

```
irrigation_application__rate = irrigation_level
```

OUTFLOWS:

```
actual_evapotranspiration__rate = actual_evapotranspiration__level
deep_percolation__rate = deep_percolation__feasible
```

```
total_irrigation(t) = total_irrigation(t - dt) + (irrigation_rate) * dt
INIT total_irrigation = 0.0
```

INFLOWS:

```
irrigation_rate = irrigation_level

actual_evapotranspiration__level = potential_evapotranspiration*soil_
moisture_factor
available_soil_moisture = soil_moisture-wilting_point
constant1 = 0.0
constant2 = 0.0
deep_percolation__feasible = IF(sum_of_field_plus_evapo = constant2)
THEN(constant1)ELSE(−sum_of_field_plus_evapo)
field_capacity = 260
field_capacity_above_soil_moisture = field_capacity-soil_moisture
potential_evapotranspiration = evaporation*crop_factor
sum_of_field_plus_evapo = field_capacity_above_soil_moisture
+ actual_evapotranspiration__level-irrigation_level
wilting_point = 80

crop_factor = GRAPH(TIME)
(0.00, 0.3), (12.7, 0.35), (25.5, 0.4), (38.2, 0.55), (50.9, 0.65),
(63.6, 0.85), (76.4, 1.10), (89.1, 1.20), (102, 1.10), (115, 1.05),
(127, 0.9), (140, 0.75)

evaporation = GRAPH(TIME)
(0.00, 3.80), (11.0, 4.20), (22.0, 4.60), (33.0, 1.10), (44.0, 2.40),
(55.0, 2.30), (66.0, 2.10), (77.0, 2.30), (88.0, 2.70), (99.0, 3.40),
(110, 3.00), (121, 3.20)

irrigation_level = GRAPH(TIME)
(7.00, 0.00), (8.00, 26.8), (9.00, 0.00), (10.0, 0.00), (11.0, 0.00),
(12.0, 0.00), (13.0, 0.00), (14.0, 0.00), (15.0, 27.0), (16.0, 0.00),
(17.0, 0.00), (18.0, 0.00), (19.0, 0.00), (20.0, 0.00), (21.0, 0.00),
(22.0, 27.4), (23.0, 0.00), (24.0, 0.00), (25.0, 0.00), (26.0, 0.00),
(27.0, 0.00), (28.0, 0.00), (29.0, 0.00), (30.0, 0.00), (31.0, 13.8),
(32.0, 0.00)

soil_moisture_factor = GRAPH(available_soil_moisture)
(0.00, 0.00), (9.00, 0.03), (18.0, 0.06), (27.0, 0.09), (36.0, 0.12),
(45.0, 0.16), (54.0, 0.19), (63.0, 0.23), (72.0, 0.26), (81.0, 0.32),
(90.0, 0.38), (99.0, 0.45), (108, 0.53), (117, 0.62), (126, 0.72),
(135, 0.86), (144, 0.95), (153, 1.00), (162, 1.00), (171, 1.00),
(180, 1.00)
```

4.11.9 Pollution Model

Pollution is the action that causes environmental degradation. Yes, pollution is one of the causes of degradation and also the pollution generated affects the quality of life. Environmental degradation due to pollution caused by human actions can be viewed in terms of population and pollution normal due to human action. Environmental considerations are now increasingly becoming important components of planning and computer modelling can provide greater insight of the systems and better understanding of the control measures to be adopted. Stock–flow diagram of the pollution model is shown Fig. 4.32.

Pollution level increases by human activities and decreases by absorption.

```
pollution(t) = pollution(t - dt) + (genration_rate - absorption_rate) * dt
INIT pollution = 10000000 Pollution generation is taken as population
multiplied by pollution normal.
```

```
genration_rate = population*pollution_normal
pollution_normal = 0.25
```

Pollution absorption depends on the existence of pollution to be absorbed. It depends on the natural processes that will determine the amount absorbed in a specified time. Pollution absorption is determined by the amount of pollution divided by absorption time.

```
absorption_rate = pollution/pollution_absorption_time
```

The pollution absorption time depends on the pollution ratio, and it is represented as a graphical function.

```
pollution_absorption_time = GRAPH(pollution_ratio)
(0.00, 0.6), (10.0, 2.50), (20.0, 5.00), (30.0, 8.00), (40.0, 11.5),
(50.0, 15.5), (60.0, 20.0)
```

Pollution ratio is defined as the ratio of pollution level to pollution standard.

```
pollution_ratio = pollution/pollution_standard
pollution_standard = 15000000
```

Population is increased by birth rate and decreased by death rate.

```
population(t) = population(t - dt) + (births - deaths) * dt
INIT population = 100000000
```

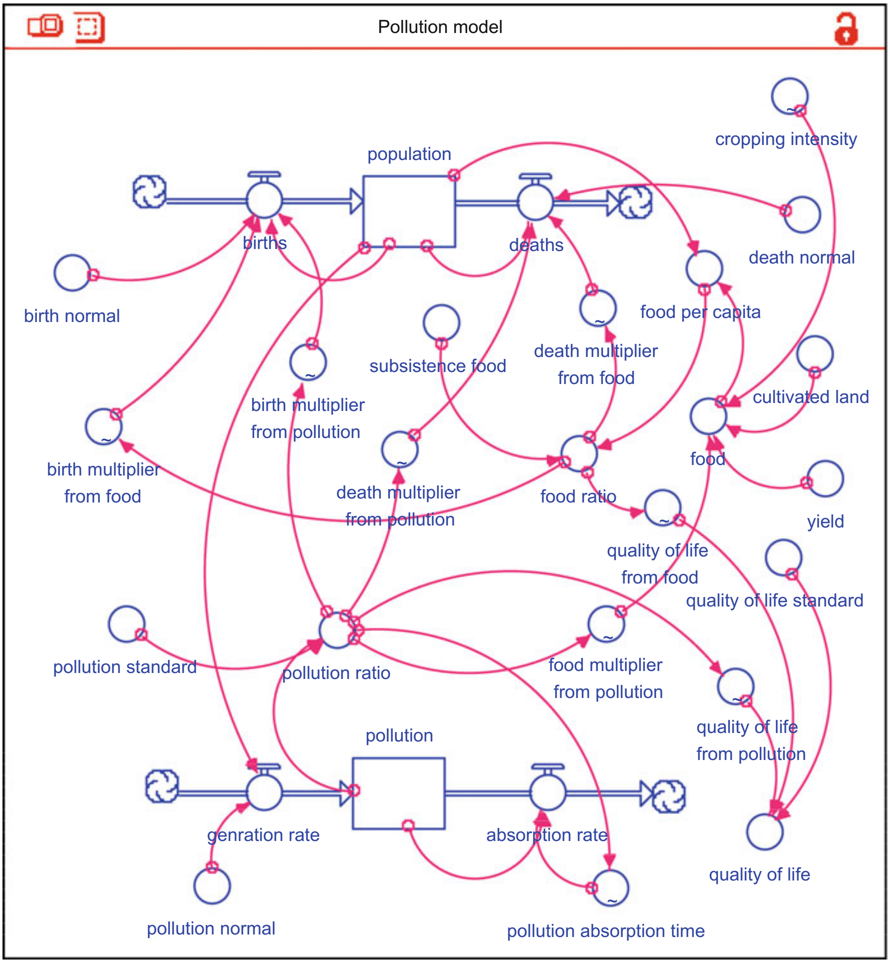


Fig. 4.32 Stock–flow diagram of the pollution model

Actual birth rate is computed from population level, birth rate normal, birth rate from food multiplier and birth rate from pollution multiplier.

```
births = population*birth_normal*birth_multiplier__from_food*birt-
h_multiplier__from_pollution
birth_normal = 0.04
```

Birth multiplier from food is non-linearly related to food ratio, and it is presented graphically. The food ratio is defined as the ratio of food per capita to food per capita standard.

```
birth_multiplier__from_food = GRAPH(food_ratio)
(0.00, 0.00), (1.00, 1.00), (2.00, 1.60), (3.00, 1.90), (4.00, 2.00)

food_ratio = food_per_capita/subsistence_food
subsistence_food = 180
```

Birth multiplier from pollution is non-linearly related to pollution ratio, and it is presented graphically.

```
birth_multiplier__from_pollution = GRAPH(pollution_ratio)
(0.00, 1.02), (10.0, 0.9), (20.0, 0.7), (30.0, 0.4), (40.0, 0.25),
(50.0, 0.15), (60.0, 0.1)

food_ratio = food_per_capita/subsistence_food
subsistence_food = 180
```

Death rate depends upon population level, death rate normal, death rate from food multiplier and death rate from pollution multiplier.

```
deaths = population*death_normal*death_multiplier__from_food*death_
multiplier__from_pollution
death_normal = .028
```

Food can be a powerful indicator of population. The non-linear relationship between death rate multiplier from food and food ratio is represented graphically.

```
death_multiplier__from_food = GRAPH(food_ratio)
(0.00, 30.0), (0.25, 3.00), (0.5, 2.00), (0.75, 1.40), (1.00, 1.00),
(1.25, 0.7), (1.50, 0.6), (1.75, 0.5), (2.00, 0.5)
```

Death multiplier from pollution is non-linearly related to pollution, and this relationship is expressed graphically.

```
death_multiplier__from_pollution = GRAPH(pollution_ratio)
(0.00, 0.92), (10.0, 1.30), (20.0, 3.30), (30.0, 4.80), (40.0, 6.80),
(50.0, 9.20), (60.0, 9.50)
```

Food per capita is defined as the ratio of food available to population.

```
food_per_capita = food/population
```

The food availability depends on cultivated land, yield, cropping intensity and food from pollution multiplier.

```
food = cultivated_land*yield*cropping_intensity*food_multiplier__f-
rom_pollution
cultivated_land = 7400000
yield = 2200
```

Food multiplier pollution is non-linearly related to pollution, and it is expressed graphically.

```
food_multiplier__from_pollution = GRAPH(pollution_ratio)
(0.00, 1.02), (10.0, 0.9), (20.0, 0.65), (30.0, 0.35), (40.0, 0.2),
(50.0, 0.1), (60.0, 0.05)
```

The cropping intensity changes with time, and it is expressed graphically as a function of time.

```
cropping_intensity = GRAPH(TIME)
(0.00, 1.75), (10.0, 1.80), (20.0, 1.90), (30.0, 2.00), (40.0, 2.30),
(50.0, 2.50)
```

Food has the most powerful influence on quality of life. The quality of life multiplier from food depends on food, and it is expressed graphically.

```
quality_of_life_from_food = GRAPH(food_ratio)
(0.00, 0.00), (1.00, 1.00), (2.00, 1.80), (3.00, 2.40), (4.00, 2.70)
```

Pollution affects the quality of life and the quality of life multiplier from pollution depends on pollution, and it is expressed graphically.

```
quality_of_life__from_pollution = GRAPH(pollution_ratio)
(0.00, 1.05), (10.0, 0.85), (20.0, 0.6), (30.0, 0.3), (40.0, 0.15),
(50.0, 0.05), (60.0, 0.02)
```

Quality of life is used here as the measure of performance of the system. It is computed as a multiplication of quality of life standard multiplied by multipliers derived from food and pollution.

```
quality_of _life = quality_of_life_standard*quality_of_life_from_
food*quality_of_life__from_pollution
quality_of_life_standard = 1
```

Simulated population, food per capita, pollution and quality of life are shown in Fig. 4.33.

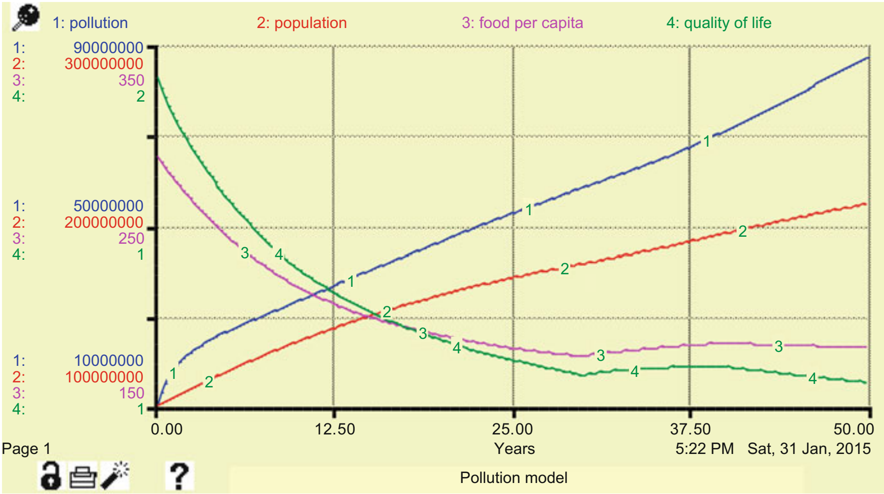


Fig. 4.33 Simulated population, food per capita, pollution and quality of life

Simulated results show that pollution increases as the population increases which is the observed phenomenon. Also food per capita decreases with time. As a result quality of life decreases with time.

STELLA model of pollution is given below:

Pollution Model

```
pollution(t) = pollution(t - dt) + (genration_rate - absorption_rate) * dt
INIT pollution = 10000000
```

INFLOWS:

```
genration_rate = population*pollution_normal
```

OUTFLOWS:

```
absorption_rate = pollution/pollution_absorption_time
```

```
population(t) = population(t - dt) + (births - deaths) * dt
INIT population = 100000000
```

INFLOWS:

```
births = population*birth_normal*birth_multiplier__from_food*birth_
multiplier__from_pollution
```

OUTFLOWS:

```
deaths = population*death_normal*death_multiplier__from_food*death_
multiplier__from_pollution

birth_normal = 0.04
cultivated_land = 7400000
death_normal = .028
food = cultivated_land*yield*cropping_intensity*food_multiplier__
from_pollution
food_per_capita = food/population
food_ratio = food_per_capita/subsistence_food
pollution_normal = 0.25
pollution_ratio = pollution/pollution_standard
pollution_standard = 15000000
quality_of_life = quality_of_life_standard*quality_of_life_from_
food*quality_of_life__from_pollution
quality_of_life_standard = 1
subsistence_food = 180
yield = 2200

birth_multiplier__from_food = GRAPH(food_ratio)
(0.00, 0.00), (1.00, 1.00), (2.00, 1.60), (3.00, 1.90), (4.00, 2.00)

birth_multiplier__from_pollution = GRAPH(pollution_ratio)
(0.00, 1.02), (10.0, 0.9), (20.0, 0.7), (30.0, 0.4), (40.0, 0.25),
(50.0, 0.15), (60.0, 0.1)

cropping_intensity = GRAPH(TIME)
(0.00, 1.75), (10.0, 1.80), (20.0, 1.90), (30.0, 2.00), (40.0, 2.30),
(50.0, 2.50)

death_multiplier__from_food = GRAPH(food_ratio)
(0.00, 30.0), (0.25, 3.00), (0.5, 2.00), (0.75, 1.40), (1.00, 1.00),
(1.25, 0.7), (1.50, 0.6), (1.75, 0.5), (2.00, 0.5)

death_multiplier__from_pollution = GRAPH(pollution_ratio)
(0.00, 0.92), (10.0, 1.30), (20.0, 3.30), (30.0, 4.80), (40.0, 6.80),
(50.0, 9.20), (60.0, 9.50)
```

```
food_multiplier__from_pollution = GRAPH(pollution_ratio)
(0.00, 1.02), (10.0, 0.9), (20.0, 0.65), (30.0, 0.35), (40.0, 0.2),
(50.0, 0.1), (60.0, 0.05)

pollution_absorption_time = GRAPH(pollution_ratio)
(0.00, 0.6), (10.0, 2.50), (20.0, 5.00), (30.0, 8.00), (40.0, 11.5),
(50.0, 15.5), (60.0, 20.0)

quality_of_life_from_food = GRAPH(food_ratio)
(0.00, 0.00), (1.00, 1.00), (2.00, 1.80), (3.00, 2.40), (4.00, 2.70)

quality_of_life__from_pollution = GRAPH(pollution_ratio)
(0.00, 1.05), (10.0, 0.85), (20.0, 0.6), (30.0, 0.3), (40.0, 0.15),
(50.0, 0.05), (60.0, 0.02)
```

Exercises

Exercises 4.1 Draw the stock–flow diagram for the simple biological model of a fish shown in Fig. 4.34.

Exercises 4.2 The birth rate of population of a country is 0.045 for adults, and the average life expectancy is 50 years. After a delay of 5 years, they reach school age, and their education takes 10 years. Assume initial number of babies, school children and adults to be 2500, 30,000 and 90,000, respectively. Draw the causal loop and stock–flow diagram of the system and plot the dynamic responses of the model.

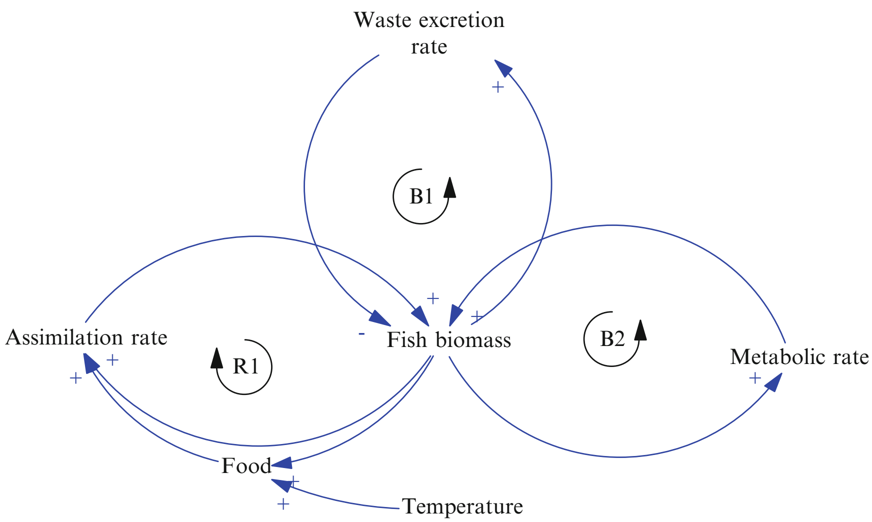


Fig. 4.34 Causal loop diagram of a simple biological model of fish

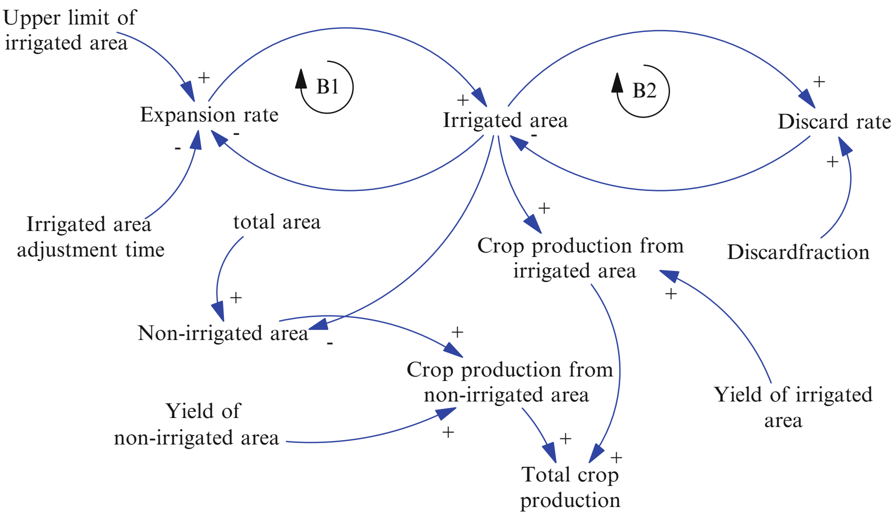


Fig. 4.35 Causal loop diagram of crop production model

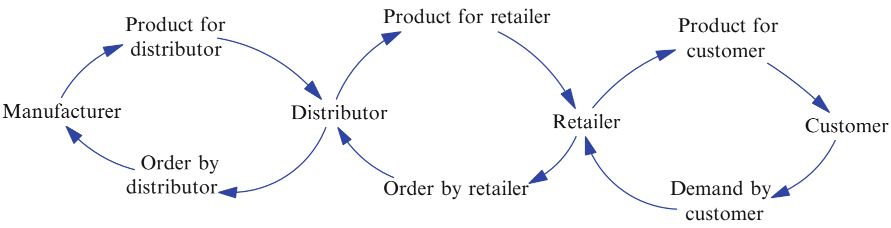


Fig. 4.36 Causal loop diagram of a simple food supply chain

Exercises 4.3 Draw stock–flow diagram and plot dynamic response of the crop production model shown in Fig. 4.35. Assume initial irrigated area = 1.22E6 ha, irrigated area adjustment time = 10 years, upper limit of irrigated area =7.4E6 ha, total area = 7.4E6 ha, yield of irrigated area = 2800 kg/ha, yield of nonirrigated area = 1300 kg/ha and average life time of irrigation device =15 years.

Exercises 4.4 Causal loop diagram of simple supply chain of food product is shown in Fig. 4.36. Elaborate the causal loop diagram and convert it into stock–flow diagram and plot dynamic response of the supply chain for a product of your locality.

Exercises 4.5 Identify the causal loops and draw stock–flow diagram, and plot dynamic response of food grain storage management system as shown in Fig. 4.37. Use food supply = rural food stock + released stock and food supply = 1.275E6 tons, rural storage, rural stock = 1E6 tons, govt. storage = 0.725E6 tons, grain on order = 0.05E6 tons, security reserve =

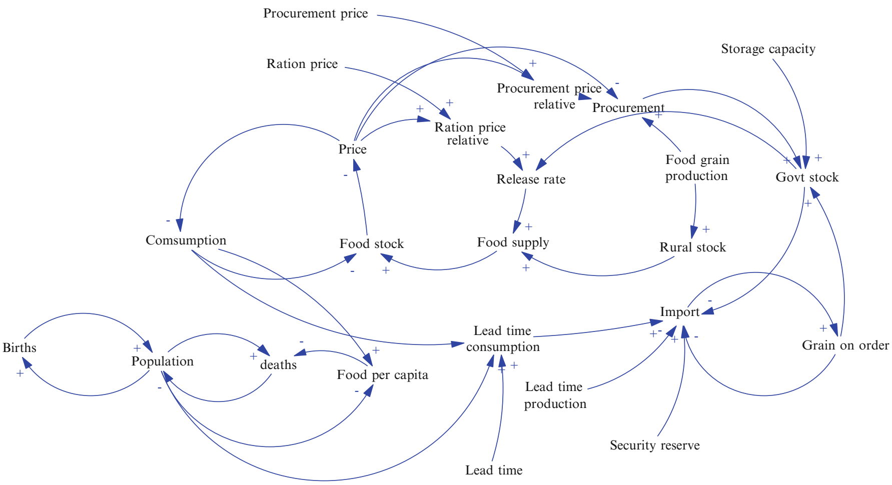


Fig. 4.37 Food grain storage management system

1.5E6 tons, delay in ordering grain =2 days and delay in receiving grain = 3 days, population = 1E8, birth rate normal = 0.003, death rate normal = 0.00125. Lead time = 3 days, ration price = 0.80 \$/kg and procurement price = 1.20 \$/kg.

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Parameter Estimation and Sensitivity Analysis

5

The computer model based on stock–flow diagram discussed in Chap. 4 needs estimation of parameters and sensitivity analysis of the parameters. This chapter presents parameter estimation and sensitivity analysis. Parameter estimation using aggregated and disaggregated data are discussed. Estimation of table function, conversion factor and normal fractional flow rate is highlighted with examples. Sensitivity analysis and size of solution interval have been explained, and some examples of sensitivity analysis have been presented.

5.1 Introduction

System dynamics modelling offers an attractive tool for policy testing and evaluation. Policy alternatives can be simulated by computer. But simulation requires a model, and model building is still an art in many respects. After formulation of dynamic hypothesis, including mapping stock and flow diagram of a model, the parameters of the model should be either assigned numerical values or expressed in terms of equations with parameter values to simulate the model. The estimation of parameters is one of the important steps in model building. The correct estimation of parameters is required to provide plausible behaviours of the system over time. Also sensitivity analysis of the parameters is important to assess how the parameter values affect the system behaviour and how important it is to determine the parameters accurately. This chapter discusses parameter estimation techniques and sensitivity analysis.

5.2 Parameter Estimation Techniques

Parameter estimation techniques can be classified on the basis of assumption and data. The data may be categorised in two categories which are disaggregated and aggregated data.

B.K. Bala et al., *System Dynamics*, Springer Texts in Business and Economics,
DOI 10.1007/978-981-10-2045-2_5

5.3 Estimation Using Disaggregated Data

Many system dynamics studies including the studies of Forrester use parameters determined on the basis of descriptive information obtained from the participants in the systems modelling. Such information is disaggregated data.

For an example of parameters that can be estimated with disaggregated data, consider an equation below which represents death rate of the population model:

$$\text{Death rate(person/year)} = \frac{\text{Population (person)}}{\text{Average life expectancy (year)}} \tag{5.1}$$

In STELLA

death_rate = population/average_life_expectancy

The model assumes a constant average life expectancy, so that every year, 1/average life expectancy of the population is dead. Average life expectancy can be estimated many ways from disaggregate data, and the equation is not used for computation of average life expectancy. The equation is only needed to define the function in the model. There are many ways to find the average life expectancy. One time-consuming approach is to make a survey to find the number of people dead and their ages at the time of death. A second approach is to examine the ages of the people alive and observe the age at which very few people are alive. The third approach is to ask the oldest people who have observed a lot of deaths, about the ages at which most of the old people died. The fourth approach is to examine the health conditions and extrapolate life time expectancy. The fifth approach is to study the descriptive history of population, food and society, etc., and can have some idea of life expectancy. There may be some other means also to find the life expectancy. The data discussed above come from records, a history book, expert testimony and the modeller's own day-to-day experience. Thus, disaggregated data are by far the most abundant source of knowledge about real systems.

Another example is organic degradation equation in paddy production model as represented below:

$$\text{Organic degradation (tonne/year)} = \frac{\text{Cumilative organic (tonne)}}{\text{Organic degradation time (year)}} \tag{5.2}$$

The model estimates a constant degradation time. Every year, 1/organic degradation time of cumulative organic is degraded. As discussed above, the same approach also can be used to estimate the degradation time either by survey, experiment, historical data or any other sources of information.

5.3.1 Table Functions

Many of the relationships between the variables in complex systems are non-linear especially in socio-economic systems, and such non-linear relationships are expressed in the form of table functions. This section describes a less straightforward but a common technique to estimate the table function. The table function seems to be a formidable estimation problem, but it can be broken into subproblems, which are:

1. Estimate the value and the slope of the function at (a) one extreme, (b) the normal value, and (c) the other extreme.
2. Connect these known values and slopes with a smooth curve.

Once these subproblems are solved, the table function is known within a narrow range of values.

For example, consider market price and inventory relationship of the commodity production cycle model.

The non-linear relationships between the price and inventory in STELLA are:

```
price = GRAPH(inventory)
(0.00, 100), (1000, 96.5), (2000, 94.0), (3000, 90.0), (4000, 80.0),
(5000, 70.0), (6000, 50.0), (7000, 30.5), (8000, 20.0), (9000, 16.0),
(10000, 10.0)
```

To estimate table function for price, first consider the extreme condition of zero inventory, where the price would be maximum. After that, consider the normal condition when there is some moderate quantity of inventory and the table function has a negative slope. At the other extreme, the inventory is large, and the price is very low. Now draw a smooth curve through the estimated points (Fig. 5.1). Thus, solving the subproblems of extreme conditions, and connecting known points with smooth curves, allows the modeller to estimate a non-linear table function with confidence.

For another example, consider the relationship between soil moisture factor and available soil moisture of the crop irrigation model.

The non-linear relationships between soil moisture factor and available soil moisture in STELLA are:

```
soil_moisture_factor = GRAPH(available_soil_moisture)
(0.00, 0.00), (9.00, 0.03), (18.0, 0.06), (27.0, 0.09), (36.0, 0.12),
(45.0, 0.16), (54.0, 0.19), (63.0, 0.23), (72.0, 0.26), (81.0, 0.32),
(90.0, 0.38), (99.0, 0.45), (108, 0.53), (117, 0.62), (126, 0.72),
(135, 0.86), (144, 0.95), (153, 1.00), (162, 1.00), (171, 1.00), (180, 1.00)
```

To estimate table function for soil moisture factor, first consider the extreme condition of zero available soil moisture, where the soil moisture factor would be zero. Now consider the normal conditions when there are some moderate values

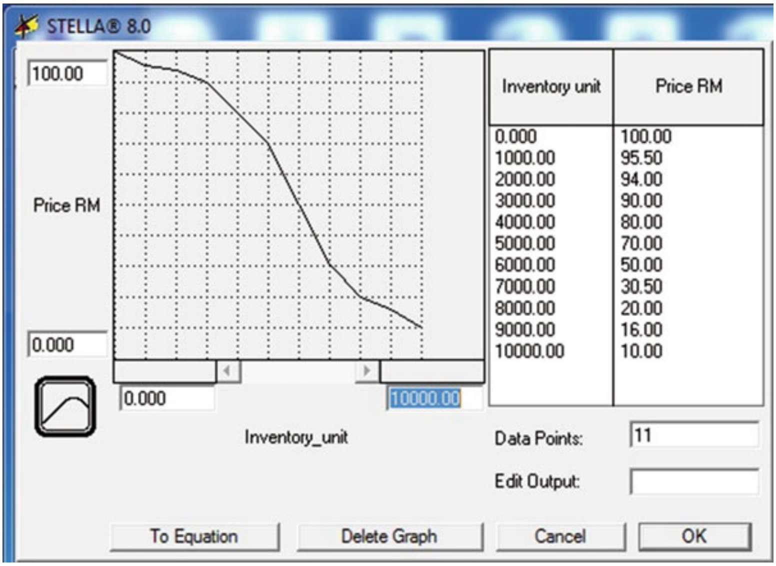

Fig. 5.1 Price versus inventory relationship

and the table function has a positive slope. At the other extreme, the available soil moisture is large and the soil moisture factor is unity. Now draw a smooth curve through the estimated points (Fig. 5.2). Thus, solving the subproblems of extreme conditions, and connecting known points with smooth curves, allows the modeller to estimate a non-linear table function with confidence.

The non-linear relationships between rice per capita consumption and gross domestic product per capita can be expressed in the form of table function. This relationship is illustrated in Fig. 5.3.

```
rice_per_capita_consumption = GRAPH(GDP_per_capita)  (4000,  83.7),
(4500, 84.8), (5000, 85.6), (5500, 85.8), (6000, 85.7), (6500, 85.0),
(7000, 84.0), (7500, 82.4), (8000, 80.5), (8500, 78.0), (9000, 75.2)
```

Table functions can also be estimated in normalised form. Consider a cumulative input such as chemical and organic fertilisers in food production. In the long term, the cumulative application of these inputs will affect land fertility, and the fertility will change over time non-linearly. The use of inputs depends on technology and variety of the crop. To develop meaningful relationship between the land fertility effect and cumulative input, it is better to normalise the relationship. In order to normalise the cumulative input, the cumulative input should be divided by its initial value and the land fertility by initial land fertility to determine the fertility effect. After that, the effect of cumulative input on land fertility can be expressed in normalised form as in Fig. 5.4.

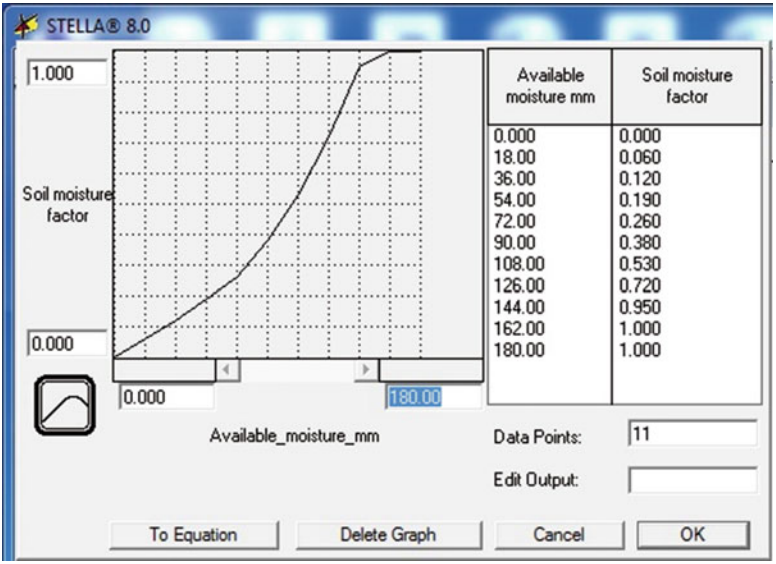

Fig. 5.2 Soil moisture factor versus available soil moisture relationship

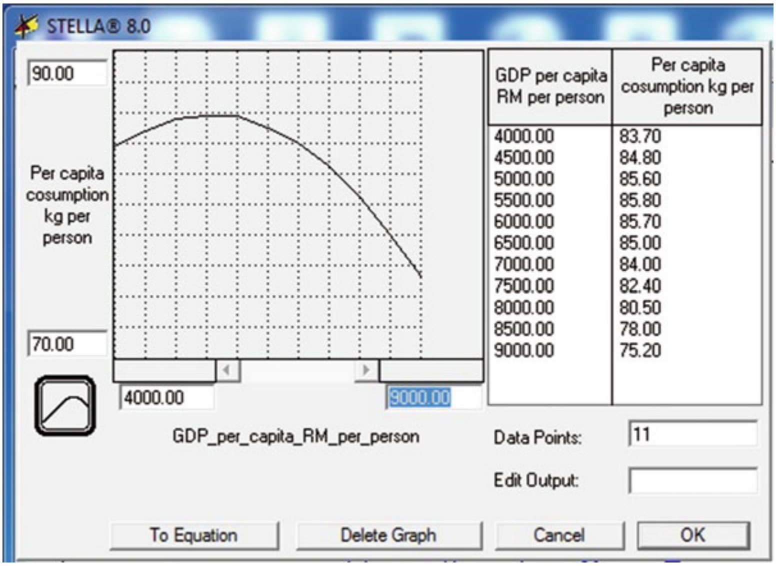

Fig. 5.3 Rice per capita consumption (kg/person) versus GDP per capita (RM/person)

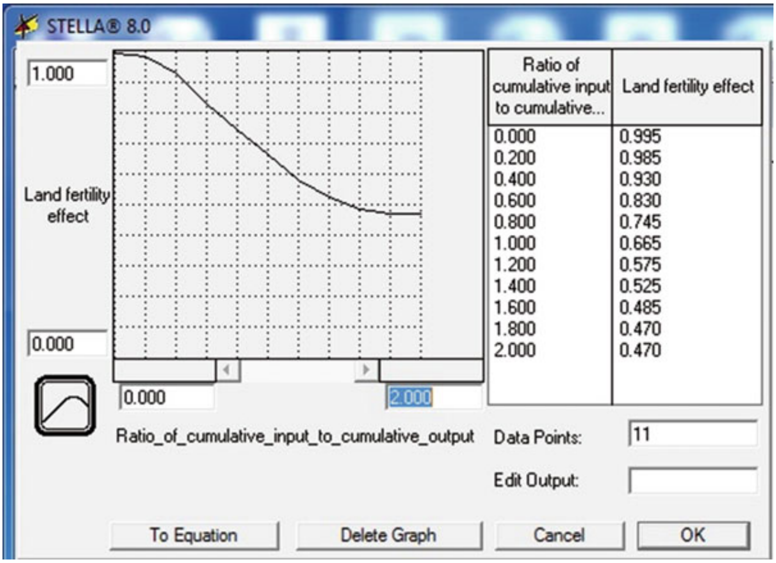

Fig. 5.4 Effect of cumulative input on land fertility

5.4 Estimation Using Aggregated Data

When using aggregated data to estimate parameters, the correctness of model equation(s) is (are) assumed. Two main techniques of parameter estimations using aggregated data are using (a) single equation and (b) multiple equations.

5.4.1 Estimation Using a Model Equation

The model equation is assumed to be correct and the aggregated data that correspond to model variables are used to estimate the parameter value. Estimation using a model equation encompasses all single equation regression techniques.

For an example of estimation using a model equation, consider the population model for calculating the death rate in Eq. 5.1. If the data for death rate and population are available, LE can be estimated by rearranging the formulae in Eq. 5.1. Therefore, the equation for estimated LE is as follows:

$$DR = \frac{P}{LE} \tag{5.3}$$

$$LE = \frac{P}{DR} \tag{5.4}$$

DR Death rate (person/year)
P Population (person)
LE Average life expectancy (year)

Parameters in biological and aquacultural models are essentially estimated using regression techniques. For example, the relation between fasting metabolic rate and body weight of a fish can be expressed as follows:

$$\text{FMR} = \alpha \times \left(\text{WoF}^{\gamma}\right) \tag{5.5}$$

FMR Fasting metabolic rate (Mole ATP/day)
WoF Weight of fish (g)

α and γ are the parameters estimated regressing the experimental data on fasting metabolic rate and body weight of fish. For catfish, these parameters are $\alpha = 0.0012$ and $\gamma = 0.8$.

Estimation using a model equation is less frequent in socio-economic system dynamics studies. However, two forms of model equation estimation—one involving conversion factors and the other fractional rates of flow—have been useful in many studies and are discussed below.

Conversion Factors

Many model parameters are conversion factors, and they convert quantities from one dimension to another. For example, consider the housing sector of the residential community model. Land per house (LPH) converts housing units (H) to an equivalent number of hectares:

$$\text{LFO} = \frac{(H \times \text{LPH})}{A} \tag{5.6}$$

LFO Land fraction occupied (dimensionless)
H Housing unit (unit)
LPH Land per house (ha/unit)
A Area (ha)

Such equation can be manipulated to compute the parameter as function of the real data, in this case, the real LFO, H and A:

$$\text{LPH} = \frac{(\text{LFO} \times A)}{H} \tag{5.7}$$

Consider another example. Here, straw feed per cattle converts cattle population to an equivalent amount of straw feed. The following equation uses straw feed per cattle in the definition of fraction of available straw used as cattle feed (FoS):

$$\mathrm{FoS} = \frac{(\mathrm{SFC} \times CP \times DY)}{\mathrm{ASF}} \tag{5.8}$$

FoS Fraction of Straw (dimensionless)
SFC Straw feed per cattle (kg/day)
CP Cattle population (head)
DY 365 days (day)
ASF Available straw feed (kg/year)

This equation can be used to compute the parameter as a function of the real data in this case FoS, ASF, *CP* and *DY*:

$$\mathrm{SFC} = \frac{(\mathrm{FoS} \times \mathrm{ASF})}{(CP \times DY)} \tag{5.9}$$

Estimating conversion factors offers a straightforward means of ensuring that the absolute magnitudes of model variables are realistic.

Normal Fractional Rates of Flow

Equation below defines the death rate in terms of a level population, a normal fractional rate of death (DRN) and dimensionless multipliers:

$$DR = \mathrm{POP} \times \mathrm{DRN} \times \mathrm{DRFM} \times \mathrm{DRPM} \tag{5.10}$$

DR Death rate
POP Population
DRN Death rate normal
DRFM Death rate multiplier from food
DRPM Death rate multiplier from population

The format for above equation is:

$$\mathrm{Rate} = \mathrm{Level} \times \mathrm{Normal\,fraction} \times \mathrm{Multipliers} \tag{5.11}$$

This format is widely used and the multiplier can be easily estimated when it is normalised around 1.0. It also facilitates the estimation of the normal fraction, and it can be represented by:

$$\mathrm{Normal\,fraction} = \frac{\mathrm{Rate}}{(\mathrm{Level} \times \mathrm{Multipliers})} \tag{5.12}$$

Under normal conditions the multipliers assume a value of 1.0, so the fractional flow rate can be obtained by dividing the observed rate by the observed level. For example, suppose 1970 is the normal period for the population model. Then the birth rate normal is obtained from the number of births during 1970 divided by the number of population in 1970. Choosing a normal condition does not bias behaviour of the model. A normal condition is merely a system state about which parameters are defined.

5.5 Estimation Using Multiple Equations

Estimation using several multiple equations consists of using several equations to compute a parameter value. For example, birth rate normal (BRN) can be estimated by finding the value of BRN that causes population growth rate to fit the observed rate of growth. This estimation will use all the equations. The fitting could be performed either with repeated simulations or, if possible, by computation. For an example of such a computation, the population growth rate is 2.5 %. Also from observations of the dead, the life expectancy (LE) is estimated to be 66 years, that is, 1/66 of the population are dead per year. Therefore the BRN should be $1/66 + 0.025 = 0.04$.

5.6 Sensitivity Analysis

Here we consider the parameter sensitivity analysis, and it is conducted to assess how sensitive is the model behaviours to the changes in the values of the parameters. Parameter sensitivity analysis is usually conducted by setting different values such as ±15 % changes in the parameter to study the changes in the model behaviours. Sensitivity analysis provides an opportunity to determine the level of accuracy needed in the estimation of the parameter to make the model valid and useful. If the parameter is insensitive to the model behaviour, it may be used in the policy analysis and design. On the other hand, parameters significantly affecting the model behaviour should be chosen as candidates for additional data collection (Sterman 2000).

The parameters of a system dynamics models are subject to uncertainty. So, sensitivity analysis is an important task for reliability of the simulated results and checking the robustness of the model behaviour for the changes in parameter values. The sensitivity of the important parameters should be estimated. The productivity is one of the most important parameters affecting the model behaviour, i.e. self-sufficiency ratio which is the focus of the food security model (Bala et al. 2014). Figure 5.5 shows the changes in food self-sufficiency ratio for rice productivity for changes of 2.50 t/ha (curve 1), 3.50 t/ha (curve 2) and 4.50 t/ha (curve 3). The food self-sufficiency ratio changes from decrease to increase in values for the changes in the rice productivity from 3.50 t/ha to 2.50 t/ha and 4.50 t/ha, and this corresponds with real-world situation.

Another example of sensitivity analysis is the sensitivity of cocoa production systems in Malaysia to the changes in the subsidy level (Fatimah et al. 2015). Figure 5.6 shows the simulated cocoa plantation area for full subsidy (curve 3),

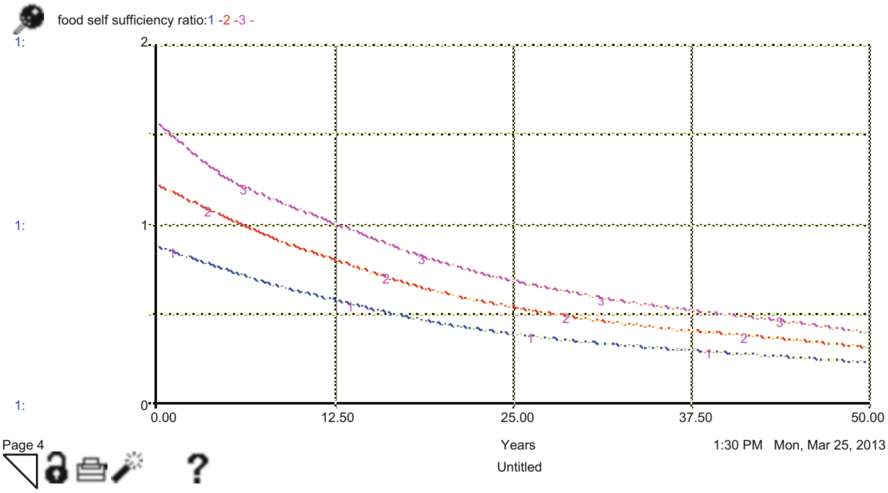

Fig. 5.5 Sensitivity of food self-sufficiency ratio to rice productivity (2.50 t/ha, 3.50 t/ha and 4.50 t/ha)

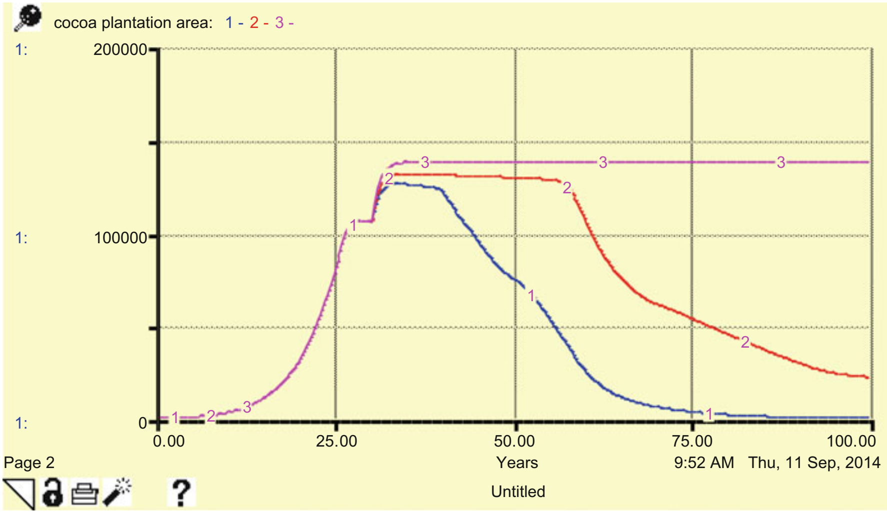

Fig. 5.6 Sensitivity analysis of subsidy for cocoa production systems in Malaysia

80 % subsidy (curve 2) and 60 % subsidy (curve 1) of the cost to cover conservation practices and insect control. The system is sustainable for full subsidy since financial support is provided for joint trade-off of biodiversity and yield along with integrated pest management (IPM) pest control through farmer field schools (FFS), but the sustainability decreases with the degree of reduction of subsidy as lesser opportunities available to maintain biodiversity and insect control in terms of financial support.

5.7 Size of Solution Interval (DT)

It has been mentioned in Chap. 4 that solution interval should be half or less than of the shortest time delay in the model. Let us now consider a simple model of grain storage system as shown in Fig. 5.7 to address the effects of the size of solution interval, and the STELLA equations of the model are given below:

STELLA Equations

```
grain_stock(t) = grain_stock(t - dt) + (receiving_rate) * dt
NIT grain_stock = 50
```

INFLOWS:

```
receiving_rate = (desired_grain_stock-grain_stock)/receeiving_delay
desired_grain_stock = 100
receeiving_delay = 0.5
```

Here in this model, the initial grain stock is 50 tons and desired stock is 100 tons, and receiving time delay is 0.5 months. Let us see what happens to the simulated behaviour of this simple system if solution intervals are 0.20, 0.50 and 1.0. Figures. 5.8, 5.9 and 5.10 show the simulated responses of the system for the solution intervals of 0.20, 0.50 and 1.0, respectively. The simulated response of the system in Fig. 5.8 is the inherent system behaviour for a solution interval of less

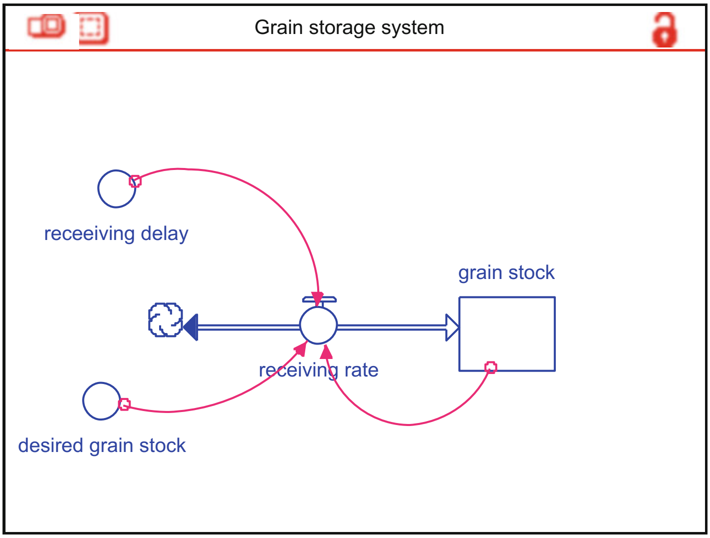

Fig. 5.7 Stock–flow diagram of a simple grain storage system

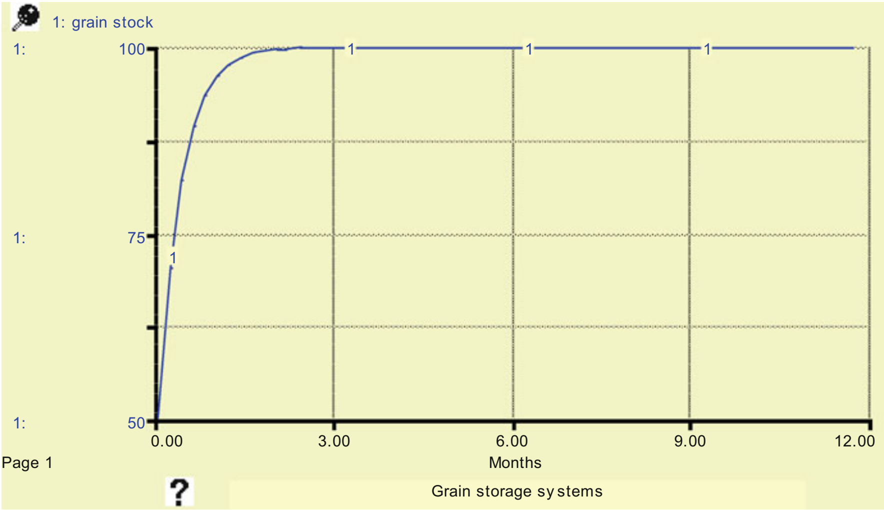

Fig. 5.8 Grain stock response for solution interval of 0.20

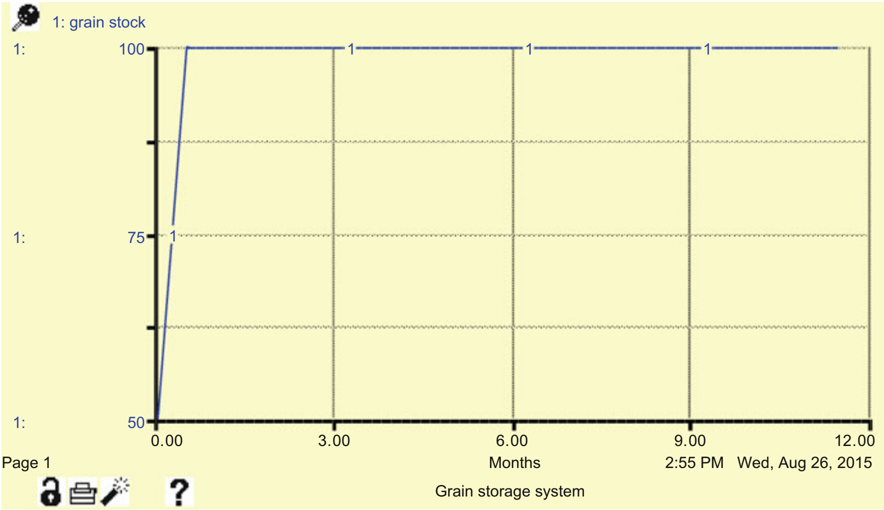

Fig. 5.9 Grain stock response for solution interval of 0.50

than half of the time delay. The simulated response in Fig. 5.9 is poor for a solution interval equal to time delay, and the simulated response in Fig. 5.10 for a solution interval of double of the time delay is the worst, and these responses are not the inherent system behaviour, but these are the results of improper size of solution interval. The solution interval is not part of the real system, but the improper size of it affects the simulated results seriously.

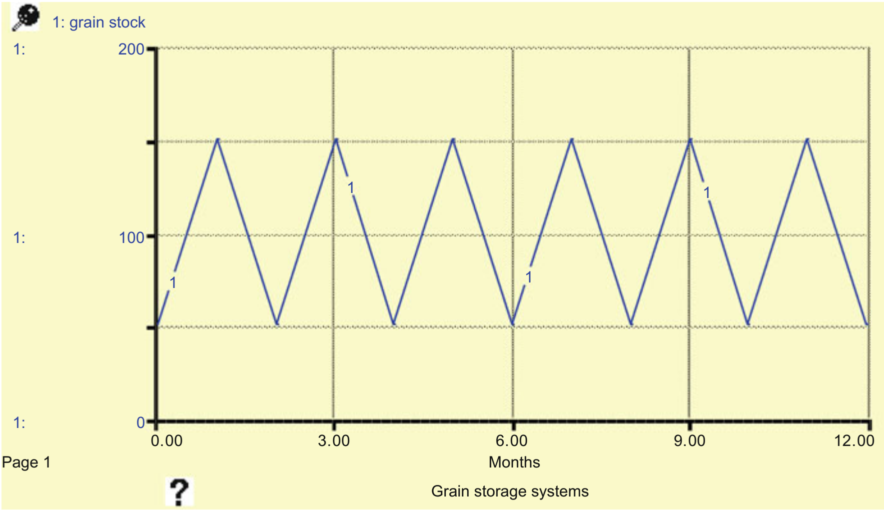

Fig. 5.10 Grain stock response for solution interval of 1.0

Exercises

Exercise 5.1 What is meant by parameter estimation? Describe briefly the techniques of the parameter estimation.

Exercise 5.2 What is table function? Show with examples how table functions are estimated.

Exercise 5.3 What are the main techniques of parameter estimation using aggregated data? Describe how multipliers are estimated?

Exercise 5.4 What is meant by sensitivity analysis? Describe with examples how the sensitivity of a parameter analysed.

Exercise 5.5 What is meant by solution interval? Show that improper use of solution interval can provide explosive behaviour which is not the behaviour of the system.

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Tests for Confidence Building

6

The models developed based on the concepts, methodology and techniques of system dynamics discussed in the earlier chapters must be tested to build up confidence in the models. This chapter presents the tests for confidence building in the system dynamics models. These tests are discussed under the broad heading of tests for structure, tests for behaviour and tests for policy implications. The logical sequences of conducting these testes are also presented.

6.1 Introduction

Once we have developed a model, how can we develop our confidence in the use of the model for developing scenarios and management strategies? How can we make others trust our model? This chapter deals with the tests for confidence building in system dynamics models. Model validation to develop confidence in the model is important, but it is a controversial aspect of any process-based model in general and system dynamics (Barlas 1996). The validity and usefulness of dynamic models should be judged, not against an imaginary perfection but in comparison with the mental and descriptive models which we would otherwise use (Forrester 1968). Models should be judged, not on absolute scale but on relative scale. If they succeed in clarifying our knowledge and insights into the systems for better understanding and management, the model should be accepted.

Tests for building confidence in system dynamics models essentially consist of validation, sensitivity analysis and policy analysis of the system dynamics models. The two important notions of building confidence in system dynamics models are testing and validation of system dynamics models. Testing means the comparison of a model to empirical reality for the accepting or rejecting the model, and validation means the process of establishing confidence in the soundness and usefulness of the model.

In testing mode, the model structures are compared directly to descriptive knowledge of real system structures, and model behaviour may be compared to

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observed real system behaviour. In validation mode, the model behaves plausively and generates problem symptoms or modes of behaviour observed in the real world. The modeller's confidence needs to be transferred to the target audience.

Validation is complicated by many relevant audiences. For a scientist, a model is useful if it generates insight into the structure of real system, makes correct prediction and stimulates meaningful questions for future research. For the public and political leaders, a model is useful if it explains the causes of important problems and provides a basis for designing policy to improve the behaviour of the system. Validity meaning confidence in a model's usefulness is inherently relative concepts. One must choose between competing models.

In system dynamics model, behaviour testing is very common. This is because very often system dynamics models incorporate such variables for which no real-life data is available. Under such circumstances, assumed relationships are based on available literatures, and the appropriateness of such relationships is justified in the overall context of the generated model behaviour. Though system dynamics modellers try to make best use of the available data for parameter estimation, sometimes by statistical methods, vigorous use of statistical tests is rare.

The main reason why system dynamics methods are not statistically tested is that the system models include variables for which no real-life data exists. Since system dynamics models include both statistically valid variables and assumed variables, it cannot be claimed that the model behaviour would deteriorate because of the use of statistically non-tested variables. In fact, the use of the assumed variables would improve the behaviour generation capacity of the model, and it may be claimed that the model has passed improvement test. In situation where the modeller has clear idea and supporting data of the mode of behaviour of the system, the model building and validation becomes relatively an easy task.

The ultimate objective of model validation is to develop confidence in predictions. The first step of the ultimate objective of system dynamics model validation is to establish the validity of the model structure. The next step is the behaviour reproduction of the model compared to the real behaviour of the system, and it is meaningful only if we have sufficient confidence in the model structure (Barlas 1996). The logical sequences of model validation are shown in Fig. 6.1. The model behaviour changes to the change in parameter values, and policy issues are also important to understand how the model will behave under changing conditions. Keeping these philosophical aspects in mind, the tests for confidence building in system dynamics models are to be designed. The tests for building confidence in system dynamics models may be broadly classified as:

1. Tests for structure
2. Tests for behaviour
3. Tests for policy implications

One must realise that not all the tests are to be considered for validation of a model, but structure and behaviour pattern tests are essential, and policy

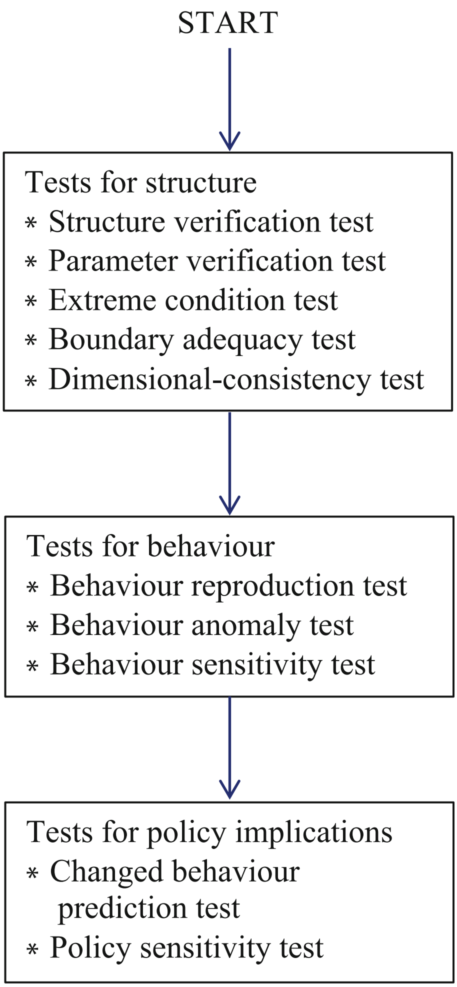

Fig. 6.1 Logical sequences of the tests for model validation

implication test makes the validation sufficient. It is rather those tests which are essential for establishing the creditability of the model are to be included.

6.2 Tests of Model Structure

The first step in the validation of system dynamics models is the structure validity tests, and this can be further classified as direct structure tests and structure-oriented behaviour tests. In direct validation structure tests, the validity of the model structure is assessed by direct comparison of the model structure with the knowledge of the real systems. It is accomplished by comparing mathematical equations and logical relationship with the available knowledge of the real systems. No simulation of the model is needed. Direct structure tests can be classified as empirical tests and theoretical tests. Empirical tests are conducted by comparing the model structure with the information (quantitative and qualitative) obtained about the system, while theoretical tests are conducted by comparing the model structure with the generalised knowledge of the system from literature such as research reports and studies. Structure confirmation tests are the toughest tasks to do as we need to compare the equations of the model directly with the knowledge of the real systems.

In structure-oriented behaviour tests, the validity of the model structure is assessed by the comparison of the behaviour of model predicted with the knowledge of behaviour of the real systems expected and usually observed in reality. It is a qualitative validation of the model.

Broadly speaking, tests of model structure may be classified as:

1. Structure verification test
2. Parameter verification test
3. Extreme condition test
4. Boundary adequacy test
5. Dimensional consistency test

6.2.1 Structure Verification Test

The structure verification test applies as empirical means comparing the form of equations of the model with relationships that exist in the real systems. The structure of the model that is the relationships in the equations should be in line with the descriptive knowledge of the system. It may also be conducted as theoretical tests by comparing the model equations with the generalised knowledge of the systems in the literatures. All the equations should be well argued and based on available information. The structure of the model should match observable goals, pressures and constraints of the real systems. Verifying a model structure is an easier task and takes less skill than some other tests.

6.2.2 Parameter Verification Test

The second structure verification test is the parameter confirmation test, and it means evaluating the constant parameters against the knowledge of the real systems both conceptually and numerically. Every constant (and variable) should have a clear real-life meaning. The basic choice is formal statistical estimation or judgemental estimation. Econometrics or other methods may be used to estimate the parameters.

The choice of appropriate initial values for stock equations, values of constants and table functions is directly related to the model description, and the values should be based on the published data from various sources. Computer software packages are now available to estimate and justify the exact values of the parameters to produce the expected behaviour of the system. Structure verification and parameter verification are interrelated, and both tests have the same basic objective.

6.2.3 Extreme Condition Test

The model should be robust under extreme conditions. There is an important direct structure test to the robustness of the model under direct extreme conditions, and it evaluates the validity of the equations under extreme conditions by assessing the plausibility of the resulting values against knowledge/anticipation of what would happen under similar conditions in real life. It is relatively easy to anticipate which variables and what values would these variables take under extreme condition in real systems.

The model must be capable to cope with external conditions. If the extreme conditions are incorporated in the model, the result is an improved model in the normal operating region. System dynamics model structure permits extreme combinations of socks in the system under study. A model should be questioned if extreme condition test is not met. It is not acceptable that extreme condition is not necessary on the plea that it does not occur in real life. Extreme condition test is effective for two reasons: (a) it is a powerful tool to detect the defect in model structure, and (b) it enhances the usefulness of the model for analysing policies that may force a system to operate outside historical regions of behaviour. Hence the extreme condition test is a strong test.

Let us consider that the supply chain model of rice milling systems is to be tested for extreme conditions to detect the defect in the model structure and enhance the usefulness of the model for policy analysis. Figure 6.2 shows simulated milling inventory, wholesale inventory and retail inventory under extreme condition of crop failure, i.e. zero crop production. Under this condition, the milling inventory and then wholesale inventory and retail inventory are reduced to zero since the rice production is zero. The model results confirmed to the expected patterns of results and realities. This model complied with the basic principles of supply chain management and was consistent with supply chain theory and research results. Thus, the model is able to provide qualitative and quantitative understanding of the supply chain performances of rice milling systems. Hence the model is reliable and validated under extreme conditions.

6.2.4 Boundary Adequacy Test

Boundary adequacy test considers structural relationships necessary to satisfy the model's purpose. Boundary adequacy test asks whether or not model aggregation is appropriate and if a model includes all relevant structure.

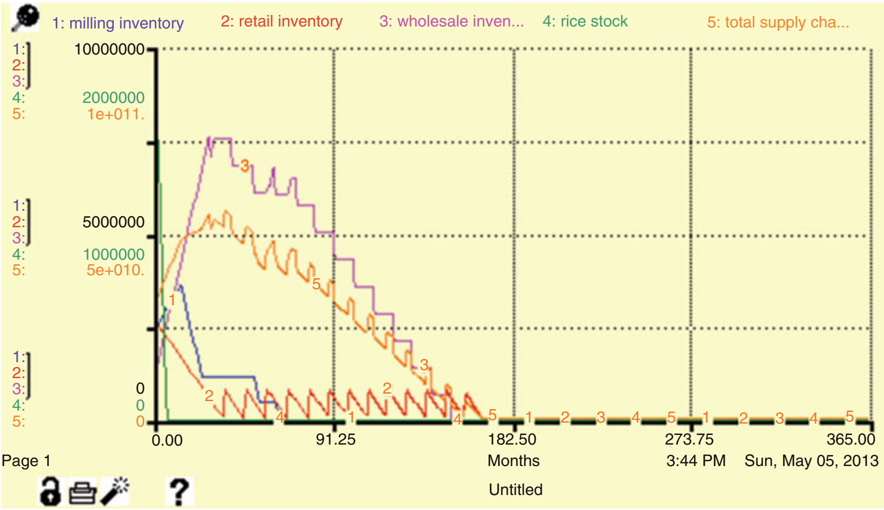

Fig. 6.2 Simulated milling inventory, wholesale inventory and retail inventory under extreme condition of crop failure, i.e. zero crop production

Once the model boundary is established, it is necessary to check whether any additional feedback loop has been omitted or not. If the additional feedback has any significant impact, it must be included. In essence, the model must include all variables and feedback loops encompassing the entire system under study which affect the dynamics or policy implications of the model.

6.2.5 Dimensional Consistency Test

Dimensional consistency test is one of the basic tests, and it must be carried out during the construction of the model. Dimensional consistency test involves checking the right-hand side and left-hand side of each of the equations of the model for dimensional consistency. It is better to specify the units of measure of each variable during construction of the model. The dimension of the left-hand and right-hand side of an equation should be the same for correct model formulation. Moreover, the dimensions of the variables should be close to their physical meaning; none of the dimension should be divorced from its actual meanings. Dimensional consistency test entails the dimensional analysis of a model's rate equation. Surprisingly many models fail this simple test. Hence, dimensional consistency test is the most powerful when applied in conjunction with the parameter verification test.

6.3 Tests of Model Behaviour

The second important step in the validation of system dynamics models is the model behaviour validity tests, and the tests for model behaviour should be conducted once the structural validation tests are completed successfully. The core tests of model behaviour may be classified as:

1. Behaviour reproduction test
2. Behaviour anomaly test
3. Behaviour sensitivity test

6.3.1 Behaviour Reproduction Test

Once the structure confirmation tests are completed successfully, the next test is the behaviour pattern tests to measure how accurately the model can reproduce the dynamic behaviour of the real systems. Behaviour reproduction tests compare how well the model-generated behaviour matches model-observed behaviour of the real system. Behaviour reproduction tests include symptom generation, frequency generation, relative phasing, multiple mode and behaviour characteristic. Behaviour reproduction tests become much more convincing when one can show why the tests are passed.

Many tools are available to assess the model behaviour to reproduce the system behaviour. Most common techniques are descriptive statistics to measure point by point fit. The most commonly used measure of the fit is the coefficient of determination (R^2), and it measures the fraction of variance explained by the model. The mean absolute error (MAE), mean absolute percent error (MAPE) and root mean square error (RMSE) all provide measures of the average error between the simulated and actual values. However, the emphasis should be on pattern rather than point prediction.

In the literature on modelling and simulation, there are a wide range of tests involving point by point comparisons of model-generated and model-observed behaviour. Despite widespread acceptance, such tests involving point by point measures of goodness of fit are generally less appropriate for socio-economic system dynamics models.

The reproduction of historical behaviour is the single most important test to build up confidence in models. Figure 6.3a shows the comparison between the predicted and historical behaviour of food self-sufficiency ratio in Malaysia. The model-simulated food self-sufficiency ratio agrees reasonably well with historical behaviour, and the model is reliable. Figure 6.3b shows the comparison of simulated and reported changes in wholesale price of rice in 2011 in Bangladesh. The model can simulate the actual behaviour of the system closely and can be used for policy analysis.

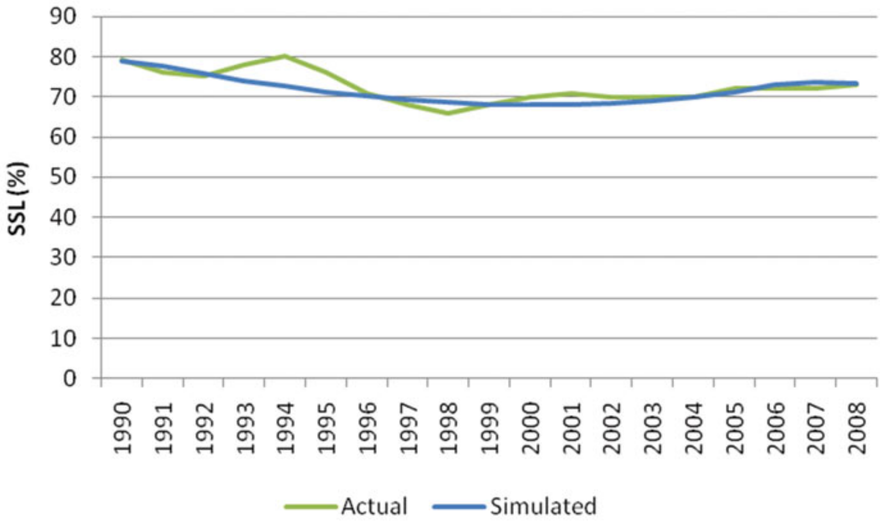

Fig. 6.3a Simulated and historical data of food self-sufficiency ratio in Malaysia

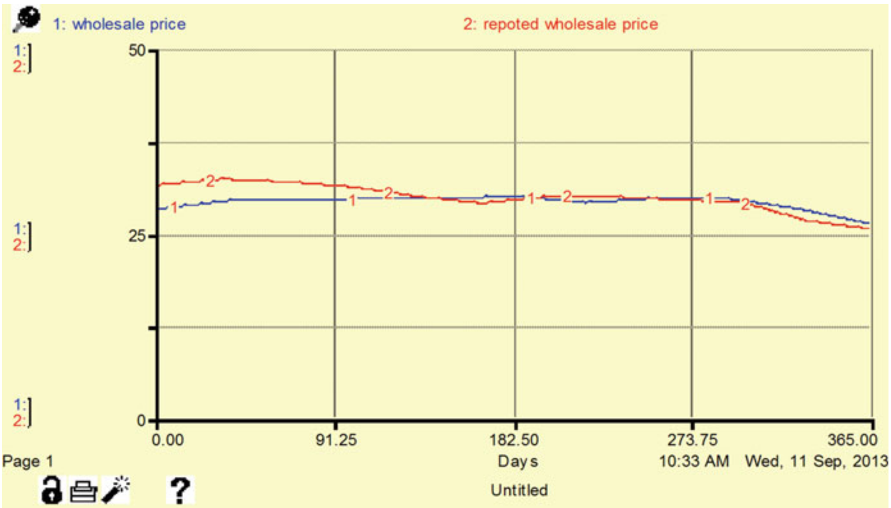

Fig. 6.3b Comparison of simulated and reported changes in wholesale price of rice in 2011 in Bangladesh

6.3.2 Behaviour Anomaly Test

While simulating a system dynamics model, one expects it to behave like real system under study, but frequently model builders face anomalous features of model behaviour, and these contradict the behaviour of the real system. Whenever there is anomaly in model behaviour, there may be defect in model assumptions. One can often defend particular assumptions by showing how implausible behaviour arises if the assumption is altered. Loop knockout analysis is a common method to search for behaviour anomalies. Anomalous behaviour resulting from knockout test suggests the importance of the loop and may help to establish the plausibility of system behaviour.

6.3.3 Behaviour Sensitivity Test

The behaviour sensitivity test shows the sensitivity of the model behaviour to changes in parameter values. The parameter sensitivity test ascertains whether or not plausible shifts in parameter values cause a model to fail behaviour tests previously passed.

The behaviour sensitivity test is typically conducted by experimenting with different parameter values and analysing their impacts on behaviour. Typically, the behaviour of system dynamics models is insensitive to plausible changes in most parameter values. It appears that systems are insensitive. On the other hand, both real systems and models or real systems are sensitive to a few parameters. Finding a sensitive parameter does not necessarily invalidate the model. Even though it has a substantial effect on behaviour, plausible variations may not lead to failure of other behaviour tests.

The model of supply chain of rice milling systems was simulated to address the impacts of rice productivity on the supply chain performances. Here the rice productivity is the yield of rice per ha. Rice productivity may be reduced from crop damage due to floods or pest infestation, and also it can be increased by development of higher yield hybrid rice through research and development. Rice productivity for this policy is defined as

$$\text{rice production rate} = \text{area under rice} \times \text{yield of rice} \tag{6.1}$$

$$\text{yield of rice} = 1.81, 2.81 \text{ and } 3.81 \text{ tons/ha} \tag{6.2}$$

Simulated milling inventory, wholesale inventory, retail inventory and total supply chain cost for rice productivity of 1.81 tons per ha, 2.81 tons per ha (present average rice productivity) and 3.81 tons per ha are shown in Figs. 6.4a, 6.4b, 6.4c and 6.4d, respectively. Milling inventory is reduced to zero for most of the period of the reduced productivity of rice (1.81 tons per ha), while it is high for bumper production of rice (3.81 tons per ha) (Fig. 6.4a). Wholesale inventory is reduced significantly in the fourth quarter of the year for reduced rice productivity (1.81 tons per ha) (Fig. 6.4b). Total supply chain cost is also reduced in the third and fourth quarter of the year for reduced rice productivity (Fig. 6.4d). However, in all the cases, the retail inventory is almost the same except towards the end of the year when both milling and wholesale inventories are empty for reduced productivity

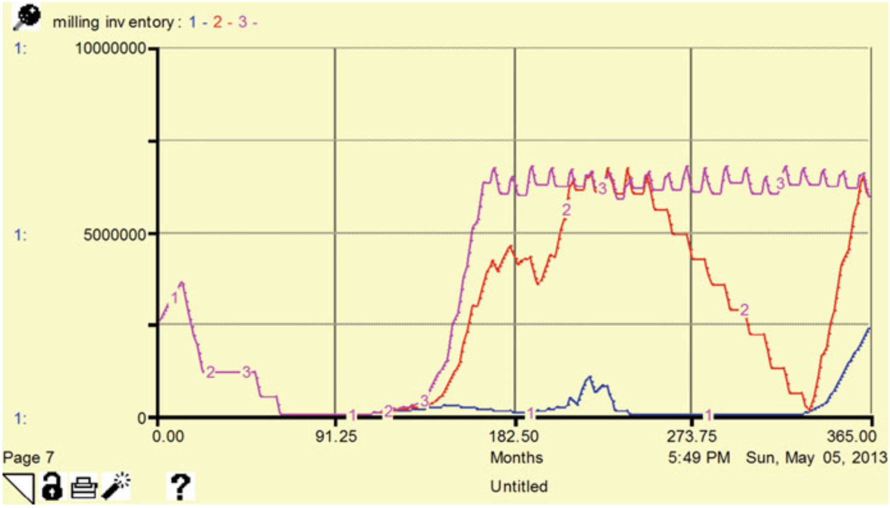

Fig. 6.4a Simulated milling inventory for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

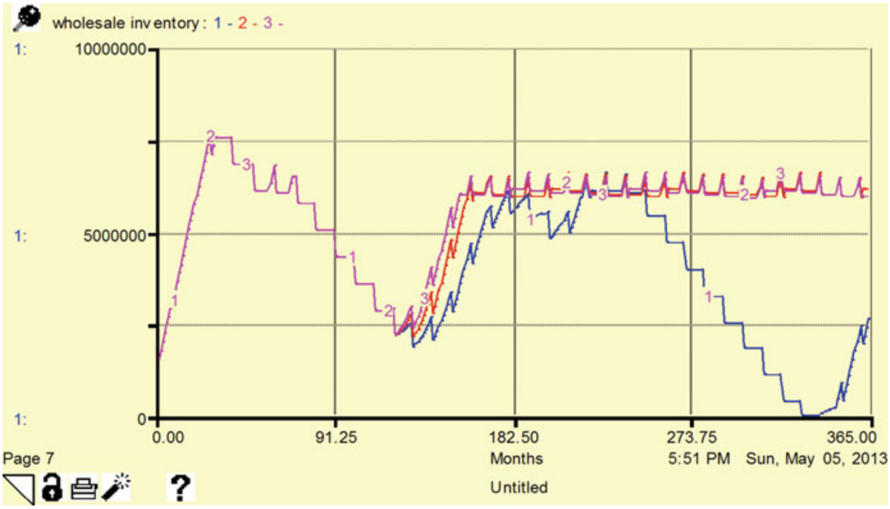

Fig. 6.4b Simulated wholesale inventory for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

(Fig. 6.4c). Thus, increased wholesale inventory is a possible solution for the retail inventory to face the shortage of rice during the off-peak harvesting season of rice production. This implies that as long as wholesale inventory is available, the retail inventory is stabilised based on economic order quantity and reordering point

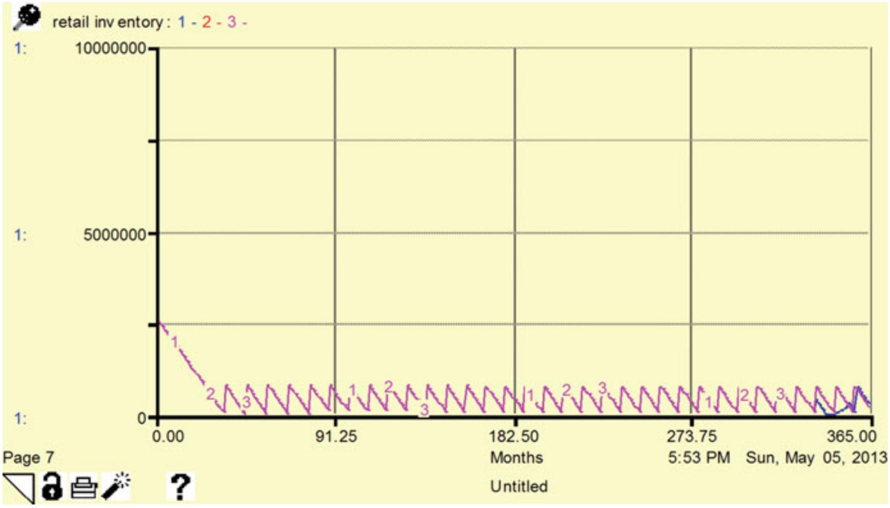

Fig. 6.4c Simulated retail inventory for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

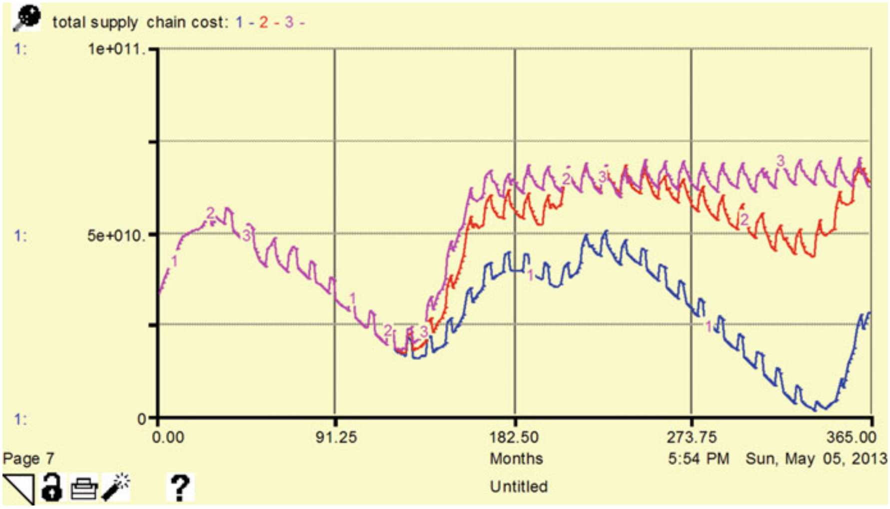

Fig. 6.4d Simulated total supply chain cost for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

operation of milling, wholesale and retail inventory. This demonstrates that the policy based on economic order quality and reordering point can ensure the availability of rice even under reduced production of rice, i.e. during crop damage/failure unless both wholesale and milling inventories are empty.

6.4 Tests of Policy Implications

Tests should be conducted to build confidence in model's implications for policy. The core tests of policy implications may be classified as:

1. Changed behaviour prediction test
2. Policy sensitivity test

6.4.1 Changed Behaviour Prediction Test

The changed behaviour prediction test shows how well the model predicts the behaviour of the system if a governing policy is changed. The test can be conducted by changing policies in the model and verifying the plausibility of resulting behaviour changes. Alternatively one can examine the response of the policy already pursued to see how well model response agrees with the real system response. This test essentially shows the impacts of exogenous policies on the model behaviour.

Figure 6.5 shows the comparison of food self-sufficiency ratios for basic run and IPCC climate scenario for base year yield and yield increase of 6 tons per ha within next 50 years. The climate change impacts on food self-sufficiency level are small for all these runs. However, food self-sufficiency levels for both the base year yield and the yield increase of 6 tons per ha follow similar patterns, and in both the cases, the food self-sufficiency levels increase for about 10 years due to expansion

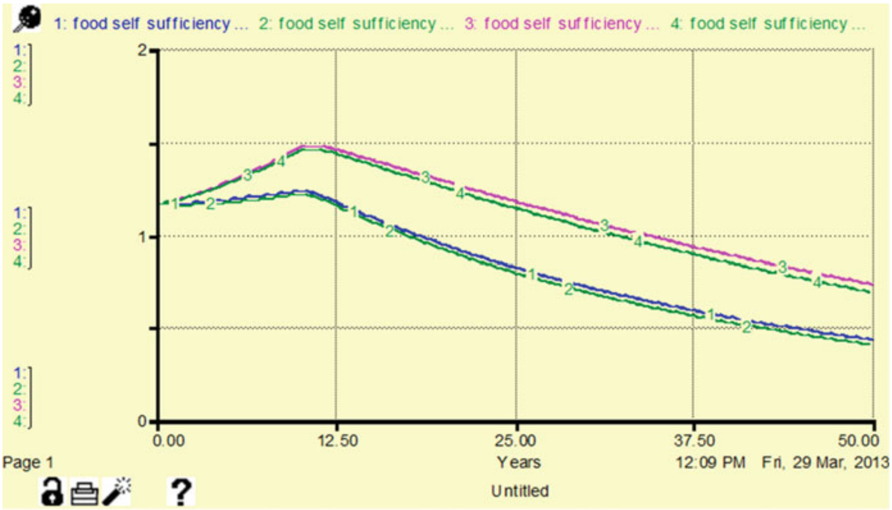

Fig. 6.5 Comparison of food self-sufficiency ratios for basic run and IPCC climate scenario for base year yield and yield increase of 6 tons per ha withinTests of policy implications:Changed behavior prediction test next 50 years

irrigation, and then it decreases as a result of the discard of irrigated area for its use for infrastructure development. The improved productivity increases the self-sufficiency level for about 12.5 years ahead, and the food self-sufficiency at the end of 50 years of simulation period increases from 43 to 73 %. Food self-sufficiency level is more seriously challenged by the decreasing cultivable land and growing population, and these are essentially demanding more increase in the productivity in the vertical direction due to the constraints of non-availability of additional cultivable irrigable land and more attention to control the growing population to improve rice self-sufficiency in the long run.

6.4.2 Policy Sensitivity Test

Researchers and decision makers have to make up their minds about where to concentrate their efforts to improve policies. When policy improvement is the desired objective, the question of policy sensitivity arises, although it may not be recognised as such. What kind of researchers should be involved? What mechanisms should be included or left out of formal and mental models? For which relationships and parameters should one seek better data and higher-quality estimates? These questions are best answered by policy sensitivity analysis.

The traditional and frequently used form of sensitivity analysis in system dynamics is to vary model assumptions and to observe how behaviour changes. In the branch of operations research using optimisation, sensitivity analysis is to vary model assumptions and to observe how optimal policies change. To avoid confusion between these two types of sensitivity, the terms behaviour sensitivity and policy sensitivity are used, of which the latter is the focus here. Policy sensitivity exists when a change in assumptions reverses the impacts or desirability of a proposed policy (Sterman 2000). For example, when one set of assumptions causes sustainable supply of palm oil, while another does not, the model exhibits policy sensitivity. If a particular policy change always produces improvement, regardless of changes in a sensitive parameter, then the policy recommendation is not affected (Forrester 1969). For example, when both sets of policy assumptions produce improvement of food security, the model exhibits policy insensitivity. These two statements clearly support and emphasise the sensitivity of the outcome of particular policies to uncertain parameters. To distinguish the two types of sensitivity analysis, we denote the latter policy outcome sensitivity.

Policy outcome sensitivity analysis is the most appropriate type of analysis when there remains uncertainty about parameter assumptions. This type of analysis can be expanded to include risk. The policy sensitivity we focus on here is the most appropriate for the purpose of model building. What parameters are most important for policy recommendations and require thorough analysis? What simplifications and aggregations are important for policies?

From a more practical viewpoint, if the simplified policy is the best one can do, or it is the type of policy that will be used in practice, then the bias is of less concern. Then it is interesting in itself to see how the optimised practical policy varies with changes in model assumptions. As a problem is demonstrated not to be very sensitive to uncertain parameters, decision makers' confidence in the problem formulation increases and so does the likelihood that some first policy measures will be implemented. That this type of analysis is needed in renewable resources management, e.g. fisheries, is indicated by the long delays in implementing appropriate policies and by laboratory experiments showing tendencies towards misperception.

We start with the problem of model validation, where a major challenge is to choose between potentially large numbers of models that pass tests of falsification. Policy sensitivity analysis is of no direct help in this choice. However, it can be used to find out if the choice of model has policy implications. If it has not, the remaining uncertainty is mostly of academic interest.

This is a potentially important insight since a heated 'academic' debate about the correctness of models can confuse the policy debate. In principle, policy sensitivity analysis could even be used to investigate the importance of the 'unavoidable a priori' assumptions of different disciplines (Meadows 1980). If different disciplines prescribe different policies, policy sensitivity analyses could be used to identify the causes of disagreement and to direct further validation effort towards the identified causes.

Next, we consider model aggregation. In principle, aggregation is a very challenging problem. Most system dynamics models resort to aggregation of people, resources, perceptions, etc. On the other hand, in non-linear dynamic models, aggregation leads to model errors except in some very special cases (Krysiak and Krysiak 2002). For this reason, Krysiak and Krysiak argue that 'environmental economics as well as other fields of economics may benefit from using more complex models'. On the other hand, increased complexity has a cost in terms of efforts to validate, analyse and explain models. Policy sensitivity analysis can be used to identify the appropriate aggregation level for policies.

Finally, policy sensitivity test shows the degree of robustness of model behaviour and policy recommendations. Such testing can help to show the uncertainty in parameter values. In the worst case, the parameter change can invalidate the recommended policies that were given. However, the policy recommendations are not likely to be affected by uncertainties in parameters.

In summary, tests for building confidence in system dynamics models should be conducted in some logical sequences, and we should move one step to the next step only if we are able to establish sufficient confidence in the current step. The logical sequences of formal steps of model validation as suggested by Barlas (1996) capture the essentials of the validation of system dynamics models to build up confidence in system dynamics models. The logical sequences of formal steps of model validation as suggested by Barlas (1996) are shown in Fig. 6.6. Once the model has passed through structural tests, we should start behaviour pattern tests. If the model passes through both direct and indirect structural tests, but fails the behaviour pattern tests, then we should re-estimate certain parameter and/or input function.

Next it would be logical to skip the structural tests and apply behaviour pattern tests. Once we have reached the final step of the behaviour pattern test, we should

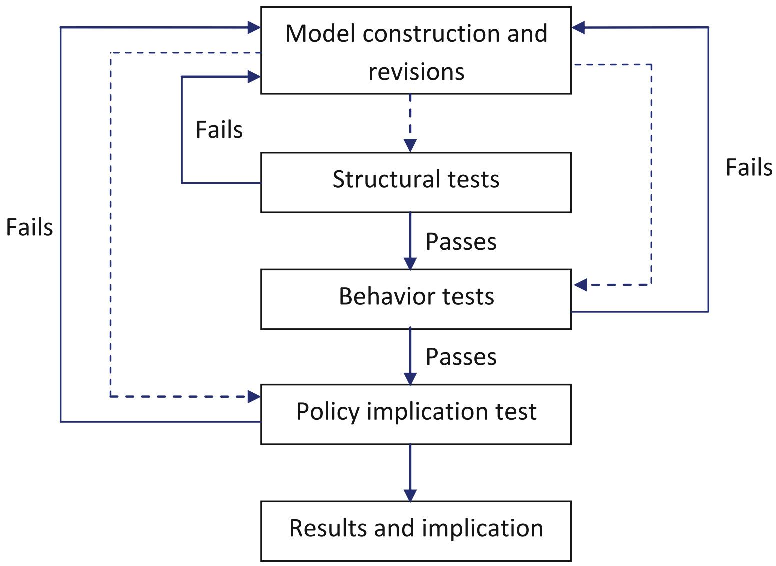

Fig. 6.6 Logical sequences of formal steps of model validation as suggested by Barlas (1996)

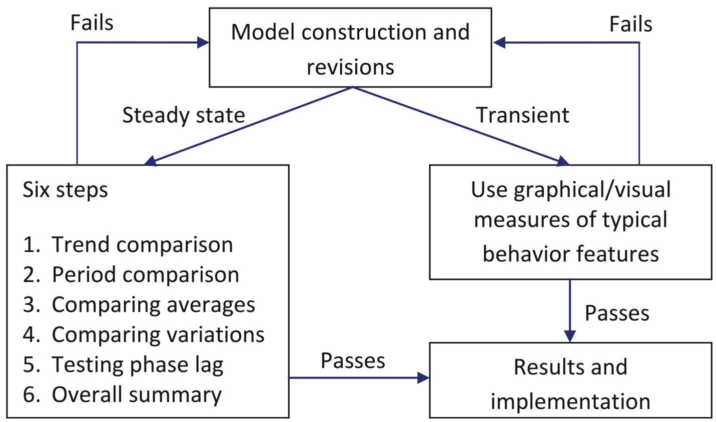

Fig. 6.7 Logical sequence of behaviour pattern tests

give emphasis on the accuracy of the pattern predictions. However, behaviour pattern tests are weak tests that provide no information on the validity of the structure of the model. Behaviour pattern tests must be carried out in logical order too. Figure 6.7 shows the logical sequence of behaviour pattern tests. If the problem involves transient and highly nonstationary behaviour, it is not possible to apply any standard statistical measure. On the other hand, if the problem involves a long-term simulation, it is possible to apply standard statistical measures and tests. Note that if the model is considered to fail the behaviour pattern tests, once again we should go back to model revisions, and the model revisions involve parameter/input changes rather any other tests.

Exercises

Exercise 6.1 What are the tests for confidence building in system dynamics models? Describe the logical sequences of the tests of model validation.

Exercise 6.2 Describe tests of model structure with examples. Discuss the importance of verification tests. Explain why extreme condition test is important with examples.

Exercise 6.3 Describe tests of model behaviour with examples. Discuss the importance of behaviour reproduction tests with examples and also show logical sequence of behaviour pattern tests.

Exercise 6.4 Describe tests of policy implications with examples. Discuss the importance of policy sensitivity test.

Exercise 6.5 Describe the logical sequences of formal steps of model validation suggested by Barlas (1996).

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Scenario Planning and Modelling 7

The models tested for building up confidence (as discussed in Chap. 6) should be used for scenario planning and modelling. This chapter presents scenario planning and modelling. Participatory system dynamics modelling and scenario planning are broadly discussed and the steps in scenario planning are highlighted. Also, policy planning for development strategy and implementation of development strategy and modelling are discussed. Some examples of scenario planning and modelling are presented.

7.1 Introduction

Once the model has been validated, the next steps are policy design and evaluation. Policy design includes management strategies and different policy options for improvement of the system performances. Policy design must involve all the stakeholders of the system being modelled not only in the simulation at the final stage but also during the development of the model. This will assist in minimising the gap between the model builders and the stakeholders. Also, this will make the stakeholders feel to be part of policy design using computer models.

Scenario planning is an approach for exploring the different possible futures and it relies on an understanding of today to explore what might happen in the future. This methodology also includes both simulation using system dynamics model and conversations with stakeholders related to scenario planning. It is to be noted that system dynamics is an approach for exploring the current structure of a system and the reasons for its behaviour, while scenario planning methodology generates scenarios as the solution derived from the simulation results of the system dynamics model.

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DOI 10.1007/978-981-10-2045-2_7

7.2 Scenario Planning and Modelling

Scenarios are descriptions of different possible futures and scenario planning is an approach designed to develop scenarios. It considers the decision-maker's current mental models and aims to question their assumptions and their model's limitations. The aim of scenario planning and scenarios is to change the mental models of decision-makers to consider new possibilities and create common language and common mental models from which to begin discussing strategic options (Featherston and Doolan 2013). Commonly cited requirements of scenarios are that they be believable, reasonable and realistic.

The difference between scenario planning and system dynamics is the different time frames upon which they focus. System dynamics focuses on present systems and the reasons for their behaviour, whereas scenario planning focuses on what may happen in the future, often between 5 and 25 years. However, scenario planning relies on an understanding of today in order to be able to map out the space into which the future might fall. Furthermore, system dynamics and scenario planning are not static approaches; as a system might evolve, they can be used to understand the causes for systemic behaviour in the evolved system and explore the spaces it might proceed to in the future.

The system dynamics approach addresses a question that remains unanswered by the scenario planning approach. Why there is gap between perceived and actual behaviour of the system is unanswered by scenario planning. But system dynamics is able to address such an issue. System dynamics also offers a more formal approach to addressing mental models. While scenario planning's focus is on informing mental models, the approaches' literature provides little besides information collection and advocacy and inquiry as means to achieving that. However, system dynamics procedural approach of forming a hypothesis, understanding a system structure and testing the hypothesis provides a guide to identifying and addressing a specific, systemic problem. The specificity of the system dynamics approach is one glaring difference between these approaches. Scenario planning is used to explore the entire system and understand how it might evolve. System dynamics, however, despite being capable of exploring such broad system applications is applied to a very specific problem with limited system scale. This perhaps limits the conclusions that can be drawn from this type of study. Perhaps as a consequence of this, the information that comes from the system dynamics process does not encourage a reassessment of the scenarios. This indicates that despite the information from the system dynamics approach providing useful information for policy development, it does not cause a change in the scenarios, but instead helps to understand why the behaviour is occurring and what could be done about it in the future, essentially informing the mental models that fill in the gaps left by the scenario narratives. The learning that occurs during the scenario planning phase is fed into the system diagrams and in effect acts as a problem structuring method to identify where a system dynamics approach is needed. System dynamics then addresses a problem that is not addressed by scenario planning. It was then the combination of these results depicts a situation where the organisation is in a stalemate and begins to provide a framework from which policies could be addressed to influence this.

Both system dynamics modelling and system dynamics-based scenario planning are advocated for involving all the stakeholders in modelling and scenario planning. We present here first participatory system dynamics modelling and then participatory system dynamics-based scenario planning.

7.3 Participatory System Dynamics Modelling

System dynamics uses simulation models to support policy and policy planning. More specifically, system dynamics models are based on causal loop diagrams, stock and flow diagrams and non-linear finite difference integral equations, and the stakeholders form an important part of the methodology (Forrester 1961; Gardiner and Ford 1980; Vennix 1996; Hsiao 1998; Elias et al. 2000; Maani and Cavana 2000). Group model building is a system dynamics model-building process which involves a client group deeply in the process of modelling (Vennix 1996, 1999; Andersen and Richardson 1997; Rouwette et al. 2011).

Many reasons can be found in the literature to take stakeholders into account in the process of model building (de Gooyert et al. 2012), and the participatory model-building interventions can be classified into three distinct types: modelling stakeholder behaviour, modelling with stakeholders and modelling stakeholder behaviour with stakeholders. When the stakeholders are involved in the client group as well as modelling the behaviour of those stakeholders, the intervention should include several iterations. The intervention will support learning for the stakeholders, and learning will change the behaviour and this will invalidate the simulation model used to base on a decision. The simulation model should be updated after each iteration to take the new stakeholder behaviour into account.

Participatory modelling is an approach that includes a broad group of stakeholders in the process of formal decision analysis. It generally includes the stakeholders in the development and/or use of a computer model, although some soft approaches, such as cognitive mapping, does not (Mendoza and Prabhu 2006). Voinov and Gaddis (2008) describe participatory modelling as the process of incorporating stakeholders, often including the public, and decision-makers into an otherwise purely analytic modelling process to support decisions. It involves all the stakeholders to a greater or lesser degree in the process. A fully participatory process is one in which participants help structure the problem, describe the system, create an operational computer model of the system, use the model to identify and test policy interventions and choose one or more solutions based on the model analysis. A minimally participatory modelling process is one in which a model is used to help stakeholders understand the basis for an already selected decision.

Involving the stakeholders in the development process helps them understand a system's interactions and behaviour and can help design management strategy relevant to local concerns. It provides an opportunity to integrate scientific knowledge with local knowledge and builds a shared representation of the problem. When involving stakeholders in the setting of goals, make sure that the model assumptions are appropriate and develop politically feasible solution scenarios to build trust among stakeholders (Tàbara and Pahl-Wostl 2007). Simulation models also allow experimentation for policy design and policy analysis.

Participatory system dynamics modelling uses system dynamics perspective, and the stakeholders or clients participate to some degree in different stages of the modelling process: problem definition, system description, identification of policy levers, model development and/or policy analysis. The steps of the participatory system dynamics modelling and simulation are illustrated in Fig. 7.1. Participatory system dynamics modelling is more than simply eliciting knowledge from clients about the problem and the system. It involves building shared ownership of the analysis, problem, system description and solutions or a shared understanding of the trade-offs among different decisions. Steps in participatory system dynamics modelling are summarised as:

1. Define the problem and develop dynamic hypothesis.
2. Identify and recruit the 'right' stakeholders.
3. Elicit collective understanding of the 'system'.
4. Triangulate collective theory with data and literature.
5. Simulation modelling.

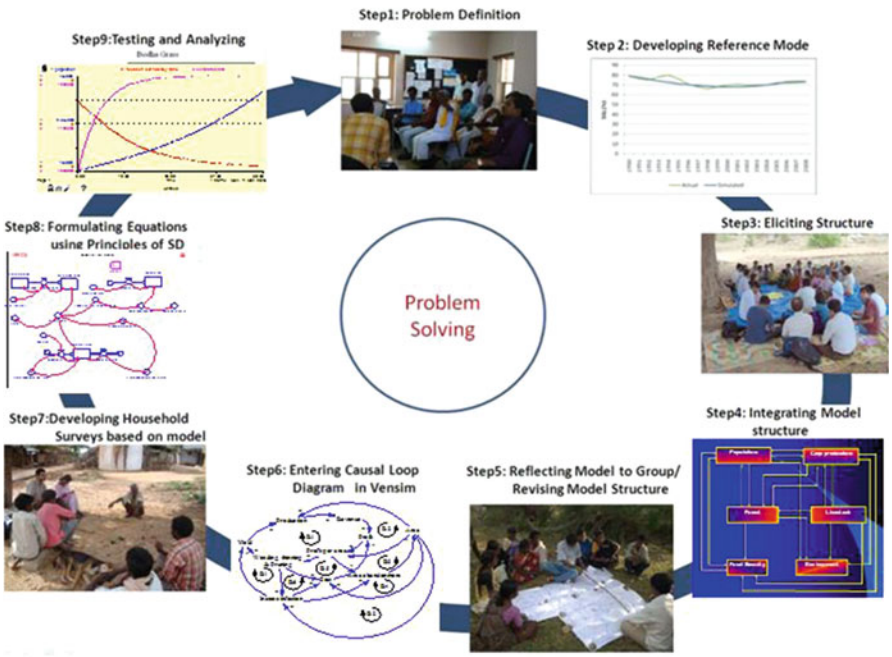

Fig. 7.1 Steps of the participatory system dynamics modelling and simulation (Source: Yadama et al. 2010)

6. Policy levers.
7. More simulation modelling.
8. Policy insights.

The goal of a system dynamics approach is to understand how a dynamic pattern of behaviour is generated by a system and to find leverage points within the system structure that have the potential to change the problematic trend to a more desirable one. The key steps in a system dynamics approach are identifying one or more trends that characterise the problem, describing the structure of the system generating the behaviour and finding and testing leverage points in the system to change the problematic behaviour. System dynamics is an appropriate modelling approach for sustainability questions because of the long-term perspective and feedback dynamics inherent in such questions. One of the key benefits of participatory system dynamics modelling is participant learning about system connections and feedback, both about the system and about other participants.

System dynamics modelling has been used in a number of applications with stakeholder groups examining difficult environmental issues (van den Belt 2004; Mendoza and Prabhu 2006; Langsdale et al. 2009; Beall and Zeoli 2008; Beall and Ford 2010). More recently, Beall and Ford (2010) compared nine cases that used a variety of techniques for engaging stakeholders and problem-solving. These case analyses illustrate the range of issues and settings in which participatory system dynamics modelling can be used and represent the beginnings of efforts to develop best principles and practices.

In participatory model building, the core modelling team mainly builds the model. Multiple participatory model-building sessions are conducted. The structures developed are later integrated to form a larger model. During this process, the community team takes the models to the community and bring back vital information and feedback as given to them by the community members. This iterative process provides significant insights from the community members. These insights are incorporated into the model and are again taken back to the community for reflection. This process is resource intensive, but is imperative to build confidence in the system dynamics modelling. The modelling workshop/focus group discussion is a significant part of the project for many reasons. From the model point of view, the system dynamics workshop/focus group discussion holds special significance because it ensures that the model was built based on key stakeholders embedded in the system and experiencing the dynamic problem and the experts who have been working with the system for many years.

Yadama et al. (2010) reported a participatory system dynamics approach of engaging poor communities and households to model the interactions between household livelihood strategies and natural resource dependence, with a particular focus on forest resources. Drivers of socio-economic and ecological systems and feedback mechanisms between the two are multiple, difficult to generalise and hard to reduce to a core representative set. The methodological strategy of using participatory rural appraisal techniques in combination with participatory system dynamics model building was used to elicit data on a key dynamic problem over time in a forest-dependent community. The goal was to develop dynamic models based on the knowledge and behaviour of actors most directly embedded in particular social–ecological systems. It was emphasised that people, dependent on natural resources for their living, are the real experts to help develop dynamic models of human and natural system interaction and outlined the four phases in which participatory approaches were used to work with a community to identify a dynamic problem that concerns forest resource dependence and their livelihoods, the associated reference modes that portray the dynamic model. In this way confidence in the initial models that emerge from the community were built up and reflections on community-driven participatory modelling were developed.

7.4 Participatory System Dynamics-Based Scenario Planning

Scenario planning attempts to capture the richness and range of possibilities, stimulating the decision-makers and managers to consider changes they would otherwise ignore. At the same time, it organises those possibilities into stories that are easier to grasp than huge volume of data. Above all, however, scenarios are aimed at challenging the manager's mental models and their prevailing mindsets (Cavana 2010). A scenario is not a forecast or an intention to describe a future state, but it is intended to provide a possible set of future conditions. However, scenarios must help decision-makers develop their own feel for the future of the system, the forces at work within it, the uncertainties that underlie the alternative scenarios and the concepts useful for interpreting key data (Wack 1985).

There are several alternative ways of constructing scenarios, but a method most consistent with system dynamics modelling and simulation proposed by Nakajima et al. (2014) is presented here (Fig. 7.2). This method consists of creating policy options based on system dynamics modelling and scenario repeatedly and then better scenario is achieved, and in this method the simulation results play the role to system dynamics and scenario planning.

We can easily perform the simulation using causal loop diagrams and stock–flow diagrams and system dynamics model strongly related to causal loop diagram and stock–flow diagram. The model can be used to get simulation results. Conversation

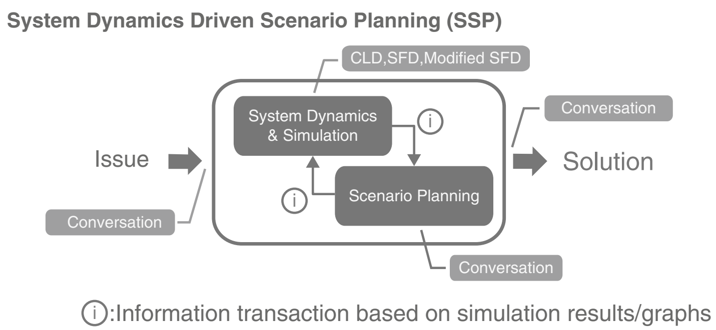

Fig. 7.2 Method of scenario planning

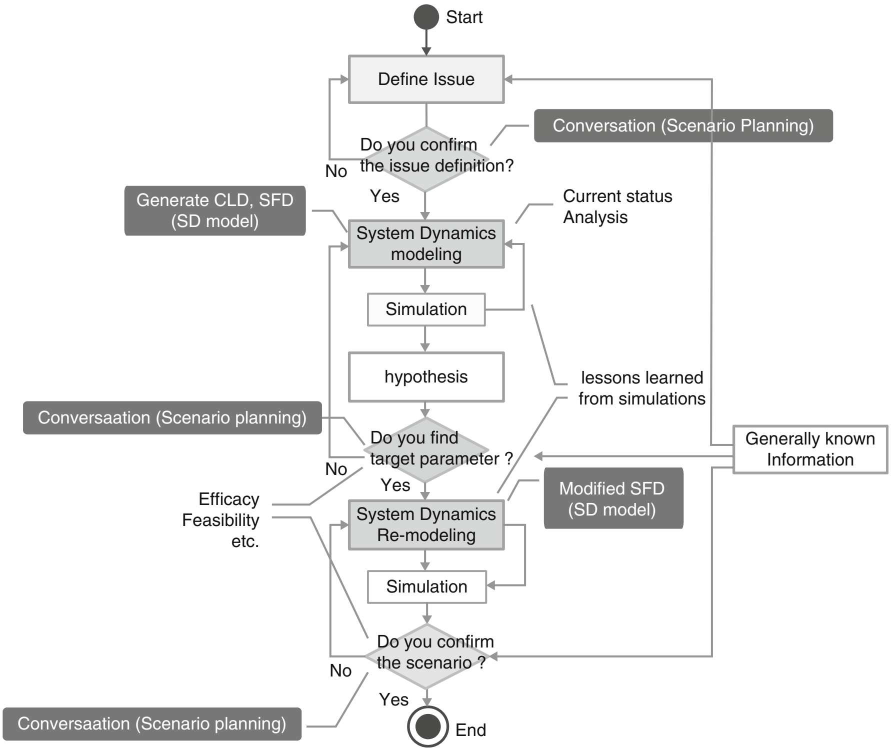

Fig. 7.3 Process of scenario planning

is an effective way in the process of scenario planning. The scenario is a kind of hypothesis. If it is validated, it becomes a theory. Thus, scenario is a speculative idea. There are merits and demerits of conversation in scenario generation. But there are more merits than demerits to improve the accuracy of the generated scenarios as a solution through the conversation. Of course, conversation is a kind of human interface to confirm the important decision among the members.

Now participatory process of scenario planning is discussed (Fig. 7.3). First of all, the issue, i.e. the problem, is defined involving the stakeholders through conversation as an approach of scenario planning. The next step is to develop causal loop diagrams and stock–flow diagrams. After this, the model is simulated to generate the dynamic behaviour. Once the model is simulated, a hypothesis is made and target parameters are identified having conversation with the stakeholders. Finally, policy scenarios are developed based on the simulation results having conversation with the stakeholders.

In order to understand the current status of rice self-sufficiency in Malaysia, we simulated the food security model of Malaysia. We used the simulation model to derive a policy scenario. Though it is known that a simulation is useful for discussion regarding rice food security in Malaysia, the discussion process which is based on simulation result is tied to a policy scenario.

The system dynamics model is not to predict point by point. Rather, it is intended to understand the behaviour of the system and to confirm how the behaviour of the system changes as a result of setting different values of parameters. In addition, changing the values of the parameters or changing the model, we can learn the behaviour of the system from the simulation results. However, to undertake scenario analysis, we cannot consider every possible change that may take place in the future. Instead, we need to identify the changes that are likely to happen or could have the largest impact on the system performance. Also, we need to consider the variables, parameters and factors that are uncertain or are most important to the system.

7.4.1 Simulation

The modelling of food security in Malaysia was simulated and it confirmed the behaviour of the food security in Malaysia. The purpose of this simulation was to make policy scenarios for food security in Malaysia.

Firstly, the model was simulated to know the possibility of occurrence of rice self-sufficiency in Malaysia. Next, the model was simulated to know how much food self-sufficiency in rice in Malaysia can be achieved. The factors which have the possibility to control were identified and simulations were conducted. From the simulation it was realised that a rice self-sufficiency of 73% can be achieved in 2025 which then gradually decreases to 22% in 2050.

7.4.2 Scenario

Having identified a range of uncertainties and factors that could have an impact on the system performance, scenarios are developed. These scenarios are then needed to be checked for internal consistency, and some additional research is needed to determine the realistic boundary values for the parameters and graphical relationships so that learning scenarios can be developed.

7.5 Steps in Scenario Planning

The steps in the scenario planning using system dynamics are as follows:

1. Define and confirm the issue through conversations.
2. Recognise current status using simulation results.
3. Make a hypothesis to solve the problem.
4. Figure out the parameters which change the behaviour of the system using causal loop diagram, stock–flow diagram and simulation results.
5. Learn the effectiveness of the parameter which influences the system behaviour using remodelling stock–flow diagram and simulation.

6. Verify the feasibility of the parameter using generally known information and generate scenario.
7. Confirm the scenarios through conversation.

7.6 Policy Planning for Different Development Strategies and Modelling

Policy planning for the strategic management process allows top managers to find answers to questions related to strategy effectiveness under a variety of alternative policy scenarios. Particularly, specific initiatives for awakening the awareness of the target stakeholders could be identified, ideas could be generated of how to stir up with the different policies, discovery could also occur of what would be the best strategies to stimulate growth and so on. In turn validated simulation models can verify answers to the above questions with a specific degree of certainty. Further, sensitivity analysis can provide a deep understanding of the structure and behaviour of future scenarios and may be modelled. Based on the investigative research method of computer simulation and experimentation, plausible strategies can be tested for their effectiveness prior to their implementation. In this way possible mistakes which can prove detrimental can be avoided.

7.7 Policy Planning for Implementation of the Development Strategy and Modelling

Once confidence in the structure and behaviour of the model has been established and policy design has been completed involving all the stakeholders, the model can be considered for implementation. For successful implementation, emphasis should be given on involving the target stakeholders, communicating modelling insights and demonstrating different development scenarios and outcomes of the short-run and long-run policy implication.

7.8 Policy Design and Evaluation

Once system dynamics models are developed and tested for building confidence, these can be used for policy design and evaluation. Policy design is more than changing the values of the parameters. Policy design includes creating new strategies, structures and decision rules (Sterman 2000). Policy design should be based on the interventions needed to achieve the desired goals from the dynamics of policy scenarios developed involving all the stakeholders. Of course, the policy options should be selected based on the dynamics of some selected indicators of the simulated scenarios. Also, the robustness of the policies and their sensitivities to the uncertainties of the model parameters and structures must be assessed. Policy evaluation should be conducted before and during implementation phases involving all the stakeholders to design corrective measures needed.

7.9 Some Examples of Scenario Planning and Modelling

System dynamics is an effective systematic method for making policy scenario. An example of the system dynamics model used for scenario planning is shown in Fig. 7.4, and from simulation results, the parameter that impacted the behaviour of the system is recognised. Our main focus is scenario planning and modelling. In this phase we formulate and test different policies and strategies of food security in Malaysia. Here policy refers to changes to a single internal variable such as

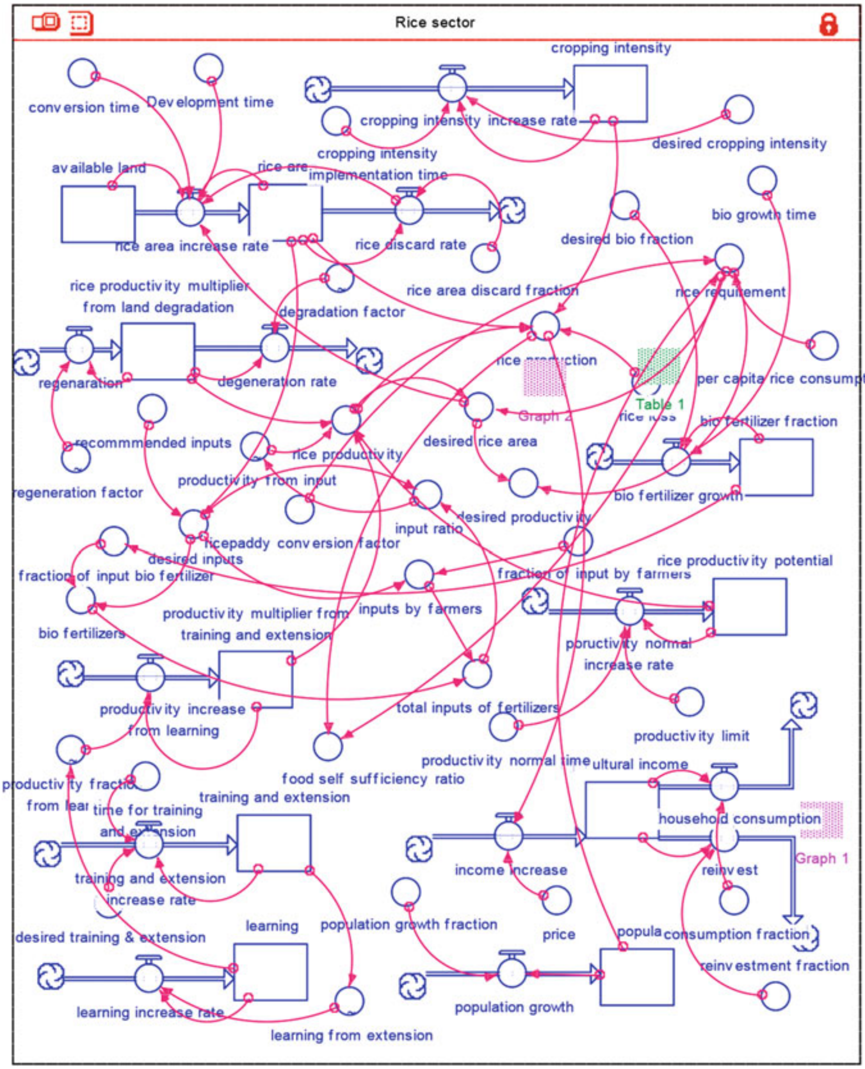

Fig. 7.4 Flow diagram of the system dynamics model of rice production systems

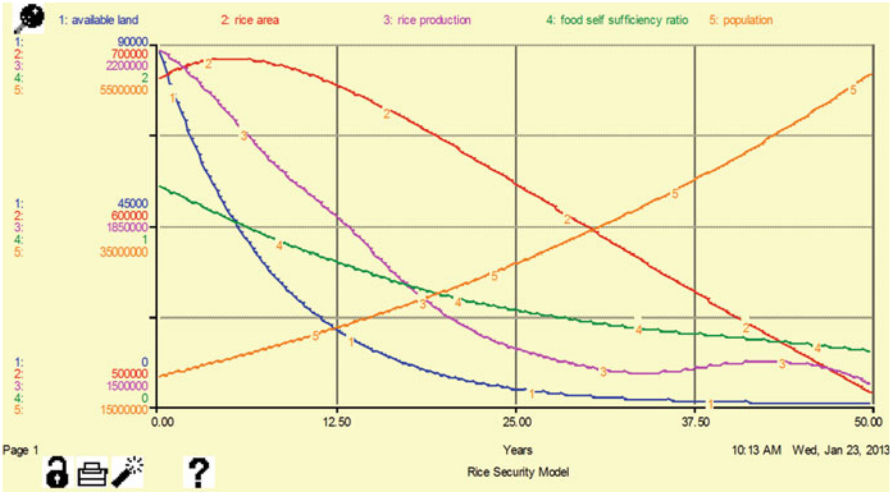

Fig. 7.5 Simulated rice production and rice self-sufficiency level for agricultural subsidies in inputs

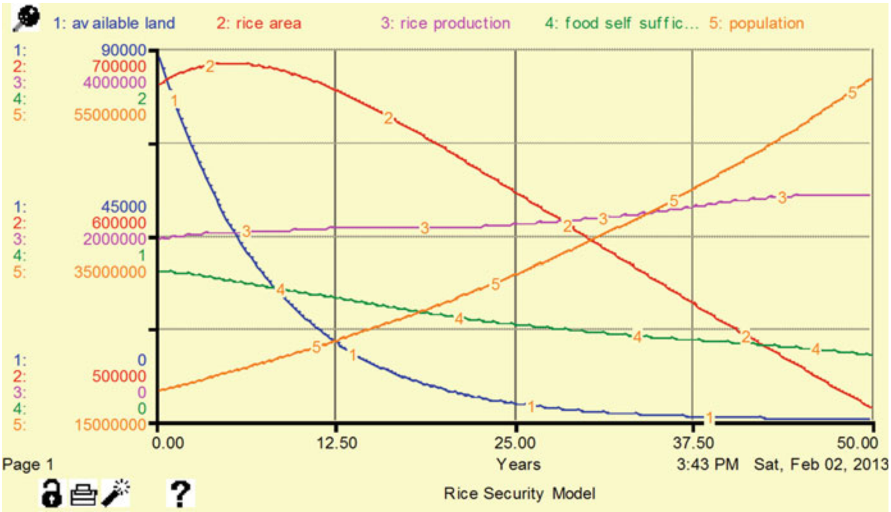

Fig. 7.6 Simulated rice production and rice self-sufficiency level for gradual transition to bio-fertilisers (50 %) and R & D

potential yield and extension services. Strategy is the combination of a set of policies and as such deals with internal or controllable changes. When these strategies are tested under varying external conditions, this is termed as a scenario modelling. This involves working closely with all major stakeholders. Figure 7.5 shows the behaviour of food security in Malaysia under business as usual condition. Figures 7.6, 7.7 and 7.8 show three scenarios for sustainable development of rice

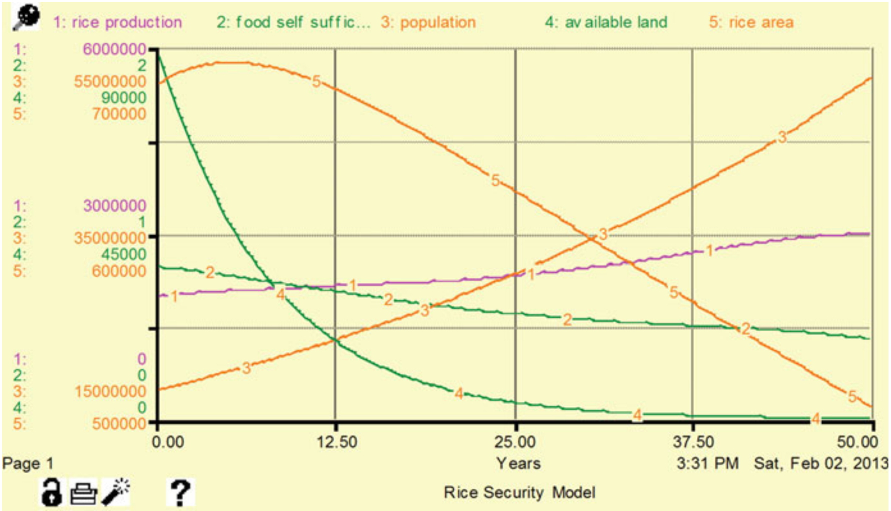

Fig. 7.7 Simulated rice production and rice self-sufficiency level for gradual transition to bio-fertilisers (50 %), R &D and training and extension

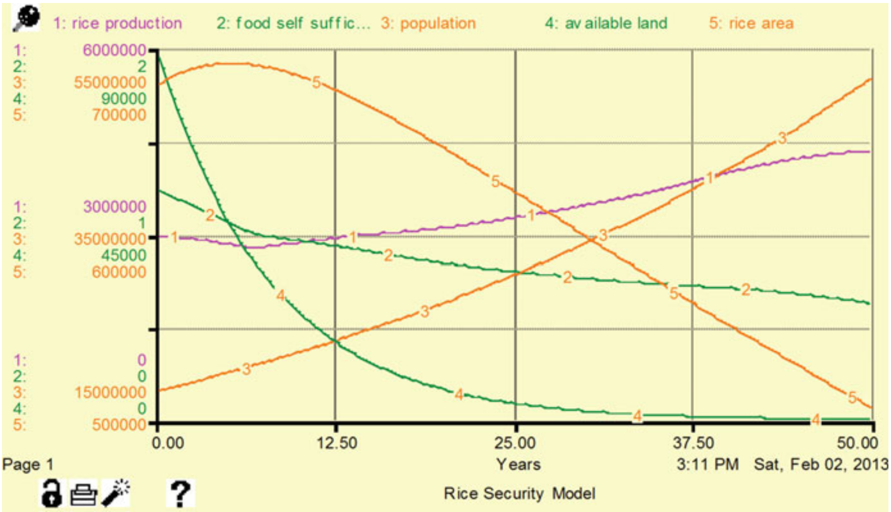

Fig. 7.8 Simulated rice production and rice self-sufficiency level for gradual transition to bio-fertilisers (50 %), R & D, training and extension and cropping intensity

self-sufficiency in Malaysia. These scenarios as the solution of rice self-sufficiency in Malaysia are derived from system dynamics simulation results and scenario making through conversations of rice self-sufficiency in Malaysia. Finally, we have developed scenario planning based on the results of the simulations.

Exercises

Exercise 7.1 What is scenario planning and modelling? How stakeholders can be involved in scenario planning and modelling?

Exercise 7.2 What is participatory system dynamics modelling? Describe steps in participatory system dynamics modelling.

Exercise 7.3 What is participatory system dynamics scenario planning? Describe the method of system dynamics-based scenario planning.

Exercise 7.4 What is scenario planning? Describe the process of scenario planning. What are the steps in scenario planning?

Exercise 7.5 How policy planning for different development strategies and modelling can aid the managers to avoid the possible mistakes? For successful implementation, what should be emphasised?

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Part II

Cases and Applications

8 Modelling of Boom and Bust of Cocoa Production Systems in Malaysia

In the previous chapters in Part I, the concepts, methodology and techniques of system dynamics modelling and simulation in the areas of agricultural, biological, environmental and socio-economic systems are presented. This chapter presents applications of system dynamics modelling in ecological systems of boom and bust of cocoa production systems in Malaysia to demonstrate how to construct a system dynamics model and simulate it for policy planning and design. The model presented is an illustration of modelling and simulation of practical problems, and such an experience is essential to face the challenge of modelling and simulation of dynamic systems. To achieve this goal, the model of this case study is organised as follows: (1) introduction, (2) dynamic hypothesis, (3) causal loop diagram, (4) stock–flow diagram, (5) model validation, (6) simulation and policy analysis and (7) conclusion. The simulated results indicate that the collapse of cocoa production systems can be avoided through biodiversity conservation and insect control resulting from sustainable production systems and implementation of such policy demands adequate subsidy to retain high biodiversity, control pest and disease and attain acceptable yields through extension services through farmer field schools.

8.1 Introduction

The cocoa tree (*Theobroma cacao L.*) is an understorey forest species which evolved in the Amazon (Motamayor et al. 2008), and it is currently grown in many countries of the humid tropics. The largest cocoa-producing countries are Cote d'Ivoire, Ghana, Indonesia, Nigeria, Cameroon, Brazil, Ecuador and Malaysia, and these contribute 90 % of world production (Latiff 2007). Cocoa beans are primarily exported to Europe and North America to be processed to produce cocoa and chocolate.

Cocoa was introduced into Malaysia for commercial cultivation in 1950, became the third major commodity product in Malaysia after palm oil and rubber and was

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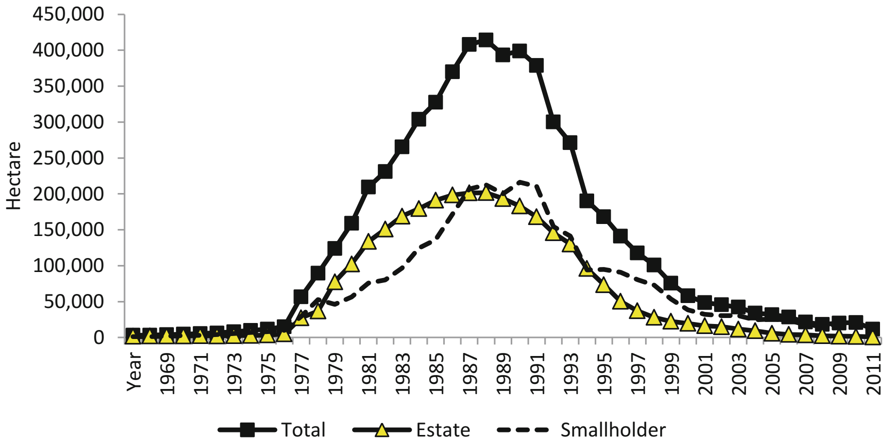

Fig. 8.1 Cocoa cultivation by type of holdings in Malaysia (Source: Department of Statistics, Malaysia 2014)

considered to be a crop for agricultural diversification in the Second Malaysia Plan, 1971–1975. The availability of superior planting materials and planting technology and the implementation of the government policy to encourage the growing of cocoa as an intercrop with coconuts coupled with the high favourable prices led to the rapid expansion of the cocoa planting industry in Malaysia (Fig. 8.1). The area planted increased to 123,855 ha in 1980 and 414, 236 ha in 1989. The high plantation rate is attributed to the unprecedented high cocoa bean prices in the 1970s and 1980s. (Lee 2013). But post-1980s marked a decrease in cocoa planting area with the decline of cocoa production due to poor world cocoa prices, labour constraints, competition for land use from oil palm cultivation and the severe spread and infestation of the cocoa pod borer (Lee 2013). The cultivated area decreased sharply from 393,465 ha in 1990 to 190,127 in 1995, and it continued till 2005 and the area was reduced to 33,398 ha due to severe pest infestation. By 2013, the cocoa planted area was reduced to only 13,728 ha. Fluctuations with small decline in cocoa areas were noted from 2005 (33,398 ha) to 2013 (13,728 ha), and during this period, strong government support was provided for cocoa planting especially in the rural and outlying areas to improve livelihood and elevate income with poverty reduction with targeted area of 40,000 ha by 2020 (MPIC 2011). However, there is an apparent uptrend of cocoa dried bean prices throughout the three regions of Malaysia as that of world cocoa prices. Malaysia has been dropped to the 12th position from 4th position in the world cocoa production (Lee 2013).

Questions remain to answer: What caused the boom and bust of cocoa plantation in Malaysia in particular? Why do cocoa plantations exhibit an extremely unstable pattern of development with ecological damages of biodiversity resulting from outbreak of severe pest infestation and diseases? What should be the policy for sustainable development of cocoa production systems in Malaysia?

Several studies have reported on the boom and bust of agricultural commodities like the shrimp aquaculture industry (Arquitt et al. 2005; Bala and Hossain 2010; Prusty et al. 2011). In these cases, from a systems perspective, we can conclude that when the industry is prone to exceed and consume its environmental carrying capacity, a boom and bust type of development results. Clough et al. (2009) reported a qualitative model of the boom and bust of the cocoa production systems. Franzen and Mulder (2007) highlighted the important ecological, economic and social considerations for sustainable cocoa production. This clearly indicates that there is a large research gap to understand the boom and bust and to search for policies for sustainable development of cocoa production and marketing in Malaysia.

Cocoa trees can be planted in the forest or under planted shade, but most cocoa plantations are planted into thinned forests. Shade removal increases the yield in the short run which damages ecosystems and reduces the biodiversity. As the boom busts, the plantation area falls sharply to a very low level due to extremely low productivity. Underlying production busts are failures of the industry participants particularly the policy makers to understand the problem and take effective measures. However, the boom and bust of cocoa production in Malaysia has been well documented (Lee 2013). Current cocoa production systems are not sustainable because of non-eco-friendly production of cocoa beans, although there is a demand of cocoa in chocolate industries. Sustainable development of cocoa production and marketing is a major concern for the policy makers and authorities who are searching for a sustainable planning to accomplish the targeted goals. Although boom and bust is the major concern, in addition, the sustainable development aims to achieve social, economic and ecological success in the cocoa production. However, sustainability cannot be achieved unless the ecological imbalance is rectified. The sustainable production should increase profit within the framework of ecological conservation of biodiversity. To cover this gap of understanding of boom and bust and designing sustainable production of cocoa beans and propose a realistic model which can add not only knowledge of boom and bust but also the implementation knowledge of sustainable production of cocoa in Malaysia, Fatimah et al. (2015) developed a system dynamics model to examine the underlying causes of the boom and bust of cocoa production systems in Malaysia and developed policies for sustainable development of production of cocoa in Malaysia. The modelling of the boom and bust of cocoa production systems presented here is adopted from Fatimah et al. (2015).

8.2 Dynamic Hypothesis

The dynamic hypothesis is a conceptual model typically consisting of a causal loop diagram, a stock–flow diagram or their combination. The dynamic hypothesis seeks to define the critical feedback loops that drive the system's behaviour. When the model based on the feedback concept is simulated, the endogenous structure of the model should generate the reference mode behaviour of the system, and thus, the endogenous structure causes the changes in dynamic behaviour of the system (Sterman 2000). The boom and bust of cocoa production systems can be represented by causal loop diagram and stock–flow diagram, and the simulation model based on the causal loop diagram and stock–flow diagram can generate dynamic behaviour of the cocoa production systems. The cocoa production systems in the form of causal loop diagram and stock–flow diagram are hypothesised to generate the observed boom and bust of cocoa production systems in the reference mode. In essence, the degradation of the biodiversity resulting from the reduction of shade level and subsequent large-scale insect infestation caused the boom and bust of cocoa production systems in Malaysia (Fig. 8.1), and this dynamics resulted from the endogenous consequences of the feedback structure (Sterman 2000).

8.3 Causal Loop Diagrams

The key factors influencing cocoa production are yield, thinning of shading trees and area under cultivation. The boom and bust of cocoa production in Malaysia is described by two reinforcing loops and six balancing loops. When production of cocoa and thinning generate profit for the producers, these motivate them to continue cultivation generating a feedback loop to work (R_1). Also when production of cocoa generates profit per ha, the producers are motivated to increase cultivated area (R_2). Area under cultivation and thinning of shading trees which creates ecological imbalance invites insect infestation. When insect infestation becomes intolerable and cocoa beans are damaged significantly, the cocoa production is affected negatively (B_1), and also cultivation is abandoned due to severe insect infestation (B_2). Profit per ha also is deciding factor for abandonment of cultivation area (B_3), and the cultivation cost affects the profit per ha (B_4). Thinning cost and cost incurred in insect infestation also affect profit per ha (B_5 and B_6). The dynamic interaction between cocoa production and ecology gives rise to the feedback loops. The causal loop diagrams of cocoa production systems are shown in Fig. 8.2 which shows the initial dynamic hypothesis of the boom and bust of cocoa plantation, and it is based on standard assumptions of how the cocoa production system typically works. If our hypothesis is correct, the model will be able to reproduce the general historical pattern of boom and bust followed by the simulated boom and bust of cocoa plantation.

8.4 Stock–Flow Model

Figure 8.3 shows the stock–flow diagram of the boom and bust of cocoa production systems in Malaysia. Fundamental equations that correspond to major state variables shown in Fig. 8.3 are as follows:

The cocoa plantation area is increased by the cocoa plantation rate based on the profitability of the cocoa plantation, and also the cocoa plantation area is abandoned based on yield and profit. This is expressed as:

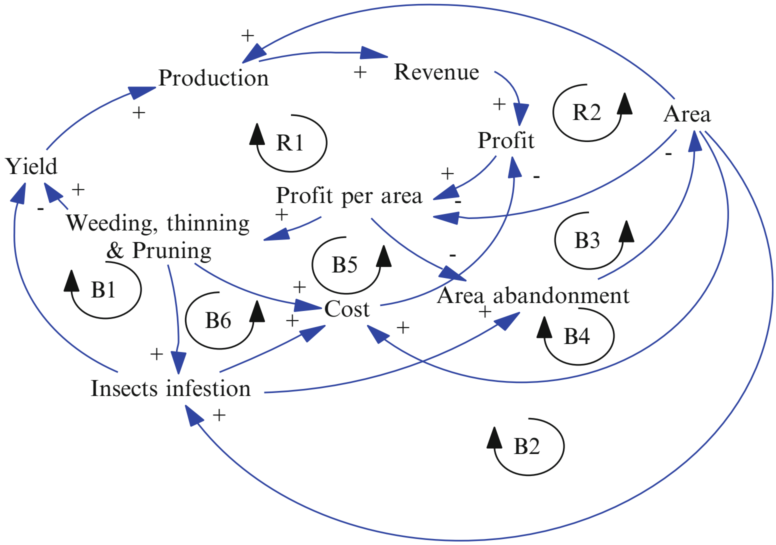

Fig. 8.2 Causal loop diagrams of cocoa production system

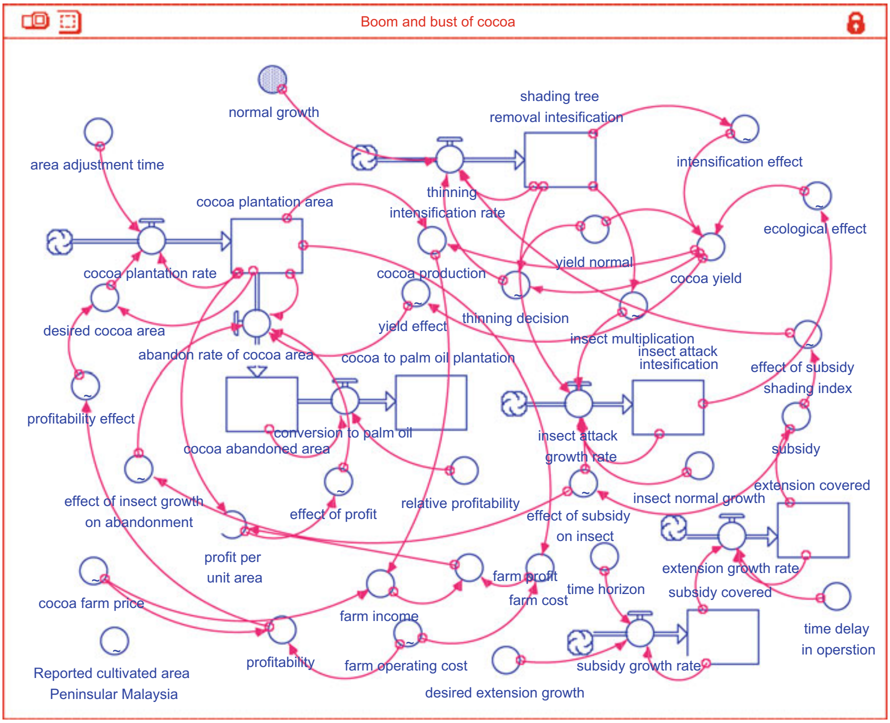

Fig. 8.3 Stock–flow diagram of boom and bust of cocoa production in Malaysia

$$\text{cocoa plantation area}\,(t) = \text{cocoa plantation area}\,(t-\Delta t) + \text{cocoa plantation rate} \times \Delta t - \text{abandon rate of cocoa} \times \Delta t \tag{8.1}$$

The cocoa plantation rate depends on the present level of the cocoa plantation area, the desired cocoa area and the time delay to reduce the gap between the desired cocoa area and level of cocoa plantation area, and it is expressed as:

$$\text{cocoa plantation rate} = \text{MAX}\big(0, (\text{desired cocoa area} - \text{cocoa plantation area}) / \text{area adjustment time}\big) \tag{8.2}$$

Desired area is computed from the level of the cocoa plantation area and profitability effect as:

$$\text{desired cocoa area} = \text{cocoa plantation area} \times \text{profitabilty effect} \tag{8.3}$$

The expansion of the cocoa area depends on the profitability of cocoa production and the non-linear relationship between profitability effect and profitability is expressed as:

profitability_effect = GRAPH(profitability)
(0.00, 0.02), (0.1, 0.738), (0.2, 1.16), (0.3, 1.50), (0.4, 1.76), (0.5, 2.00), (0.6, 2.14), (0.7, 2.21), (0.8, 2.24), (0.9, 2.24), (1, 2.27)

Abandon rate of the cocoa area depends on the level of the cocoa plantation area, yield effect and effect of profit, and it is expressed as:

$$\text{abandon rate of cocoa area} = \text{cocoa plantation area} \times \text{yield effect} \times \text{effect of profit} \tag{8.4}$$

The abandonment of cocoa area under cultivation depends on the yield of cocoa and the non-linear relationship between yield effect on the abandonment of cocoa cultivation area and yield of cocoa is expressed as:

yield_effect = GRAPH(cocoa_yield)
(0.00, 0.645), (1.00, 0.555), (2.00, 0.47), (3.00, 0.41), (4.00, 0.37), (5.00, 0.32), (6.00, 0.29), (7.00, 0.26), (8.00, 0.23), (9.00, 0.215), (10.0, 0.21)

Also the abandonment of cocoa area under cultivation depends on the profit per unit area and the non-linear relationship between effect of profit on the abandonment of cocoa cultivation area and profit per unit area is expressed as:

effect_of_profit = GRAPH(profit_per__unit_area)

(0.00, 1.11), (10.0, 1.09), (20.0, 1.08), (30.0, 1.07), (40.0, 1.06), (50.0, 1.05), (60.0, 1.04), (70.0, 1.03), (80.0, 1.03), (90.0, 1.03), (100, 1.02)

Cocoa yield is increased by the development of new hybrid varieties of cocoa through research and development, and also it depends on the ecological effect resulting from insect infestation due to limiting the shading index and intensity of shading index. This is described as:

$$\text{cocoa yield} = \text{yield normal} \times \text{ecological effect} \times \text{intensification effect} \tag{8.5}$$

The ecological effect resulting from the degradation of biodiversity and hence insect infestation affects the cocoa yield and the non-linear relationship between ecological effect and insect attack intensification, and it is expressed as:

ecological_effect = GRAPH(insect_attack__intesification)
(0.00, 1.00), (8.33, 0.87), (16.7, 0.725), (25.0, 0.535), (33.3, 0.41), (41.7, 0.335), (50.0, 0.24), (58.3, 0.2), (66.7, 0.11), (75.0, 0.075), (83.3, 0.045), (91.7, 0.02), (100.0, 0.005)

The shading tree removal enhances not only the cocoa yield, but it also invites insect infestation and the non-linear relationship between intensification effect and shading tree removal intensification is expressed as:

intensification_effect = GRAPH(shading_tree__removal_intesification)
(0.00, 1.04), (8.33, 1.18), (16.7, 1.24), (25.0, 1.29), (33.3, 1.34), (41.7, 1.37), (50.0, 1.41), (58.3, 1.45), (66.7, 1.46), (75.0, 1.48), (83.3, 1.48), (91.7, 1.48), (100.0, 1.48)

Yield normal is increased by development of new high-yielding/hybrid varieties through research and development.

Shading index reduction increases the yield in the short run, but large-scale reduction of shading index invites insect infestation which results in ecological degradation in the long run. Shading index is reduced by thinning the trees for higher yields in case of cocoa plantation under forest trees, and also shading index can be adjusted by changing the plant-to-plant distance of the coconut tree in case of cocoa plantation under coconut plantation, and the shading removal intensification is expressed as:

$$\begin{aligned}\text{shading tree removal intensification}\,(t) &= \text{shading tree removal intensification}\,(t - \Delta t)\\ &\quad + \text{thinning intensification rate} \times \Delta t\end{aligned} \tag{8.6}$$

The thinning intensification rate depends on the present level of shading tree removal intensification, cocoa yield and subsidy for shading.

Shading tree and cocoa plants invite the insects, and the severity of insect damage depends on the intensity of insect attack, and the insect attack intensification is expressed as:

$$\begin{aligned}\text{insect attack intensification}\,(t) = {} & \text{insect attack intensification}\,(t - \Delta t) \\ & + \text{insect attack growth rate} \times \Delta t\end{aligned} \tag{8.7}$$

The insect attack growth rate depends on the present level of insect population, insect multiplication, shading tree removal intensification level and subsidy to control insects.

Cocoa production in Fig. 8.3 depends on cocoa yield (tons/ha) as well as on area under cocoa plantation, and it is computed as:

$$\text{cocoa production} = \text{cocoa yield} \times \text{cocoa area} \tag{8.8}$$

The coverage of the subsidy and extension through farmer field schools is expanded with a broad policy of high biodiversity and acceptable yields for sustainable development. These are described as:

$$\begin{aligned}\text{extension covered}\,(t) = {} & \text{extension covered}\,(t - \Delta t) \\ & + \text{extension growth rate} \times \Delta t\end{aligned} \tag{8.9}$$

and

$$\text{subsidy covered}\,(t) = \text{subsidy covered}\,(t - \Delta t) + \text{subsidy growth rate} \times \Delta t \tag{8.10}$$

The extension growth rate depends on the subsidy covered, present level of subsidy and time horizon in operation.

These systems of equation are solved by Runge–Kutta fourth-order method using STELLA software.

8.5 Model Validation

Initial values and the parameters were estimated from the primary and secondary data collected from different research reports, statistical year books of Malaysia and field visits. Tests were also conducted to build up confidence in the model. Tests for building confidence in system dynamics models essentially consist of validation, sensitivity analysis and policy analysis (Bala 1999). The two important notions of the building confidence in the system dynamics models are testing and validation of the system dynamics models. Testing means the comparison of a model to empirical reality for accepting or rejecting the model, and validation means the process of establishing confidence in the soundness and usefulness of the model. In the

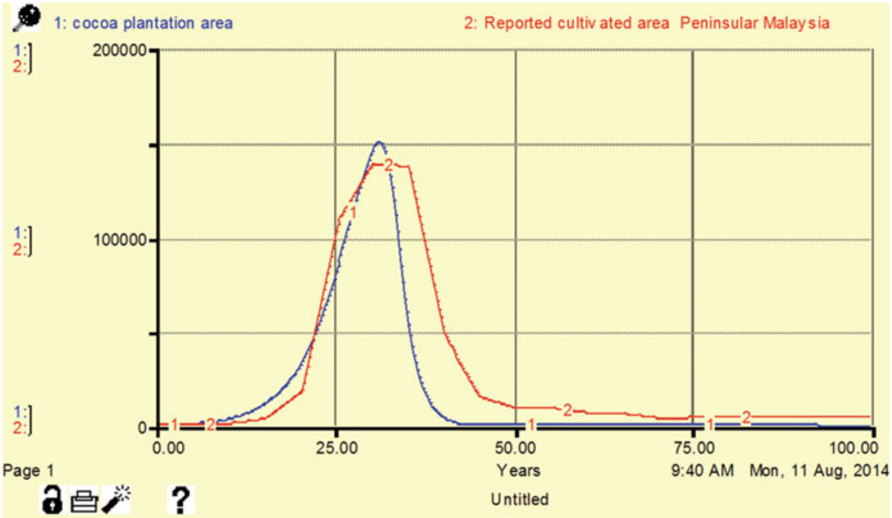

Fig. 8.4 Simulated and historical patterns of boom and bust of cocoa production systems in Peninsular Malaysia

behaviour validity tests, emphasis should be on the behavioural patterns rather than on point prediction (Barlas 1996).

To build up confidence in the predictions of the model, various ways of validating a model such as model structures, comparing the model predictions with historical data, checking whether the model generates plausible behaviour and checking the quality of the parameter values were considered.

Figures 8.4, 8.5 and 8.6 show the comparisons of simulated behaviours of plantation area of cocoa with the historical data. The historical data of cocoa plantation area in Peninsular Malaysia, Sabah and Sarawak show the boom and bust of cocoa production area in Malaysia. Simulated behaviours are numerically sensitive to parameters and shapes of the table functions. However, the basic patterns of the historical and simulated behaviours agree adequately, and model predictions represent reality.

8.6 Simulation and Policy Analysis

Figures 8.4, 8.5 and 8.6 show the collapse of cocoa production systems which may be attributed to mainly the reduction of the shade level which reduces the biodiversity and resulting large-scale insect infestation. The model was simulated to test how cocoa plantation changes with the changes in subsidy for maintaining high biodiversity attain acceptable yields and IPM-FFS (integrated pest management-farmer field schools) for pest management. The subsidy coverage (0–100 %) was gradually increased to cover the extension services (0–100 %) through farmer field schools for maintaining the recommended shading index and hence the biodiversity

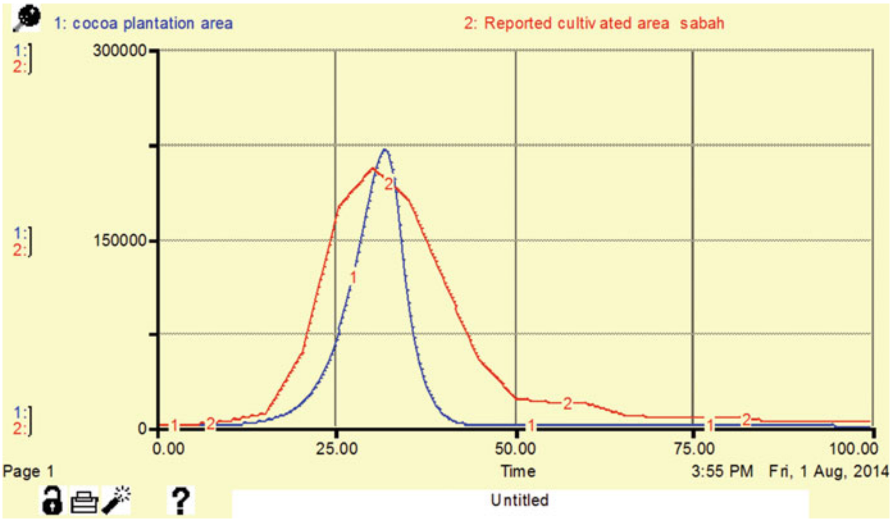

Fig. 8.5 Simulated and historical patterns of boom and bust of cocoa production systems in Sabah, Malaysia

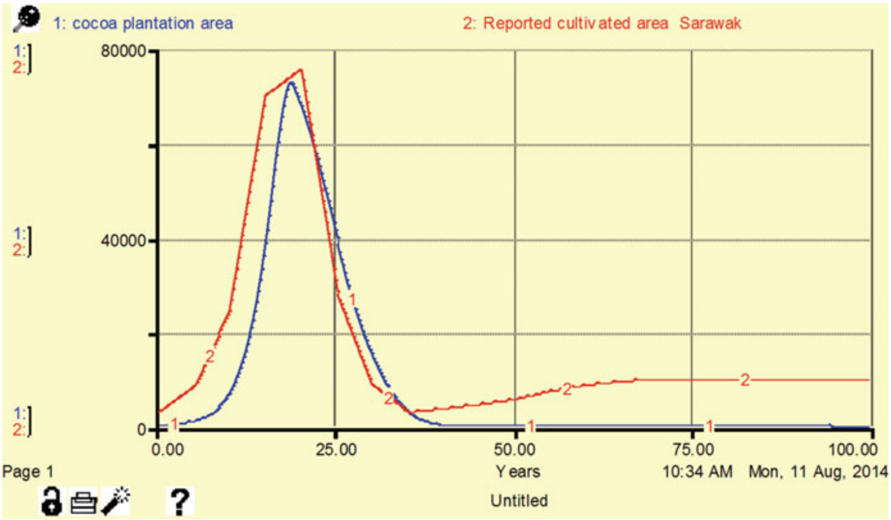

Fig. 8.6 Simulated and historical patterns of boom and bust of cocoa production systems in Sarawak, Malaysia

and providing pest control including IPM. Figure 8.7 shows the simulated cocoa plantation area for full subsidy (curve 3), 80 % subsidy (curve 2) and 60 % subsidy (curve 1) of the cost to cover conservation practices and insect control. The system is sustainable for full subsidy since financial support is provided for joint trade-off

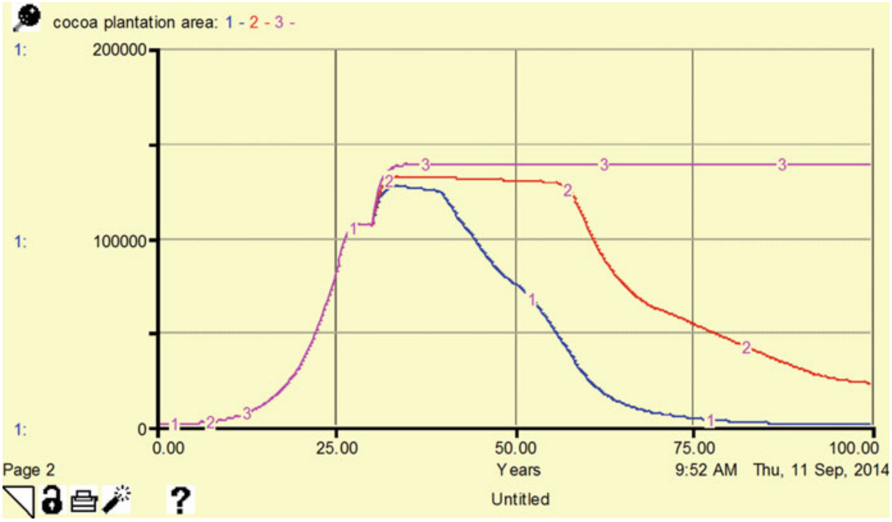

Fig. 8.7 Sensitivity analysis of subsidy for cocoa production systems in Malaysia

of biodiversity and yield along with IPM pest control through FFS, but the sustainability decreases with the degree of reduction of subsidy as there are lesser opportunities available to maintain biodiversity and insect control in terms of financial support. Waldron et al. (2012) also suggest that a simple development help specifically targeted at cocoa smallholders as the best short-term means to improve the long-term stability of the production in a sustainable environment, together with cocoa smallholders' economic status.

The model was also simulated for integration of subsidy with extension through farmer field schools to retain high biodiversity and attain acceptable yields along with proper integrated pest management for sustainable development of cocoa production systems in Malaysia. The model was simulated for two options: (1) First option is starting the joint programme of subsidy and extension at the peak of the boom. The subsidy coverage (100 %) at the peak of the boom covers the extension services (100 %) through farmer field schools for maintaining the recommended shading index and hence the biodiversity and providing pest control including IPM and (2) Second option is starting the joint programme of subsidy and extension at the beginning of the boom of cocoa. The subsidy coverage (0–100 %) was gradually increased from the beginning of the simulation period to cover the extension services (0–100 %) through farmer field schools for maintaining the recommended shading index and hence the biodiversity and providing pest control including IPM. Figure 8.8 shows reported results and simulated cocoa plantation area with subsidy and extension through farmer field schools at the peak of the boom, while Fig. 8.9 shows simulated cocoa plantation area with subsidy and extension through farmer field schools for coverage of the cocoa plantation with subsidy and extension through farmer field schools with 5 years of time horizon for

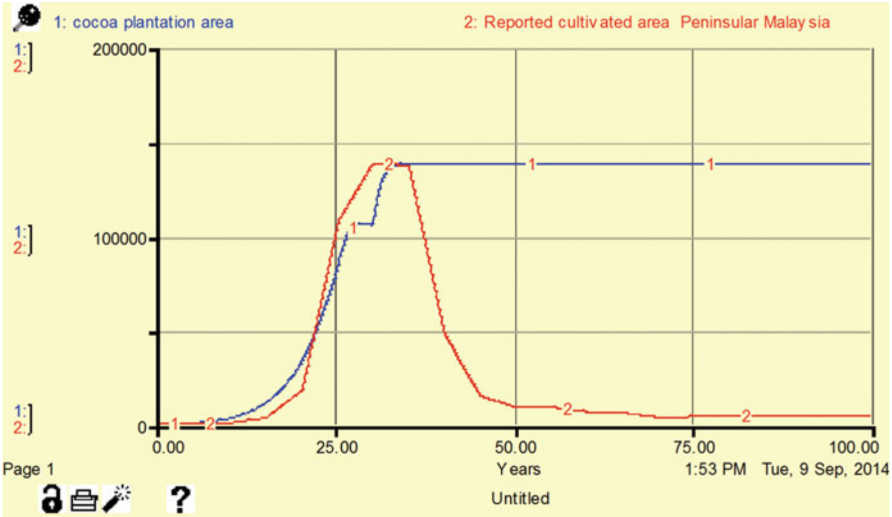

Fig. 8.8 Simulated results for subsidies for thinning and insect control

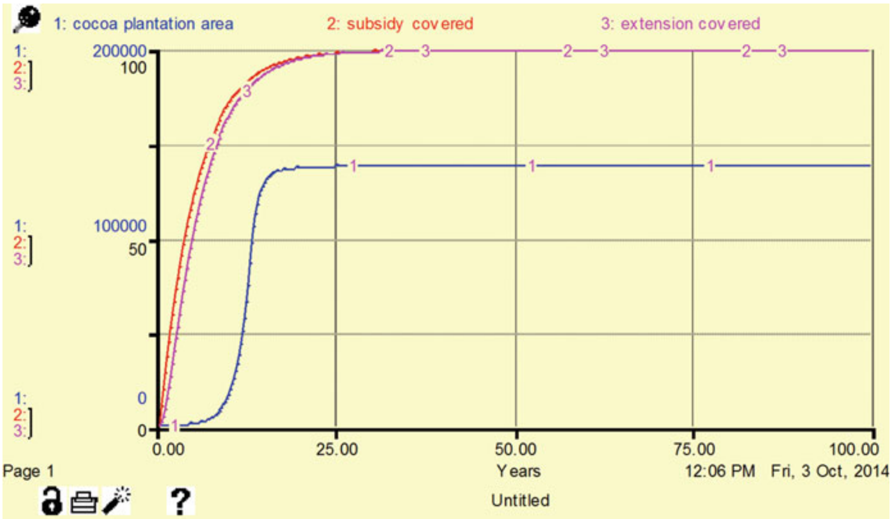

Fig. 8.9 Simulated cocoa plantation area, subsidy covered and extension covered for cocoa production systems in Malaysia

implementation of the subsidy and extension programme. In both the cases, the cocoa plantation area becomes stabilised. The cocoa production with subsidy and extension through farmer field schools at beginning of the production cycle not only stabilises the system but also returns to the stable condition much more quickly. The achievement of the stable cocoa production system largely depends on the success of integrated subsidy and extension programme to attain high biodiversity and acceptable yields through farmer field schools.

8.7 Conclusion

The boom and bust of cocoa production is one of the consequences of the short-term benefit of higher yield at the expense of reducing the biodiversity, thereby decreasing local habitat diversity and subsequently inviting pest and diseases. The subsidy policy proposed limits cocoa production to ecological carrying capacity which can be achieved by maintaining a joint trade-off between the shading index and proper actions for insect control of the cocoa production systems and acceptable yields. Simulated results support that suggested policy can lead to a sustainable production system. The Malaysian case study of the boom and bust of the cocoa production system gives an opportunity to develop a hypothesis of cocoa boom and bust and provided structure for policy simulation for sustainable development. Of course, adequate subsidy with effective extension of technologies from R&D for policy implementation is needed.

Exercises

Exercise 8.1 What do you mean by boom and bust? What caused the boom and bust of cocoa production systems in Malaysia?

Exercise 8.2 Draw the causal loop diagrams of cocoa production systems and then include insect infestation and finally shading of top covers.

Exercise 8.3 Draw a stock–flow diagram of cocoa production systems and explain how a causal loop diagram and stock–flow diagram represent the dynamic hypothesis of cocoa production systems. Also simulate the model.

Exercise 8.4 How can we make somebody to build up confidence in the system dynamics model of cocoa production systems? Also discuss the usefulness of the cocoa production system model.

Exercise 8.5 Discuss the policy issues to stabilise the boom and bust of cocoa production systems in Malaysia. How can the policy of stabilisation of cocoa production systems be implemented using the participatory systems approach?

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Modelling of Hilsa Fish (*Tenualosa ilisha*) Population in Bangladesh

9

In the previous chapter, the modelling and simulation of boom and bust of cocoa production systems in Malaysia have been presented. This chapter demonstrates how to construct a system dynamics model of hilsa fish and simulate the model for policy planning and design for sustainable development. The model presented in this chapter is organised as follows: (1) introduction, (2) dynamic hypothesis, (3) causal loop diagram, (4) stock–flow diagram, (5) model validation, (6) simulation and policy analysis and (7) conclusion to illustrate the system dynamics applications based on systems thinking. Such experiences are essential to face the challenge of modelling and simulation of dynamic systems. The model predicts the long-term trends in the hilsa population over several decades and assesses the impacts of harvesting the juveniles and spawning adults. Simulated results show that increased harvesting of the adults entering the rivers and the juveniles in the rivers cause gradual decline in hilsa fish population and even may cause this valuable resource to disappear within a short period of time. Also the optimal strategies for sustainable development of hilsa fish have been addressed.

9.1 Introduction

Hilsa (*Tenualosa ilisha*) is the national fish of Bangladesh. It is the largest single species fishery in Bangladesh especially during the monsoon and contributes about 22–25 % of the total fish production of the country. The average annual production of hilsa is 200,000 tons, and its value is Tk 20,000 million (1 US dollar = taka 70.00). The contribution of this fish in the GDP of Bangladesh is 1 %, and annually taka 500–600 million is earned as foreign currency from the export of hilsa. It is harvested mainly by gill net, and about 2 % of the total population of Bangladesh is directly or indirectly involved in this fishery.

There is a decline of fisheries worldwide due to overexploitations of the stocks (FAO 1995), and there is also a decrease of about 19 % in harvesting of hilsa in the

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recent years. If this trend continues, the existence of this fish will be at risk, and eventually it will become a rare species.

The sustainable management of marine renewable resources requires integration of biological, economic and social aspects (Nunes et al. 2004; Bald et al. 2009). Considering the importance of hilsa fish in nutrition, diet, employment and economy, the sustainable management of hilsa fishery is very important. For sustainable production of hilsa fish as well as increase in production, sound development policy and management strategies are urgently needed.

Several studies have been reported on modelling of population dynamics of fish (Tian et al. 2004; Robadue and Simanek 2007) and other species such as gooseneck barnacle (Bald et al. 2006). Few studies have been reported on the contributions of overfishing on the decline/collapse of the fish stock (Lillegard et al. 2005; Kaitala et al. 2003). Limited studies have been reported on parameters such as mortality, catch rate and maximum sustainable yield of hilsa using FISAT software (Miah et al. 1997; Amin et al. 2000; Haldar and Amin 2005; Hashemi et al. 2010). Mome and Arnason (2007) reported a simple bioeconomic model similar to FISAT software, and it is not a true model; rather, it is a supplementary model.

The system dynamics simulation model of population dynamics of hilsa fish presented here to assess the policy options and management strategies for sustainable development of hilsa fish is adopted from Bala et al. (2014). To understand and model the population dynamics of hilsa fish, a knowledge of the reproduction system of hilsa fish is essential. To bridge this gap, we present a brief and comprehensive description of the reproduction system of hilsa fish relevant to system dynamics modelling of population dynamics of hilsa fish. Then we focus on the system dynamics modelling of hilsa fish population and examine the harvesting policies of juveniles and spawning adults and the policies for sustainable exploitation of hilsa fish.

There are five species of hilsa under *Tenualosa* genus found in the world. The two species, *Tenualosa ilisha* and *Tenualosa toli* are found in Bangladesh. The availability of hilsa is 50–60 % in Bangladesh, 20–25 % in Myanmar and 10–15 % in India and the rest 5–10 % all over the world.

The species of hilsa is heterosexual, and the females due to faster growth rate attain larger sizes than the males. Shafi et al. (1977a, b) observed that the body of females is broader and the girth is comparatively larger. Opinions differ whether one sex predominates over the other in different phases of the life history of hilsa or whether the distribution conforms to the normal 1:1 ratio. Quereshi (1968) observed that although the sex ratio was 1 during the monsoon, the females dominated in October.

There is some evidence to suggest that there are two different and distinct spawning stocks or varieties. Quddus (1983) reported that the stocks responsible for the two spawnings are different—the ‘broad’ variety taking part in monsoon spawning and the ‘slender’ variety in the winter spawning. Comparative studies by Quddus (1982) of the ‘broad’ and ‘slender’ types of hilsa indicate a highly significant difference between the two types in the fecundity estimates. In the ‘broad’ type, the fecundity estimates range from 0.6 to 1.5 million for the fish in the size range of 33–51 cm and for the 'slender' type from 0.4 to 0.6 million for fish ranging in size from 32 to 49 cm. Hatching takes place in about 23–26 h at an average temperature of 23 °C (Jones and Menon 1951), about 18–26 h at 28.0 °C to 28.5 °C (Kulkarni 1950) and at about 24–28 h (Motwani et al. 1957). The length of the newly hatched larvae is recorded as 2.3 mm by Jones and Menon (1951), 3.1 mm by Kulkarni (1950), 2.50–2.55 mm by Motwani et al. (1957) and 2.4–3.0 mm by Karamchandani (1961).

The juveniles remain in the rivers/estuaries till they probably reach a length of 150–160 mm which is believed to be attained in about 5 months time. It is possible that the seaward migration is undertaken at this size/age. It has been reported that the operation of small-mesh nets in the period immediately succeeding the breeding season results in a large-scale destruction of young fish in Bangladesh waters (Quereshi 1968).

Conflicting views have been expressed on the minimum size of hilsa at first maturity. Hilsa may attain first maturity at the end of the first year or at the beginning of the second year. In Bangladesh waters (Meghna), Shafi et al. (1978) observed a size of 21 cm in the case of males and 32 cm in the case of females, as the size at first maturity.

Hilsa is essentially a plankton feeder, and generally, the items which are preponderant are crustaceans (particularly copepods), diatoms and green and blue algae; organic detritus, mud and sand have also been recorded. Pillay (1958) has reported no evidence of cessation or appreciable decrease in the feeding activity during the spawning period, but some workers reported that during spawning migration, the intensity of feeding decreases or ceases altogether (Pillay and Rosa 1963).

To model the various phases of the life cycle of hilsa fish, the information on the reproduction system such as sex ratio, eggs per nest, larva, juvenile and maturation of hilsa fish from different sources has been carefully examined and incorporated in the model to make it to represent the real-world situations of the hilsa fish in Bangladesh.

9.2 Dynamic Hypothesis

The dynamic hypothesis is a conceptual model, and it hypothesises to define the critical feedback loops to construct stock–flow diagrams that drive the system's behaviour in the reference mode. When the model is simulated, the endogenous structure of the model generates the reference mode behaviour of the system, and thus, the endogenous structure causes the changes in dynamic behaviour of the system. In system dynamics modelling, causal loop diagrams identify the principal feedback loops of a system, and the stock–flow diagrams that describe the structure of the systems are hypothesised to generate the reference mode of the behaviour over time (Stermant 2000). Hilsa population can be represented by causal loop diagrams and stock–flow diagrams, and the simulation model based on the causal loop diagrams and stock–flow diagrams would generate the dynamic behaviour of the hilsa population. The population dynamics of hilsa in the form of causal loop diagrams and stock–flow diagrams are hypothesised to generate the observed hilsa population dynamics in the reference mode. In essence the decline in hilsa population results from the overharvesting of juveniles and spawning adults, and this dynamics results from the endogenous consequences of the feedback structure.

9.3 Causal Loop Diagram

The causal loop diagram of the population dynamics model of hilsa fish is shown in Fig. 9.1. The population dynamics model of hilsa fish is dominated by one positive and four negative loops. The positive loop shows the reproductive and maturation process, ultimately producing more adult hilsa. The number of spawning adults of hilsa fish will determine the number of larvae production and leads to the production of matured adults of hilsa fish. Juvenile rate, prematuration rate, maturation rate and spawning rate have positive effect on the production of hilsa fish. In the absence of any stabilisation, this loop would result in the exponential growth of the hilsa population. The negative feedback loops are balancing loops of the different stages of the life cycle of hilsa fish, and these are deaths of larvae, juvenile, premature adults and matured adults. An increase in the number of hilsa fish population at any stage of the life cycle will increase the number of deaths, and this in turn will decrease the number of hilsa population. Also harvesting at any stage of the life cycle of hilsa fish has a negative effect on the hilsa population. The negative loops cause the stabilisation at the different stages of the life of hilsa fish due to death and harvesting of the hilsa fish.

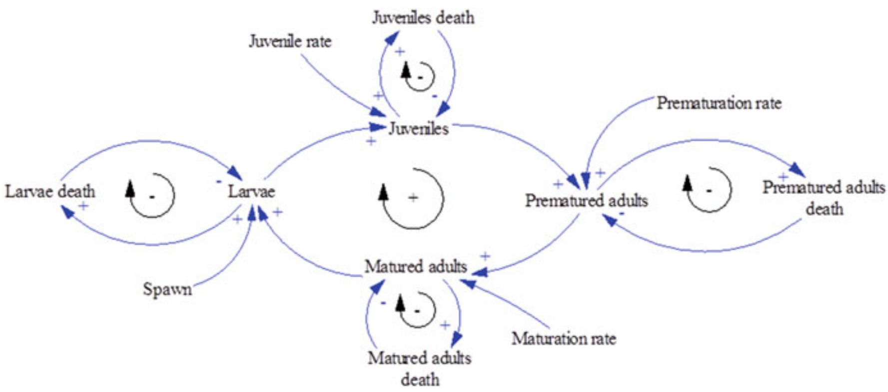

Fig. 9.1 Causal loop diagram of the population dynamics of hilsa fish

9.4 Stock–Flow Diagram

Figure 9.2 shows the stock–flow diagram of the population dynamics of hilsa fish. The flow diagram shows how stocks and flows are interconnected to produce the feedback loops and how the feedback loops interlink to create the system. The model is designed with seven stocks to keep track of the population of hilsa at the various phases of the life cycle is shown in Fig. 9.2. The life cycle begins when the adults of hilsa are about to spawn in rainy season during monsoon for laying eggs. The adults about to spawn in the rainy season for laying eggs can be described as:

$$\begin{aligned} \text{adults\_about\_to\_spawn}(t) = {} & \text{adults\_about\_to\_spawn}(t - dt) \\ & + (\text{adults\_leaving} - \text{adults\_at\_spawning} - \text{harvesting}) * dt \end{aligned} \tag{9.1}$$

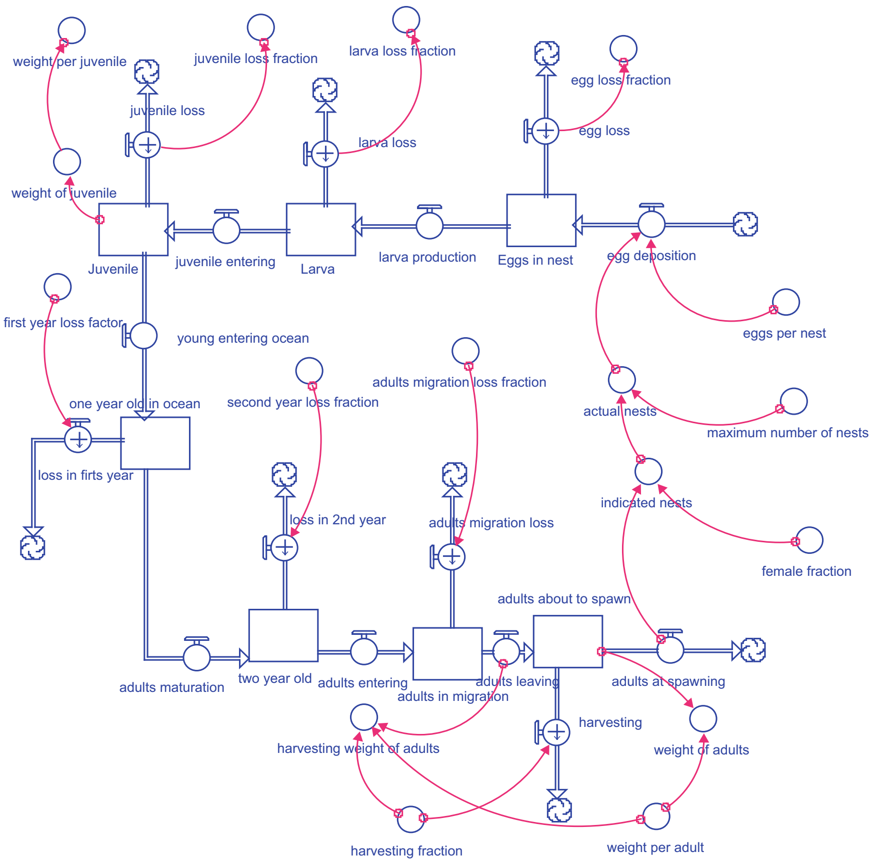

Fig. 9.2 Flow diagram of the population dynamics of hilsa fish

where adults_about_to_spawn(t) is adults about to spawn at time (t), adults_leaving is the 2-year-old adults which have left sea and joined spawning at time (t-dt), adults_at_spawning is the adults which have started spawning at time (t-dt) and harvesting is harvesting rate of adults about to spawn at time (t-dt).

The adults about to spawn lay eggs in the spawning grounds in the rivers and the eggs in the nest can be expressed as:

$$\begin{aligned}\text{Eggs\_in\_nest}(t) = {} & \text{Eggs\_in\_nest}(t - dt) \\ & + (\text{egg\_deposition} - \text{larva\_production} - \text{egg\_loss}) * dt\end{aligned} \tag{9.2}$$

where Eggs_in_nest(t) is eggs_layed in the nest at time (t), egg_deposition is egg deposited in the nest at time (t-dt), larva_production is the larva produced from eggs at time (t-dt) and egg_loss is egg lost in the nest at time (t-dt).

These eggs hatch 1 month later and larvae are produced from the eggs. The production of larvae can be expressed as:

$$\begin{aligned}\text{larva}(t) = {} & \text{larva}(t - dt) \\ & + (\text{larva\_production} - \text{juvenile\_entering} - \text{larva\_loss}) * dt\end{aligned} \tag{9.3}$$

where larva(t) is larva at time (t), larva_production is the larva produced at time (t-dt), juvenile_entering is the juvenile emerged from larva at time (dt-t) and larva_loss is larva lost at time (t-dt).

Larva takes 2 months to become juvenile. The juveniles are the recruiting phase of hilsa and the recruitment occurs more or less throughout the year with a major peak in June and July (Milton 2010). The juvenile population can described as:

$$\begin{aligned}\text{Juvenile}(t) = {} & \text{Juvenile}(t - dt) \\ & + (\text{juvenile\_entering} - \text{young\_entering\_ocean} \\ & - \text{juvenile\_loss}) * dt\end{aligned} \tag{9.4}$$

where Juvenile(t) is the Juvenile population at time (t), juvenile_entering is larva emerged into juvenile at time (t-dt), young_entering ocean is the young juvenile leaving then river at time (t-dt) and juvenile_loss is the juvenile lost in the river at time (t-dt).

The Juveniles remain in the rivers/estuaries for 8 months till they probably reach a length of 150–160 mm and then make the journey for sea. The 1-year-old in the ocean can be expressed as:

$$\begin{aligned}\text{one\_year\_old\_in\_ocean}(t) = {} & \text{one\_year\_old\_in\_ocean}(t - dt) \\ & + (\text{young\_entering\_ocean} - \text{adults\_maturation} \\ & - \text{loss\_in\_first\_year}) * dt\end{aligned} \tag{9.5}$$

where one_year_old_in_ocean(t) is the 1-year-old hilsa in ocean at time (t), young_entering_ocean is the young hilsa entering in the ocean at time (t-dt), adults_maturation is the matured hilsa at time (t-dt) and loss_ in_the_first_year is the hilsa lost in the first year in the sea at time (t-dt).

The juvenile that left the river develops maturity within 2 years in the sea and the 2-year-old matured hilsa in the sea can be described as:

$$\begin{aligned}\text{two\_year\_old(t)} = \ & \text{two\_year\_old(t} - \text{dt)} \\ & + (\text{adults\_maturation} - \text{adults\_entering} - \text{loss\_in\_2nd\_year}) * \text{dt}\end{aligned} \quad (9.6)$$

where 2_year_old(t) is the 2-year-old hilsa in the sea at time (t), adults_maturation is the young 1-year-old hilsa maturating into 2-year-old hilsa in the ocean at time (t-dt), adults_entering is the 2-year-old hilsa leaving the sea and entering the rivers/estuaries at time (t-dt) and loss_in_2nd_year is the loss of 2-year-old hilsa in the sea at time (t-dt).

The adult fish (2-year-old) from the sea return to rivers/estuaries where they lay eggs and this category of 2-year-old adults in rivers/estuaries is described as:

$$\begin{aligned}\text{adults\_in\_migration(t)} = \ & \text{adults\_in\_migration(t} - \text{dt)} \\ & + (\text{adults\_entering} - \text{adults\_leaving} - \text{adults\_migration\_loss}) * \text{dt}\end{aligned} \quad (9.7)$$

where adults_in_migration(t) is 2-year-old adult hilsa migrating from sea to river at time t, adults_entering is the adults joining migration for journey to river at time (t-dt), adults_leaving is the adults left sea and entered the river at time (t-dt) and adults_migration_loss is the loss of adult hilsa during migration at time (t-dt).

Equations 9.1, 9.2, 9.3, 9.4, 9.5, 9.6, and 9.7 are solved using Runge–Kutta fourth-order method using STELLA software. The parameters of the model are estimated from studies, reports and publications. The parameters of the model are shown in Table 9.1.

In this part of modelling, we present a simple dynamic model for optimal harvesting strategy of adult hilsa for sustainable development of hilsa fishery using the population model. The optimisation problem is defined as the problem of maximisation of the total harvest of adult hilsa for the entire simulation period under conditions that the catch of adult hilsa fish is maintained at the maximum sustainable yield, i.e. spawning biomass is conserved and the harvesting juvenile is not allowed to exceed the present level of loss fraction of juvenile for sustainable harvest for all cycles of hilsa production. The objective function is to maximise the total adult harvested biomass during the whole year for sustainable development of hilsa fishery using the population model. The harvesting of adults of hilsa was optimised for sustainable development of hilsa fishery in Bangladesh. The model was simulated to:

Maximise

$$Z = \int_0^{T_t} HB(t)\, dt \quad (9.8)$$

Subject to the constraints

Table 9.1 Parameters used in the model

Parameter	Units	Adult		Egg	Larva	Juvenile	Mature
		M	F				
Average length*	mm	400	430	0.8	17.15	180	340
Average weight*	G	810	830	–	–	90	530
Female fraction****	Decimal	–	0.5	–	–	–	–
Eggs per ground**	Million	–	–	0.20	–	–	–
Stock*	Million	187.17	187.17	7,486,800	74,868	14973.6	898.42
Loss fraction***	Decimal	–	–	0.99	0.8	0.4	0.3
Stock after loss*	Million	37.43	37.43	74,868	14973.6	8984.2	628.89
Harvesting fraction***	Decimal	0.8	0.8	–	–	0.95	–
Second year loss fraction*	Decimal	–	–	–	–	–	0.5
Stock at second year*	Million	–	–	–	–	–	314.45

Sources: Mome and Arnason* (2007), Milton** (2010), Amin et al*** (2000, 2002) and Halder and Amin**** (2005)

$$C_p = MSY$$

$$L_f \leq L_{fe}$$

$$0.0 \leq H_f \leq 1.0$$

$$\int_0^{T_{p1}} HB(t)\,dt = \int_0^{T_{p2}} HB(t)\,dt = \int_0^{T_{p3}} HB(t)\,dt = \ldots$$

where HB(t) is the harvested weight of adult hilsa at time (t), tons/month; C_p the catch (yield), tons; MSY the maximum sustainable yield, tons; L_f the loss fraction of juvenile, decimal; L_{fe} the present loss fraction of juvenile, decimal; H_{fe} the harvesting fraction of adult hilsa, decimal; T_p the period of cycle, month; and T_t the total simulation period, month.

An adaptive pattern search was used for the solution of the constrained optimisation problem stated in Equation 9.8. This method does not require derivatives or approximation to derivatives to solve the problem, and it has been found to be very effective in solving non-linear constrained optimisation problems in system dynamics (Keloharju and Wolstenholme 1989; Dangerfield and Roberts 1996). The technique consists essentially of an exploratory search and a pattern search under constrained conditions.

9.5 Model Validation

The tests for building confidence in system dynamics models include (1) tests of structure, (2) tests for behaviour and (3) tests for policy implications (Bala 1999). Various ways of validating a system dynamics model have been considered such as comparing the model results with collected data; checking whether relations among the variables are logical and real, whether the model generates plausible behaviour and whether the model can generate anticipated behaviour under extreme condition; and checking the quality of parameter's value. Parameters have been derived from studies, other reports and publications to judge the plausibility of the model.

The behaviours of the key variables in the base run were examined. However, the management decisions have not been tested with time series field data since time series data are not available but have been compared with the reported values available. Forrester and Senge (1980) pointed out that for the public and political leaders, a useful model should explain causes of important problems and provide a basis for designing policies that can improve behaviour in the future. In the behaviour validity tests, emphasis should be on the behavioural patterns rather than on point prediction (Barlas 1996). The model presented generated plausible behaviours. An extreme condition test was conducted to check whether the model is capable to cope with extreme conditions and can provide the anticipated behaviour. One such extreme condition is the destruction of the spawning grounds, and it is anticipated that first juvenile and then adults should disappear within a very short

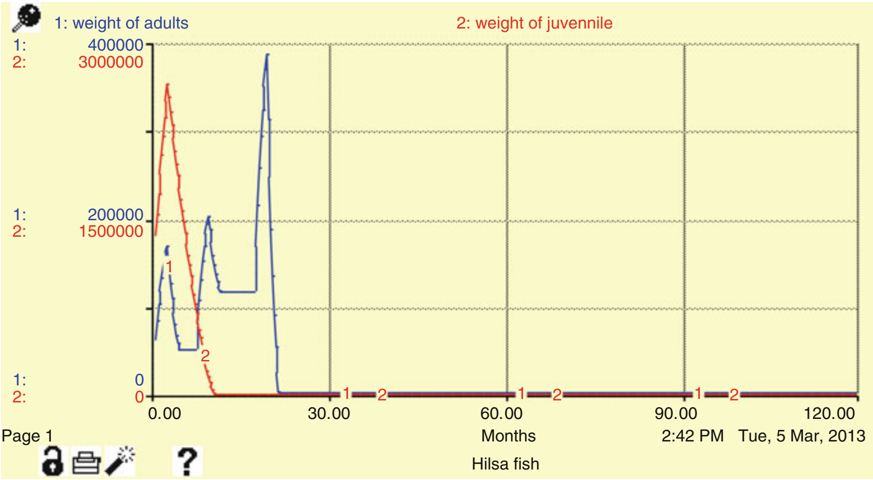

Fig. 9.3 Weights (tons) of adults about to spawn for total destruction of the habitats, i.e. eggs per nest = 0.0

time if the spawning grounds are destroyed. Figure 9.3 shows the simulated results for such a condition, and the simulated results show that first juvenile and then adults will disappear within 10 and 20 years, respectively. The model predictions are exactly what were anticipated.

The sensitivity of the important parameters was also estimated. In this study, behaviour sensitivity analysis of total weights of hilsa fish about to spawn to eggs per nest (150,000, 2,000,000 and 250,000) and adult migration loss (0.15, 0.25 and 0.35) was conducted. Figures 9.4 and 9.5 show the changes in total weights of adults for changes of eggs per nest (150,000, 2,000,000 and 250,000) and adult migration loss (0.15, 0.25 and 0.35), respectively. The total weights of adults increase with the increase of eggs per nests, while the total weights of adults decrease with the increase in values of adult migration loss, and these correspond with real-world situations.

The model is able to provide qualitative and quantitative understanding of the impacts of harvesting of juvenile and spawning adult hilsa fish, and the model represented the perceptions of reality and could be a good communication tool to advocate actions towards better management strategies of the harvesting of juvenile and spawning adult hilsa fish for sustainable exploitation of the hilsa fishery.

9.6 Simulation and Policy Analysis

System dynamics model is essentially developed to predict policy scenarios and applied to the understanding and modelling of complex systems. Because of the difficulty of documenting the effects of juvenile and adult hilsa fish, questions about

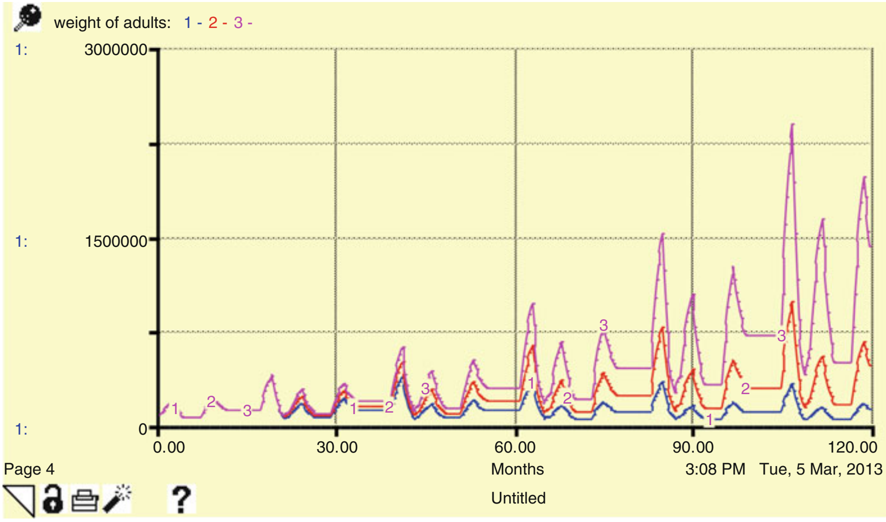

Fig. 9.4 Sensitivity analysis of the total weights of adults about to spawn to eggs per nest (150,000, 200,000 and 250,000)

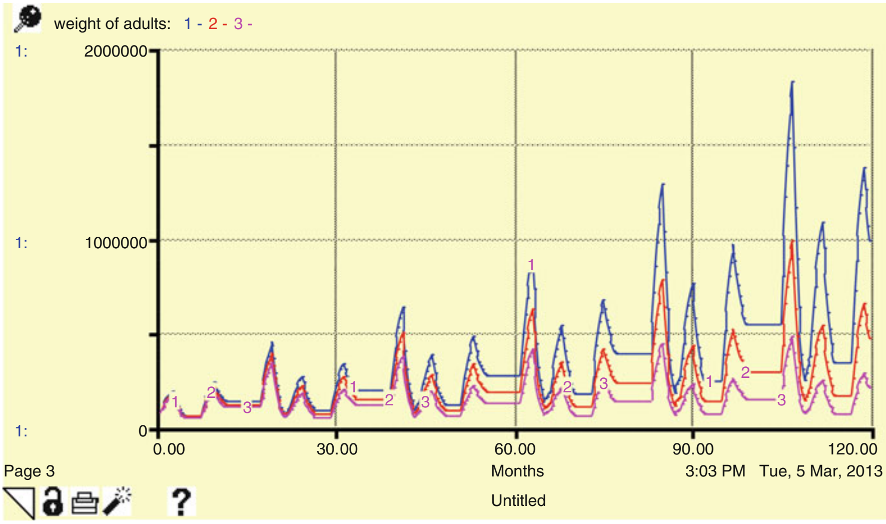

Fig. 9.5 Sensitivity analysis of the total weights of adults about to spawn to adult migration loss (0.15, 0.25 and 0.35)

the effectiveness of hilsa fishery management have been addressed through system dynamics model of hilsa fish population dynamics. In Bangladesh restricting the harvest of juvenile hilsa fish is extensively advocated for hilsa fishery management for sustainable development. This question is also addressed in this study. To examine the potentiality of the model as a tool for policy analysis, several policy options and management strategies are designed and tested. The policy options and management strategies are simulated for a time horizon of 10 years.

Scenario 1: Present practice of harvesting of juveniles and adults continued (base case)

This scenario is based on the information collected from different sources and updated to the present practices to assess the impacts of the harvesting of juveniles and adults of hilsa as usual in the coming years. Simulated weight and population of hilsa fish are shown in Figs. 9.6 and 9.7, respectively, and the time horizon is 10 years starting 2004. Figure 9.6 shows that the monthly changes in weights of adult and juvenile are stabilising with time for the juvenile loss fraction of 0.95 and harvesting loss fraction of 0.8. And also Fig. 9.7 shows that the monthly changes in population of 2-year-old fish, adults in migration, eggs in nest, juvenile and adults about to spawn are stabilising with time. The juvenile loss fraction and harvesting fraction include both the natural mortality and fishing mortality of juvenile population and adult hilsa fish population. The present harvesting practice does not result in any progressive decline of hilsa fish (Figs. 9.6 and 9.7). But in both cases, the growth rates of juveniles and adults about to spawn are very small. The monthly

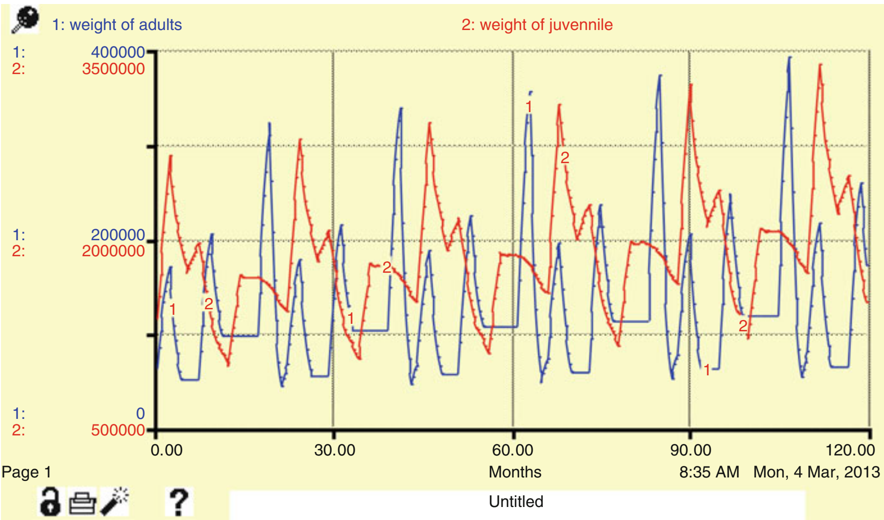

Fig. 9.6 Weights (tons) of juvenile and adult population of hilsa for the present practice of harvesting of juveniles and adults

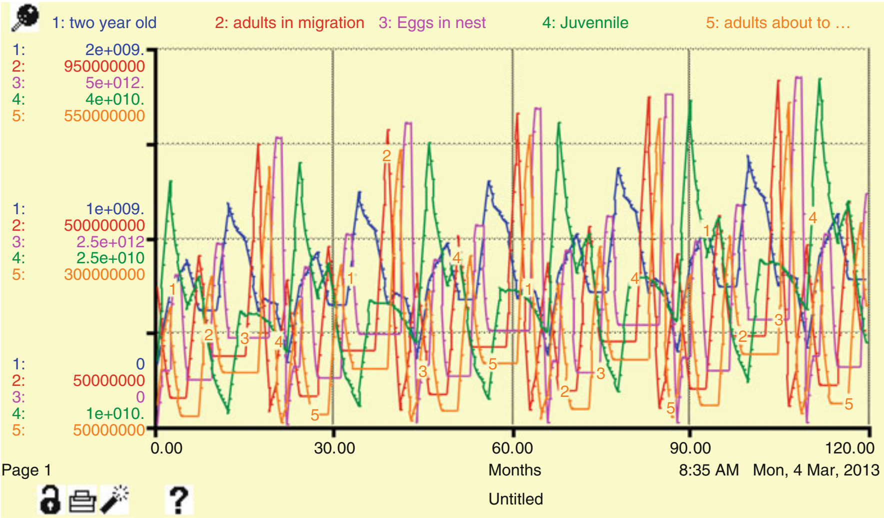

Fig. 9.7 Population of 2-year-old, adult in migration, egg and juvenile of hilsa for the present practice of harvesting of juveniles and adults

changes in the weights of adult hilsa of the standing stock during harvesting season in Fig. 9.6 show that the weights of standing stock of adult hilsa fish change from 290,000 to 3 80,000 tons which compare well with the reported value of 354,000 tons (Mome and Arnason 2007). The simulated results predicted the maximum sustainable yield to be 268, 000 tons. But Mome and Amarson (2007) reported that hilsa catch ranged between 194,981 and 280,328 tons from 1987 to 2007 and BBS (2012) reported a total catch of 313,753 tons of hilsa in Bangladesh which clearly indicates overfishing of hilsa in Bangladesh. Carrying capacity has been defined in many different ways, and it is not a constant number, and changes in environmental conditions may reduce the carrying capacity (Ayllon et al. 2012). The carrying capacity of hilsa fish was computed from the simulated results based on Gordon–Schaefer model (Siddique 2011), and it was found to be 670,000 tons. The monthly changes in the weights of juvenile hilsa during harvesting season also follow the patterns of the monthly changes in the weights of adult hilsa. The monthly changes in the population of 2-year-old, adult in migration, juvenile and egg of hilsa fish in Fig. 9.7 show similar patterns of changes with different magnitudes and time lags. No time series data are available to compare the simulated population dynamics of the hilsa fish.

Scenario 2: Harvesting mortality of juveniles is increased from 0.95 to 0.98

Scenario 2 is designed to assess the impacts of increasing the harvested amounts of juveniles, i.e. 3 % increase in harvesting mortality on the standing stock of hilsa in the future years. Figures 9.8 and 9.9 show the impacts of 3 % increase in harvesting mortality of the juvenile on the standing stock of hilsa in the future years. Figure 9.8 shows that the weights of adult hilsa fish during harvesting season decrease from 153,000 to 75,000 tons within 30 months. Figure 9.8 also shows that the weights of adult and juvenile are decreasing rapidly, and it will be almost zero after 90 months of simulation time. Figure 9.9 shows that the population of 2-year-old fish, adults in migration, eggs in nest, juvenile and adult about to spawn are

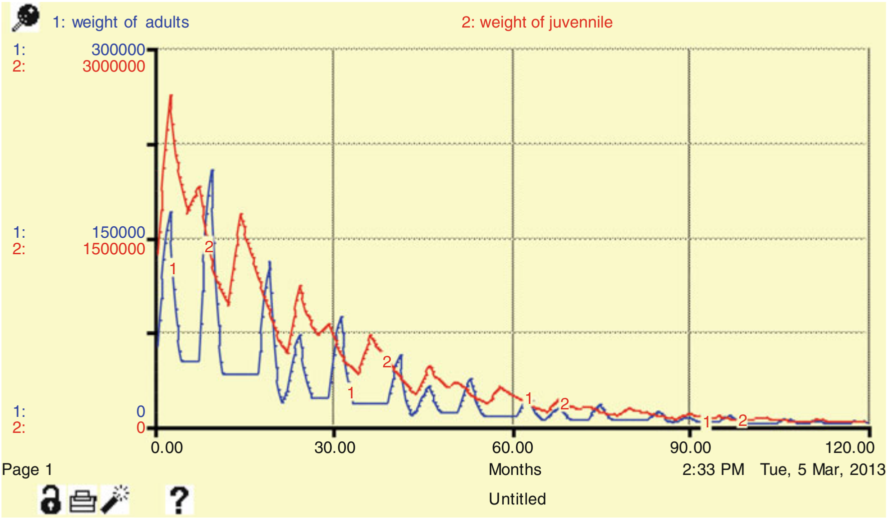

Fig. 9.8 Weights (tons) of juvenile and adult population of hilsa for the increase in harvesting mortality of juveniles from 0.95 to 0.98

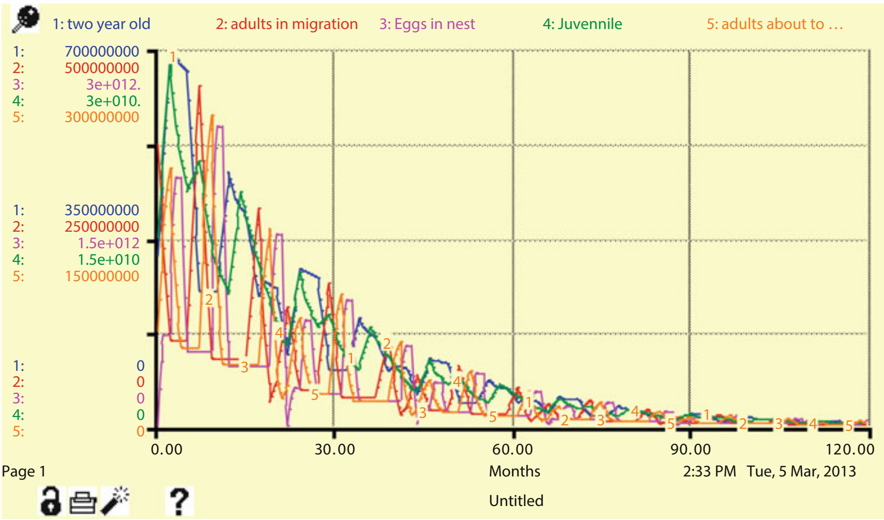

Fig. 9.9 Population of 2-year-old, adult in migration, egg and juvenile of hilsa for the increase in harvesting mortality of juveniles from 0.95 to 0.98

decreasing and ultimately become almost zero after 90 months of simulation time. Thus, increased juvenile harvesting has a negative impact on hilsa fish to disappear this valuable fish resource within a short period of time. This progressive decline of hilsa fish population for increased juvenile harvesting can be explained by the fact that the increased juvenile harvesting reduces the juvenile entering the ocean which ultimately reduces the adults in migration. This also reduces adults about to spawn and the larva production. As a result the juvenile population is further reduced resulting in progressive decline of hilsa fish population. Several researchers also reported similar findings (Amin et al. 2000; Haldar and Amin 2005; Hashemi et al. 2010). Amin et al. (2000) also reported overfishing of juvenile of hilsa for a loss fraction of 0.948 which is within the range of loss fraction of the overfishing of juvenile of hilsa in this study. To stabilise the hilsa fishery system, the juvenile standing stock/population should not exceed the level presented in Scenario 1.

Scenario 3: Harvesting of adults about to spawn is increased from 0.80 to 0.95

Scenario 3 is designed to assess the impacts of increasing the harvested amounts of adult hilsa, i.e. 15 % increase in the harvesting mortality of adults on the standing stock of hilsa in the future years. The effects of increase of the harvesting loss fraction to 0.95 on hilsa fish population are shown Figs. 9.10 and 9.11 respectively. Figure 9.10 shows that the weights of adult hilsa fish during harvesting season decrease from 153,000 to 37,500 tons within 30 months. Figure 9.10 also shows that the weights of adult and juvenile are decreasing rapidly, i.e. the production of hilsa will decrease to almost zero within 60–70 months. Figure 9.11 also gives similar trends for 2-year-old, adults in migration, eggs in nest, juvenile and adults about to spawn. It also shows that the existence of hilsa will be at risk, i.e. it will be almost zero after 70 months. This progressive decline of hilsa fish population for increased adult harvesting can be explained by the fact that the increased adult harvesting reduces the adults about to spawn which ultimately reduces the larva production. This also reduces juvenile production and entering the ocean and the adults leaving migration. As a result, the adults about to spawn are further reduced resulting in progressive decline of hilsa fish population.

Thus, the simulated results show that for increasing harvesting fraction, i.e. harvesting mortality of adult about to spawn is more effective to cause disappear hilsa species within several years. To avoid such a collapse of hilsa fishery in Bangladesh, the harvesting strategies should be not to exceed the maximum sustainable yield. Haldar and Amin (2005) also reported that fishes are harvested at a level than optimum fishing mortality and suggested some management policy to reduce the fishing mortality.

Scenario 4: Sustainable harvesting strategy of adults for the present juvenile loss fraction of 0.95

Scenario 4 is designed to develop sustainable harvesting strategy of the adults for the existing practices of overfishing of juvenile (0.95). For this policy, the

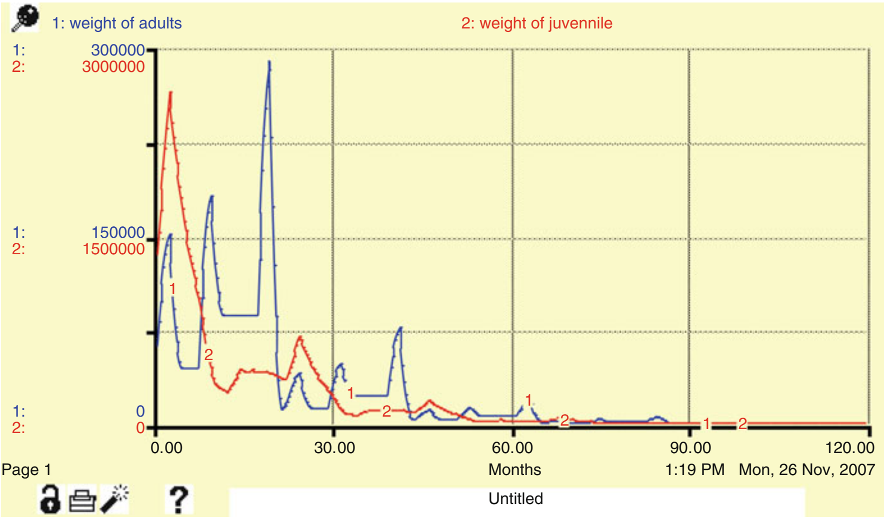

Fig. 9.10 Weights (tons) of juvenile and adult population of hilsa for the increase in harvesting mortality of adult from 0.80 to 0.95

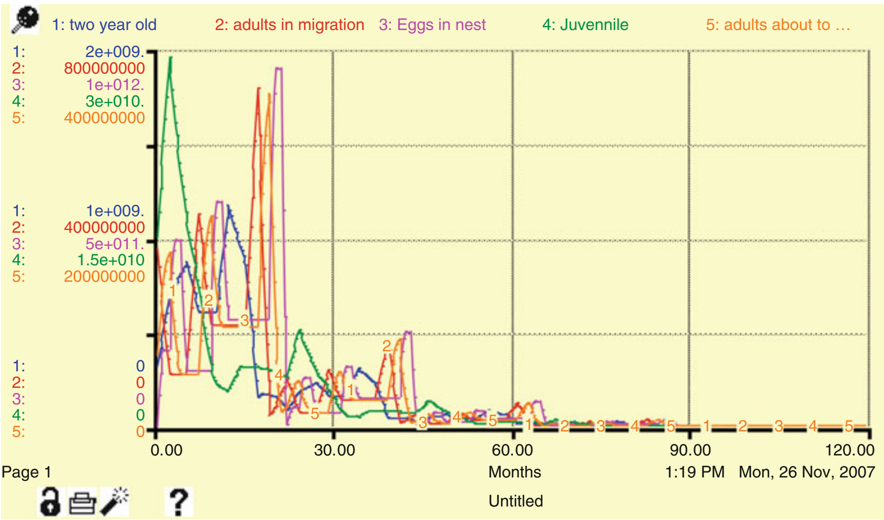

Fig. 9.11 Population of 2-year-old, adult in migration, egg and juvenile of hilsa for the increase in harvesting mortality of adult from 0.80 to 0.95

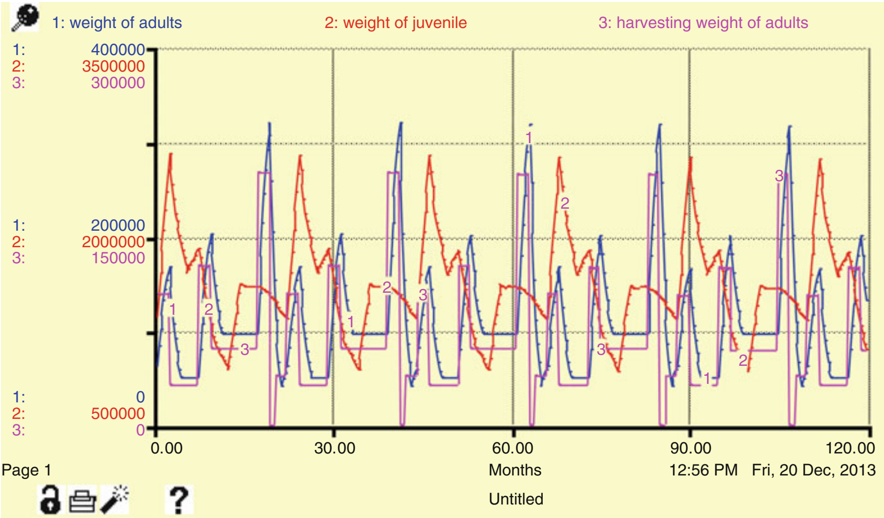

Fig. 9.12 Weights (tons) of juvenile, adult population and harvesting adults of hilsa for optimal harvesting of adult hilsa for the present loss fraction of the juveniles

restriction on maximum sustainable is relaxed. This policy considers proportional harvesting of the adults since this will ensure round-the-year fishing and hence livelihood of the fishermen. Figure 9.12 shows that simulated weights of the juvenile, adult hilsa and harvested adult hilsa for optimal harvesting strategy for sustainable development of hilsa fishery are stabilised. The optimal harvesting fraction of the adults for the existing juvenile harvesting practices of 0.95 was found to be 0.81 for sustainable development of the hilsa fishery. This will result in the stock of the adult hilsa in the peak season to be 320,137 tons and the highest peak season harvest of 200,821 tons.

Scenario 5: Sustainable harvesting strategy for sustainable development

Scenario 5 is designed to develop sustainable harvesting strategy of the adults and the reduction of the loss fraction of juvenile needed to maintain the carrying capacity of hilsa fishery. This policy also considers proportional harvesting of the adults since this will ensure round-the-year fishing and hence livelihood of the fishermen. Figure 9.13 shows that simulated weights of the juvenile, adult hilsa and harvested hilsa for sustainable development of hilsa fishery are stabilised. The optimal harvesting fraction of the adults and loss fraction of the juvenile harvesting fraction were found to be 0.85 and 0.935, respectively, for sustainable development of the hilsa fishery. This will cause to increase the stock of the adult hilsa and harvesting adults in the peak season 1.35 and 1.24 times higher than those of the previous policy (Scenario 4). Thus, this policy not only stabilises the hilsa fishery but also enhances the harvested adult hilsa and maintains the maximum sustainable yield.

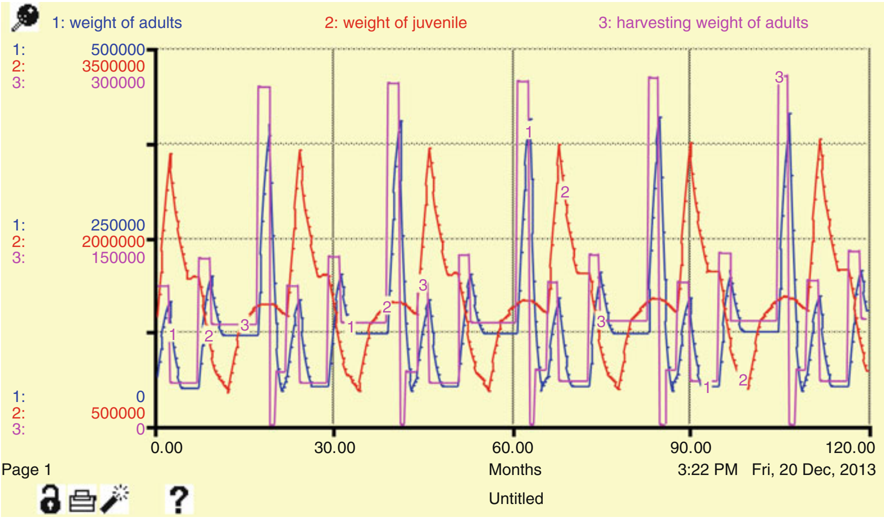

Fig. 9.13 Weights (tons) of juvenile and adult population of hilsa for optimal harvesting of adult hilsa for sustainable development of hilsa fishery

9.7 Conclusions

A computer model for hilsa fish population dynamics using system dynamics technique has been developed, and the model was simulated for the time horizon of 10 years. Two policy options such as juvenile harvesting mortality and increased level of harvesting of the adults are considered. Juvenile stage is the most critical stage for hilsa. Simulated results show that juvenile harvesting mortality and increased level of harvesting of the adults are the two sensitive policy issues for sustainable production of hilsa in Bangladesh. If appropriate policy options and management strategy for juvenile harvesting mortality and harvesting of the spawning adults are implemented, sustainable production of hilsa fish in Bangladesh could be maintained. Otherwise, this valuable resource of hilsa fish in Bangladesh will disappear within a short period of time. To address this problem, optimal harvesting strategy for sustainable hilsa fishery has been developed, and it not only enhances but also stabilises the hilsa fishery system. This model can be used to design policy options and management strategies for sustainable production of hilsa fish. However, further refinement of the model and updating of the data are needed.

Exercises

Exercise 9.1 Why is there a decline of fisheries worldwide? Discuss the importance of hilsa fishery in the context of economy and livelihood of hilsa fishing community in Bangladesh.

Exercise 9.2 Draw the causal loop diagrams of hilsa fishery which includes local price of hilsa fish and livelihood of hilsa fishing community.

Exercise 9.3 Draw stock–flow diagram of the causal loop diagram in exercise 9.2 and simulate hilsa production, local price of hilsa and livelihood of the hilsa fishing community.

Exercise 9.4 What are the two main types of harvesting practices of hilsa population in Bangladesh which are common scenario? Discuss the relative importance and trade-off for sustainable development.

Exercise 9.5 Discuss what should be the sustainable harvesting strategy for sustainable development. How can this be implemented using participatory systems approach?

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Modelling of Food Security in Malaysia 10

In the previous chapter, a case study on modelling and policy implication of hilsa fish population in Bangladesh has been presented. This chapter presents modelling of food security in Malaysia as a case study and application of system dynamics. The model is organised as (1) introduction, (2) dynamic hypothesis, (3) causal loop diagram, (4) stock–flow diagram, (5) model validation, (6) simulation and policy analysis and (7) conclusion. The findings suggest that gradual transition to bio-fertiliser, funding for R&D for development of high-yielding hybrid rice and increasing the cropping intensity hold big promise towards productivity enhancement. The promotion training and extension services using participatory approach of learning by doing or the farmer field schools are desirable to reduce the productivity gap.

10.1 Introduction

Global food security is a serious challenge to the mankind and it has emerged more seriously since the food price volatility in 2007–2008. Food security is rising to the centre of global discourse and has become an issue of national policy as well as public concern. Also, we often find food insecurity in the developing countries to mention some of the problems of complex and dynamic systems. The food crisis in 2007–2008 has affected particularly the developing and rice-importing countries in Asia. These prompted many South Asian countries to increase the domestic production and hence reduce the imports. The Malaysian government also adopted this approach and introduced the national food security policy. Malaysia has translated the food security concerns into three-pronged policy objectives and these are to ensure high price to paddy farmers to produce rice, to achieve a certain level of self-sufficiency in rice and to ensure a stable and high quality of rice to the consumers. It was perceived that under an open market, producers are susceptible to price volatility and consumers are subjected to supply instability in the world market. With these premises, the government has insulated the paddy and rice industry by

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instituting a number of market interventions, from farm to import level. At the farm level, farmers are provided with input and cash subsidies and subsidised irrigation rates, and the price is guaranteed at the RM 750 per ton (one RM = 0.31 US dollar). The import of rice is entrusted to BERNAS, a corporate entity. This is the depth and width of the government's involvement and commitment in ensuring rice security to the country.

The policy objectives have been met as proven by the achievement of the SSL (self-sufficiency level), farmers received a relatively higher income and consumers are insulated from the vagaries of the world market. While these intended outcomes are satisfactory, the unintended consequences are showing symptoms of inefficiencies which may contribute partly to the slowing down of the productivity growth in the later years. These include heavy input subsidies (petroleum-based fertiliser) which result in the reduction of soil fertility and water quality. This in turn leads to more usage of this input to replenish the soil and hence continuous dependency on the fertiliser. While this strategy is effective in the short term, its long-term effect has been proven damaging. The recent increase in petroleum price pushes the input cost by more than 70 %. The government has responded to these problems by adding more fertiliser subsidies to help farmers with the soil problem as well as to cushion the impact of price hikes of inputs. The regional divide particularly in productivity between farmers in the granary and non-granary areas suggests poor transfer of technology. This is not surprising as the current extension system has not moved in parallel to the advancement in farming practices. These issues motivate us to explore the potential of R&D (varietal improvement), bio-organic fertiliser and new extension methods (field farmer schools) in enhancing the productivity and production of rice in Malaysia. This in turn helps Malaysia to achieve the rice availability which is one of the major pillars of food security.

Food security is a social sustainability indicator, and the most commonly used indicators in the assessment of food security conditions are food production, food self- sufficiency level, income, total expenditure, food expenditure, share of expenditure of food, calorie consumption, nutritional status, etc. (Riely et al. 1999). These studies give a descriptive statistics of the food security. Accounting tools for quantifying food security are essential for assessment of food security status and also for policy planning for sustainable development. Several studies have been reported to identify the determinants of food security at the household level using logistic models (Babatunde et al. 2007; Faridi and Wadood 2010; Haile et al. 2005; Mahajan and Joshi 2011; Sikwela 2008). Recently, Bala and Hossain (2010, 2013) reported a quantitative method of food security and also reported food security at regional levels, but this study does not consider subsidies, R&D and extension service. Also more recently, Anderson et al. (2013) reported an empirical basis for re-examining the effectiveness and efficiency of various policy options of ensuring food security in Asia and elsewhere.

Food security is a worldwide problem that has called the attention to governments and the scientific community. It particularly affects developing countries. The scientific community has had increasing concerns for strategic understanding and implementation of food security policies in developing countries, especially since the food crisis in the 1970s. The process of decision-making is becoming increasingly complex due to the interaction of multiple dimensions related to food security (Giraldo et al. 2008).

Food security is a situation in which people do not live in hunger or fear of starvation. FAO (1996a, b) defined the objective of food security as assuring to all human beings the physical and economic access to the basic food they need. This implies three different aspects: availability, stability and access. Food security exists when all people at all times have access to sufficient, safe and nutritional food to meet their dietary needs and food preferences for an active and healthy life (FAO 2002). Food security includes at a minimum (1) the ready availability of nutritionally adequate and safe foods and (2) an assured ability to acquire acceptable foods in socially acceptable ways (USDA 1999). The term food security has been used over time to mean different things, and it can be a useful measure of household and individual welfare, particularly if combined with estimates of household food acquisition and allocation behaviour (Per Pinstrup-Anderson 2009).

Historically, national food self-sufficiency has been equated with food security, but the definition could also be expanded to include agricultural self-reliance (Panagariya 2002). National food security is achieved when all citizens are individually food secure; but this is less straightforward than it appears. Nations often talk self-sufficiency ratios (the proportion of domestic consumption) as a measure of food security. A ratio of 1 or more would imply that the country's production satisfies all its food consumption needs. While this may occur for particular commodities, it is almost never possible for a country to be fully self-sufficient (Majumder et al. 2012).

In the wake of recent food price spikes and growing demands for food and also the growing concerns of climate change impacts in emerging Asia and for biofuels in Europe and the United States of America, the governments are re-examining their strategies for dealing both short-term and long-term food security, and the options include boosting agricultural production rates to deal with long-term concerns and using more appropriate domestic policy measures rather than trade policy to cope with price volatility (Anderson et al. 2013).

Considering the above notions of food security and the worst experiences with food crisis following the price volatility in 2007 and 2008, understanding the impacts of the recent competition between food and biofuel for land and climatic change impacts on food production and also realising the central issue of increasing local productivity and slowing population growth, Bala et al. (2014) were motivated to study the dynamics of food security in Malaysia to understand and design policy for increasing local productivity and reducing field level productivity gaps and address the questions of withdrawal of fertiliser subsidies and gradual transition to bio-fertilisers using systems approach. Modelling of food security in Malaysia presented here is adopted from Bala et al. (2014).

10.2 Dynamic Hypothesis

The dynamic hypothesis is a conceptual model typically consisting of a causal loop diagram, stock–flow diagram or their combination which drives the system's behaviour. When the model based on feedback concept is simulated, the endogenous structure of the model generates the reference mode behaviour of the system which results from the endogenous structure of the system. In system dynamics modelling, causal loop diagrams and stock–flow diagrams are used to describe the basic cause–effect relationships hypothesised to generate the reference mode of the behaviour over time (Sterman 2000). Food security can be represented by causal loop diagrams and stock–flow diagrams, and the simulation model based on the causal loop diagrams and stock–flow diagrams can generate the dynamic behaviour of the food security. Rice production and its self-sufficiency in the form of causal loop diagrams and stock–flow diagrams are hypothesised to generate the observed rice production and food security in the reference mode. In essence the decline in food security results from both the production and population, and this dynamics resulted from the endogenous consequences of the feedback structure.

10.3 Causal Loop Diagram

The causal loop diagram of rice production system in Malaysia is shown in Fig. 10.1. Causal loop diagrams identify the principal feedback loops of the systems. The causal loop diagrams have been used to describe basic causal mechanisms hypothesised to generate the reference mode of behaviour over time (Sterman 2000). A feedback loop contains two or more casualty related variables that close back on themselves. The relationship between one variable and next in the loop can be either positive or negative. A positive relationship means that if one increases, the other also increases. In a negative relationship, the two variables change inversely. If there are an even numbers of negative relationships in total, then the loop is positive; if there are odd numbers of negative relationships, the loop is negative. Positive feedback loops generate growth, i.e. re-enforcing, and negative feedback loops are goal seeking. There are eight main feedback loops in rice production system in Malaysia, of which two are positive, i.e. re-enforcing, and six are negative, i.e. goal seeking.

10.4 Stock–Flow Diagram

The flow diagram of the system dynamics model of rice production system in Malaysia is shown in Fig. 10.2. Fundamental equations that correspond to major state variables shown in Fig. 10.2 are as follows:

Rice production in Fig. 10.2 depends on rice productivity (tons/ha) as well as on the area under rice cultivation and cropping intensity, and it is computed as

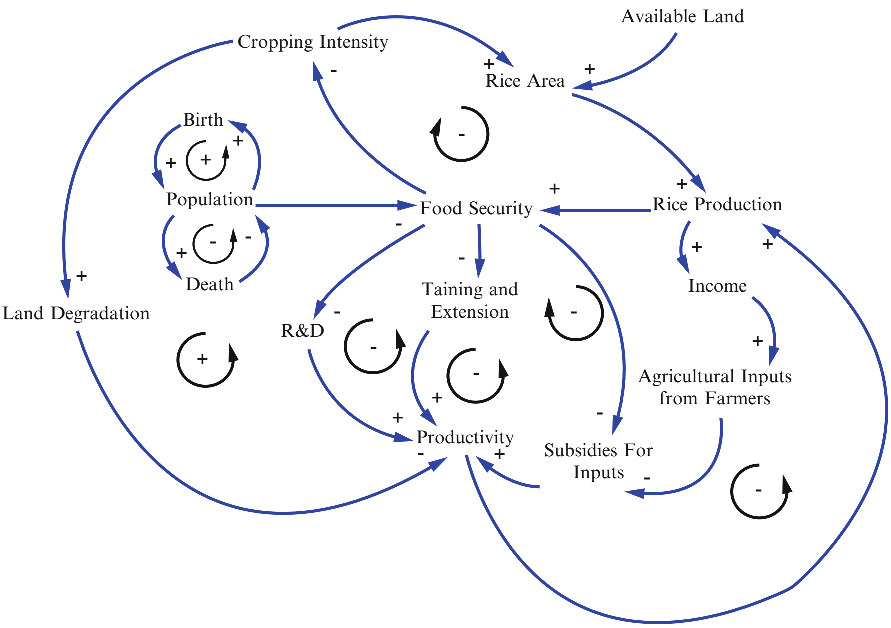

Fig. 10.1 Causal loop diagram of system dynamics model for rice production system in Malaysia

$$\text{rice production}\,(t) = \text{rice productivity}(t) \times \text{rice area}\,(t) \times \text{cropping intensity}(t) \tag{10.1}$$

The rice area is increased by transfer of land suitable for rice cultivation based on development policy of covering the land suitable for rice cultivation within 8 years, and also the rice area is decreased by a discard rate of 0.0085 fraction of rice area for housing, roads and highways and industries. This is expressed as

$$\text{rice area}\,(t) = \text{rice area}\,(t - \Delta t) + \text{rice area increase rate} \times \Delta t - \text{rice discard rate} \times \Delta t \tag{10.2}$$

Cropping intensity increases with development policy and programmes and also depends on potentiality of multiple crops and crop diversification, and it is expressed as

$$\text{cropping intensity}\,(t) = \text{cropping intensity}\,(t - \Delta t) + \text{cropping intensity increase rate} \times \Delta t \tag{10.3}$$

Rice productivity is increased by development of new hybrid varieties of rice through research and development and reducing productivity gaps through learning through training and extension. In addition, it is affected by agricultural inputs and land degradation. This is described as

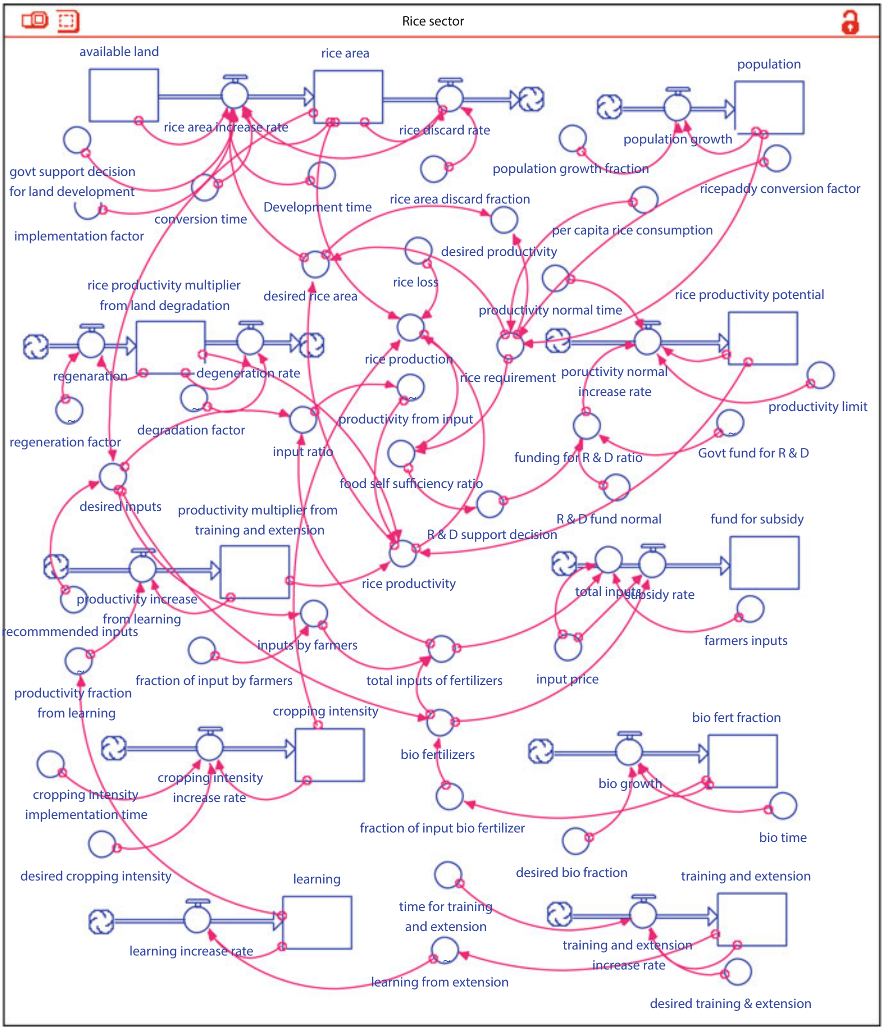

Fig. 10.2 Flow diagram of the system dynamics model of rice production systems in Malaysia

$$\begin{aligned}\text{rice productivity}\,(t) = {} & \text{rice productivity potential}(t) \times \text{productivity from input}(t) \\ & \times \text{rice productivity multiplier from land degradation}(t) \\ & \times \text{productivity multiplier from training and extension}\,(t)\end{aligned} \tag{10.4}$$

Rice productivity potential is increased by development of new high-yielding/hybrid varieties through research and development, and it is expressed as

$$\begin{aligned}\text{rice productivity potential}\,(t) = {} & \text{rice productivity potential}\,(t - \Delta t) \\ & + \text{productivity normal increase rate} \times \Delta t\end{aligned} \tag{10.5}$$

Rice productivity, i.e. yield/ha, is influenced by land degradation due to cropping intensity and can be increased by keeping the land fallow for a long time by regeneration, and it is described as a multiplier:

$$\text{rice productivity multiplier from land degradation } (t) = \text{ rice productivity multiplier from land degradation } (t - \Delta t) + \text{regeneration} \times \Delta t - \text{degeneration rate} \times \Delta t \tag{10.6}$$

The published research indicates that training and extension through farmer field schools is having a substantial impact in terms of increase in farm productivity, reduction in farmers' use of pesticides and improved farming knowledge (Davis et al. 2012; Larsen and Lilleor 2012; Mwagi et al. 2003; Praneetvatakul and Waibel 2003; Rola et al. 2002). Rice productivity can also be increased by training and extension through farmer field schools which provides an opportunity of learning by doing for the farmers to reduce the productivity gaps. Farmer field school is based on experiential learning techniques and participatory methods, and here, learning means to work based on experiences and knowledge, and it is run by training and extension service department/agency (Bala 2012). The contribution of the training and extension reduces the yield gap and it depends on learning. The productivity multiplier from training and extension is given by

$$\text{productivity multiplier from training and extension } (t) = \text{productivity multiplier from t raining and extension } (t - \Delta t) + \text{productivity increase from learning} \times \Delta t \tag{10.7}$$

Productivity multiplier from training and extension is related to learning level through multiplier. The growth rate fraction of productivity multiplier from training and extension is expressed as a non-linear function of learning level.

Learning level influences the productivity and the learning rate depends on the training extension activities, and the learning level is expressed as

$$\text{learning } (t) = \text{learning } (t - \Delta t) + \text{learning increase rate} \times \Delta t \tag{10.8}$$

Learning from training and extension services increases with the farmers under training and extension services. Learning from training and extension is expressed as a non-linear function of the farmers under training and extension services.

The training and extension service provides the knowledge, i.e. learning and the coverage of the training, and extension activities are given by

$$\begin{aligned} \text{training and extension } (t) = \text{t raining and extension } (t - \Delta t) \\ + \text{training and extension increase rate} \times \Delta t \end{aligned} \tag{10.9}$$

Commercial fertilisers create environmental degradation and also affect the soil structure and health. Gradual transition to bio-fertilisers based on a target policy is expressed as

$$\begin{aligned} \text{bio fertilizer fraction}\,(t) = {} & \text{bio fertilizer fraction}\,(t - \Delta t) \\ & + \text{bio fertilizer growth} \times \Delta t \end{aligned} \tag{10.10}$$

Rice requirement depends on the per capita consumption of rice and population level and it is computed as

$$\text{rice requirement}\,(t) = \text{per cpita consumption}\,(t) \times \text{population}(t) \tag{10.11}$$

Population level at any time t is computed from the population growth rate and it is given by:

$$\text{population}\,(t) = \text{population}\,(t - \Delta t) + \text{population growth rate} \tag{10.12}$$

Self-sufficiency level (SSL) of rice is defined as the ratio of rice production to rice requirement:

$$\text{Self sufficiency Level (SSL)}\,(t) = \frac{\text{rice production}(t)}{\text{rice requirement}(t)} \tag{10.13}$$

SSL above 1 means surplus food and SSL less than 1 means shortage in food supply to lead healthy life.

10.5 Model Validation

Initial values and parameters were estimated from the primary and secondary data collected from different research reports, statistical year books of Malaysia and field visits, and these are shown in Table 10.1.

To build up confidence in the predictions of the model, various ways of validating a model such as model structures, comparing the model predictions with historic data, checking whether the model generates plausible behaviour and

Table 10.1 Data on initial values and parameters

Name of the variable and parameter	Unit	Value
Rice area	Ha	680,647
Available land	Ha	88,000
Conversion time	Year	8
Discard rate	Per year	0.0085
Population	Million	18.1024
Population growth	Fraction per year	0.021
Per capita rice consumption	Kg per year	80
Rice productivity potential	Tons per ha	6
Rice productivity multiplier from land degradation	Dimensionless	0.99
Productivity multiplier from training land extension	Dimensionless	0.61
Bio-fertiliser	Fraction of total inputs	0.0

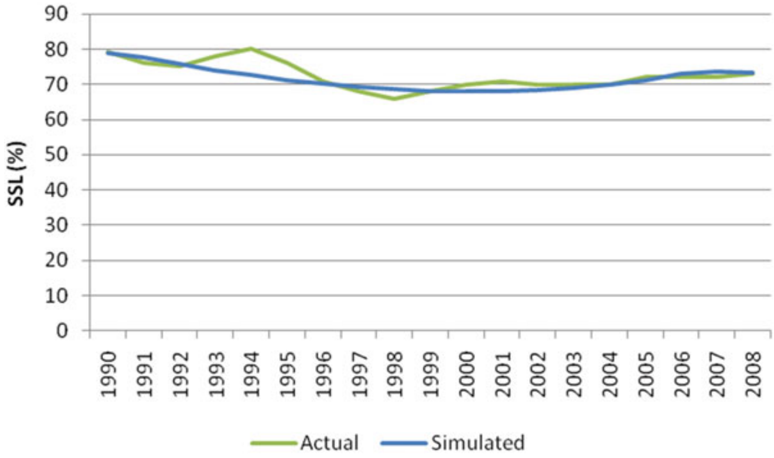

Fig. 10.3 Simulated and historical data of food self-sufficiency ratio in Malaysia

checking the quality of the parameter values were considered. Figure 10.3 shows the comparison between the predicted and historical behaviour of food self-sufficiency ratio in Malaysia. The model-simulated food self-sufficiency ratio agrees reasonably well with historical behaviour and the model is reliable. The validated model was used for baseline scenario and policy analysis.

The parameters of a system dynamics models are subject to uncertainty. So, sensitivity analysis is an important task for reliability of the simulated results and checking the robustness of the model behaviour for the changes in parameter values. The sensitivity of the important parameters was also estimated. The productivity is one of the most important parameters affecting the model behaviour, i.e. self-sufficiency ratio which is the focus of this study. In this study behaviour, sensitivity analysis of food self-sufficiency ratio to rice productivity was conducted, and Fig. 10.4 shows the changes in food self-sufficiency ratio for rice productivity for changes of 2.50 t/ha (curve 1), 3.50 t/ha (curve 2) and 4.50 t/ha (curve 3). The food self-sufficiency ratio changes from decrease to increase in values for the changes in the rice productivity from 3.50 t/ha to 2.50 t/ha and 4.50 t/ha, and this corresponds with real-world situation.

10.6 Simulation and Policy Analysis

A system dynamics model was developed to address the important policy options of rice food security in Malaysia, and the model was simulated to analyse policy issues of input subsidies, withdrawal of input subsidies, gradual transition to bio-fertilisers, R&D for increased productivity, extension services through farmer field schools (FFS) and increase in cropping intensity to address how it behaves in the long run to achieve self-sufficiency level in rice production in Malaysia. The

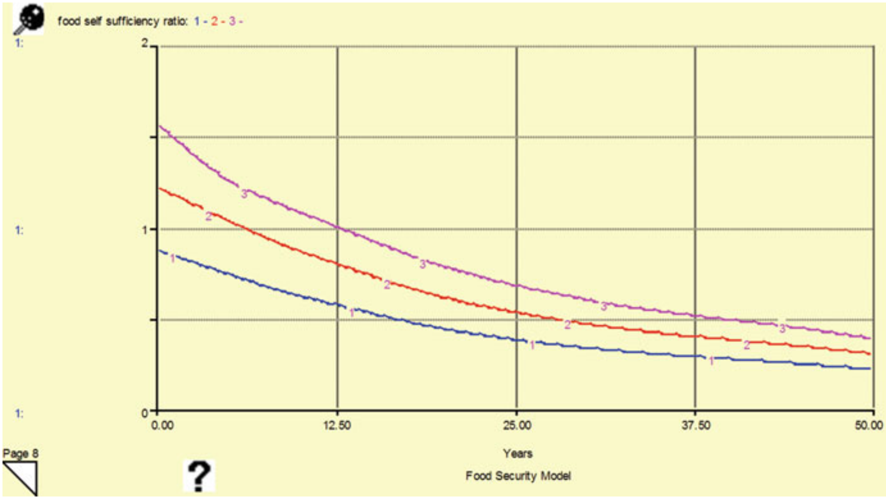

Fig. 10.4 Sensitivity of food self-sufficiency ratio to rice productivity (2.50 t/ha, 3.50 t/ha and 4.50 t/ha)

simulated results for these important policy options for a simulation period of 50 years starting from 2011 are presented and discussed here.

10.6.1 Subsidies for Agricultural Inputs

Figure 10.5 shows the simulated available land, rice area, rice production and self-sufficiency level in rice production for subsidies on agricultural inputs (67 %) and population for a simulation period of 50 years. The rice area initially increases till about 8 years and reaches the upper limit of available land suitable for rice and then decreases it due to the discard of rice area for housing and industrial enterprises. This results in the decrease in the rice production to 1.54 million tons at the end of the simulation period of 50 years. The self-sufficiency in rice decreases to 22 % due to the decrease in rice production and increase in the population. This fact implies that although subsidies on agricultural inputs have positive effect on productivity, only the subsidies on agricultural inputs are not sufficient to improve the SSL in rice production in Malaysia at the desired level, and the rice production in Malaysia is not sustainable at the desired level in the long run. However, it is good for short run. Other opportunities such as hybrid varieties for higher yields and better management practices to reduce the productivity gaps in the fields through training and extension services and increase in cropping intensity are needed to be searched.

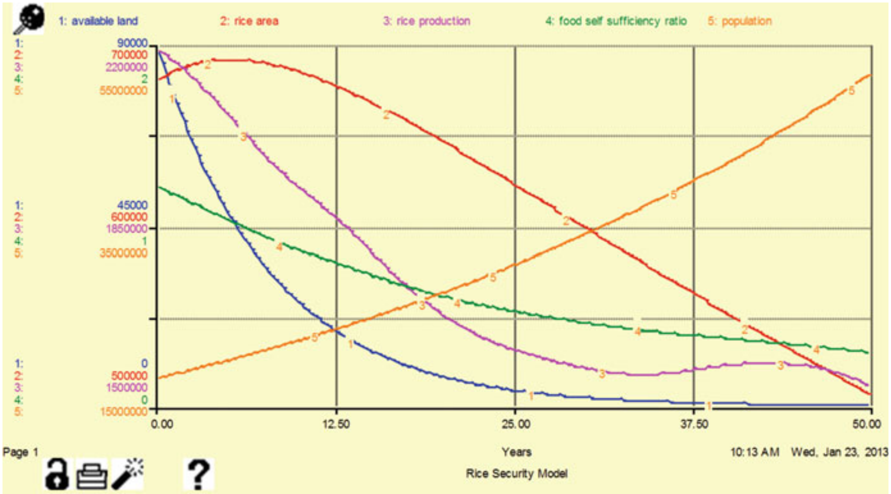

Fig. 10.5 Simulated available land, rice area, rice production and rice self-sufficiency level for agricultural subsidies in inputs and population

10.6.2 Withdrawal of Input Subsidies

Figure 10.6 shows the simulated available land, rice area, rice production and self-sufficiency level in rice production for withdrawal of subsidies on agricultural inputs and population for a simulation period of 50 years. The rice production and hence the self-sufficiency in rice fall drastically as a result of withdrawal of subsidies on agricultural inputs. This causes a further decrease in rice production to 1.33 million tons at the end of the simulation period of 50 years and hence the self-sufficiency in rice decreases to 19 %, i.e. less than 3 % of the basic as usual in Fig. 10.5. Ramli et al. (2012) also reported that the removal of fertiliser subsidy will decrease the paddy production and, consequently, decrease the self-sufficiency level (SSL) in Malaysia. This implies that the withdrawal of subsidies on agricultural inputs has a negative effect on productivity since rice production in Malaysia does not have comparative advantage in terms of the income derived. It is not a wise decision to withdraw the subsidies unless an alternative arrangement/mechanism to apply optimum level of agricultural inputs such as gradual transition to bio-fertilisers as low-cost nutrients to increase the productivity and reduce the environmental degradation and introduction of hybrid seeds and better management practices to increase the productivity of rice is ensured.

10.6.3 Gradual Transition to Bio-fertilisers (50 %)

Figure 10.7 shows the simulated available land, rice area, rice production and self-sufficiency level in rice production for gradual transition to bio-fertilisers and

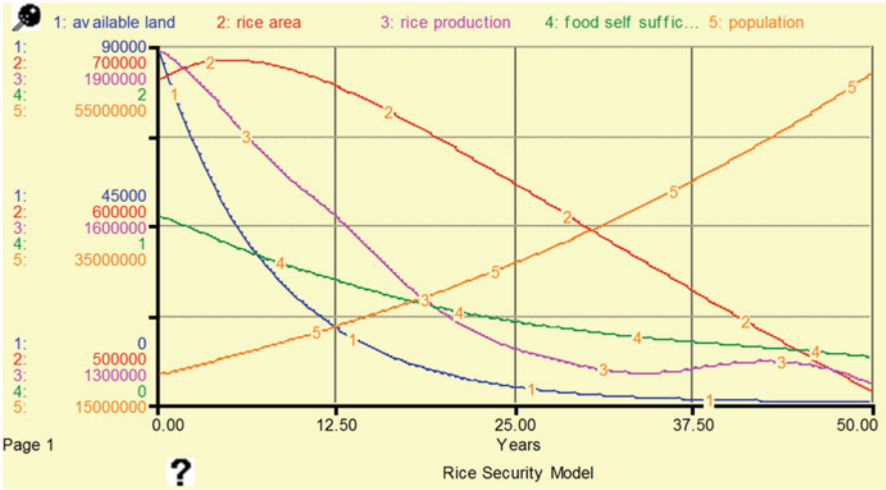

Fig. 10.6 Simulated available land, rice area, rice production and rice self-sufficiency level for withdrawal of agricultural subsidies in inputs and population

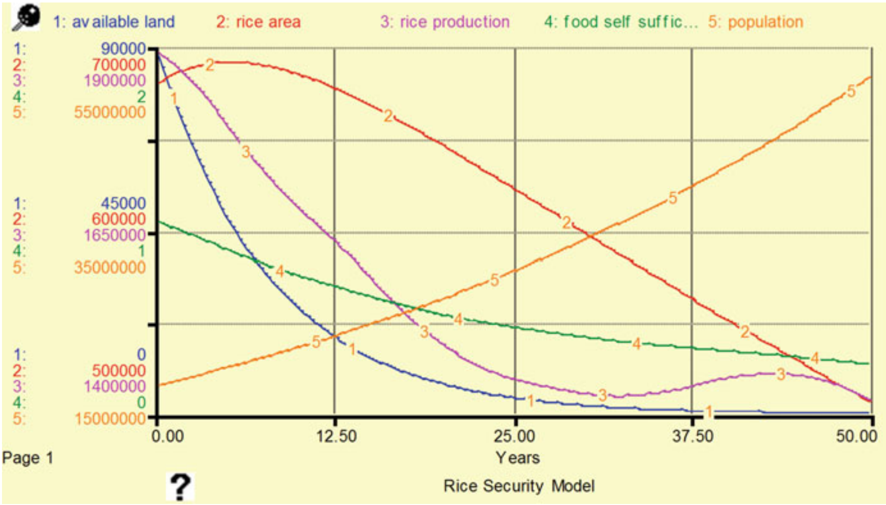

Fig. 10.7 Simulated available land, rice area, rice production and rice self-sufficiency level for gradual transition to bio-fertilisers and population

population for a simulation period of 50 years. The policy is to withdraw 50 % of the subsidy for agricultural inputs immediately and another 50 % of the agricultural input, i.e. commercial fertiliser is replaced by bio-fertilisers within next 50 years. The rice production in this policy increases from 1.33 million tons in the case of withdrawal of input subsidies to 1.42 million tons at the end of the simulation period of

50 years, and the rice self-sufficiency level settles to 21 % from 19 % for withdrawal of the subsidies. The rice self-sufficiency ratio (21 %) is comparable with the reference run in Fig. 10.5 which is 22 %. Still policy mechanisms are needed to increase the productivity which can be achieved through better management practices using farmer field schools, using hybrid variety and encouraging the farmers to use bio-fertiliser. Bio-fertilisers are eco-friendly and are environmentally safe. They form not only part of integrated nutrients but are of low cost which is of immense help to the farming community. This could increase the productivity to improve the SSL level and reduce the agricultural input costs of fertiliser subsidies. Lakshmi et al. (2012) reported that combined application of organics and blue-green algae (BGA) not only recorded higher yield but found to emit less methane in paddy cultivation. Application of BGA (blue-green algae) and *Azolla* reduced methane flux without reducing rice yields and can be used as a practical mitigation option for minimising the global warming potential of rice ecosystem and enhancement by nitrogen fixation.

10.6.4 Gradual Transition to Bio-fertilisers (50 %) and R&D

Figure 10.8 shows the simulated available land, rice area, rice production and self-sufficiency level in rice production for gradual transition to bio-fertilisers, R&D and population for a simulation period of 50 years. The R&D is designed to increase the potential rice productivity from 6 tons/ha to 12 tons/ha within the simulation period of 50 years. The rice production increases to 2.42 million tons and then becomes almost constant, but the rice self-sufficiency ratio decreases to 35 % due to the

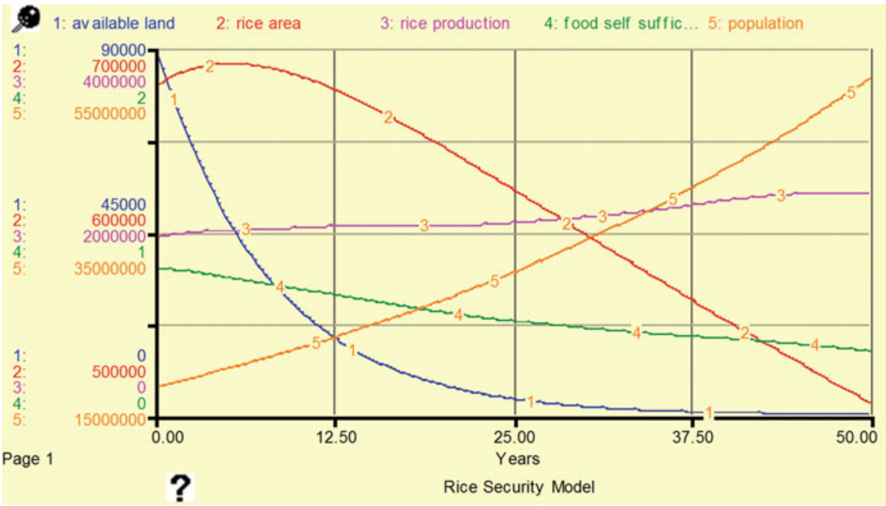

Fig. 10.8 Simulated available land, rice area, rice production and rice self-sufficiency level for gradual transition to bio-fertilisers (50 %), R&D and population

increasing population at the end of the simulation period of 50 years. Although the self-sufficiency level decreases, it rises at a much higher level in comparison to all the previous runs. Thus, this policy option is superior to the policy option illustrated in Fig. 10.7 due to R&D resulting in hybrid rice variety with much higher productivity. Anderson et al. (2013) reported that the best long-term option is investing more in agricultural R&D, and this has the potential to boost per capita consumption in both food-exporting and food-importing countries. There is no alternative to R&D to sustain the production and improve the SSL in rice production in Malaysia (Fatimah et al. 2011). The R&D policy incorporating bio-fertilisers not only improves the SSL but also minimises the global warming.

10.6.5 Gradual Transition to Bio-fertilisers (50 %), R&D and Training and Extension Services

Figure 10.9 shows the simulated available land, rice area, rice production and self-sufficiency level in rice production for gradual transition to bio-fertilisers, R&D, training and extension services and population for a simulation period of 50 years. The training and extension services for learning by doing through farmer field schools are expected to reduce the productivity gap at field levels, and these services will be provided to all of the farming communities within next 50 years. Rice production increases to about 2.99 million tons and the self-sufficiency level becomes 43 % towards the end of 50 years of the simulation period. This policy option further increases the rice production from 2.42 million tons to 2.99 million tons and the rice self-sufficiency level from 35 to 43 % from the policy illustrated in

Fig. 10.9 Simulated available land, rice area, rice production and rice self-sufficiency level for gradual transition to bio-fertilisers (50 %), R&D and training and extension and population

Fig. 10.8, and thus it is superior to the policy option illustrated in Fig. 10.8 due to incorporation of R&D resulting in higher productivity and training and extension services to reduce the productivity gaps in the fields. There exists a large yield gap at the field levels in the rice production of Malaysia. Yield gap is manageable and can be narrowed down by deploying more efforts in training and extension services as well as governments' appropriate intervention particularly on the institutional issues (Duwayri and Tran 2013). Several studies have been reported on the positive impacts of agricultural training and extension on agricultural production and food security (Bala 2012; Davis et al. 2012; Larsen and Lilleor 2012; Majumder et al. 2012).

10.6.6 Gradual Transition to Bio-fertilisers (50 %), R&D, Training and Extension Services and Cropping Intensity (150 %)

Figure 10.10 shows the simulated available land, rice area, rice production and self-sufficiency level in rice production for gradual transition to bio-fertilisers, R&D, training and extension services, cropping intensity and population for a simulation period of 50 years. Cropping intensity is expected to increase from the present level to 150 % of the present level. Rice production increases but becomes almost stagnant at 4.34 million tons towards the end of 50 years with a self-sufficiency level of 63 %. This increase of 63 % in rice self-sufficiency is due to R&D resulting higher productivity, the extension and training services to reduce productivity gaps in the fields and increasing cropping intensity to increase the area under rice crop by vertical expansion. The rice production increases from 2.99 million tons to

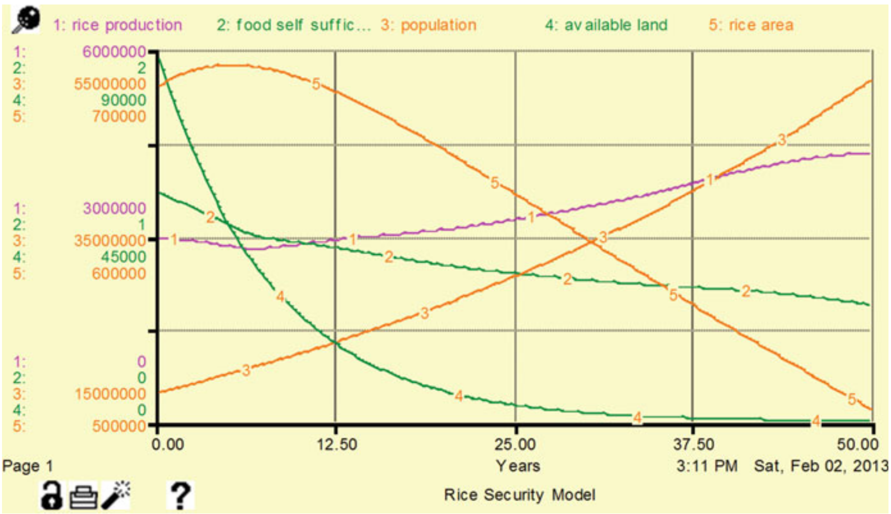

Fig. 10.10 Simulated rice production and rice self-sufficiency level for gradual transition to bio-fertilisers (50 %), R&D, training and extension and cropping intensity and population

4.34 million tons, and the food self-sufficiency ratio increases from 43 to 63 % from the policy options illustrated in Fig. 10.9. This is the best policy although the self-sufficiency in rice food security in Malaysia still remains a challenge, and Malaysia needs imports of rice for domestic food security. BERNAS is solely authorised to deal with the imports of rice in Malaysia. A recent study on rice imports in Malaysia suggests that rice import largely from Vietnam and Thailand is a weak strategy, and an effective multi-sourcing strategy for rice could be adopted to avoid such a weak strategy in securing supply from the international market rather than importing largely from Vietnam and Thailand (Tey and Radam 2010). However, it can be concluded that there is a need of further increase in rice productivity which can be realised through R&D developing hybrid variety of much more higher productivity, reducing productivity gaps in the fields and vertical expansion of the cropped area through increase in the cropping intensity to meet this challenge.

10.7 Conclusions

In the recent years, there have been increasing interests in policy issues of food security since the food crisis in 2007–2008. Malaysia's main food security concern is to achieve a certain level of self-sufficiency in rice. In this paper a system dynamics model has been developed to simulate rice food security and also to assess the policy options of the food security. Simulated results show that subsidy liberalisation or withdrawn would worsen SSL. However, gradual transition to bio-fertilisers improves SSL, and R&D with training and extension services and increased cropping intensity improve the rice food security considerably. Simulated results suggest that the best policy to achieve the targeted SSL is through R&D, training and extension services using farmer field schools and vertical expansion of cropped area increasing the cropping intensity. Food self-sufficiency in rice in Malaysia still remains a challenge. The trade-off could be to increase the real income, thereby increasing the purchasing power of the farmers with subsidised cereal production for the land suitable for irrigated rice production and highly taxed high-value crop production in the rest of the land suitable for crop production under bold national food security policy. In conclusion this model can provide better understanding and greater insights of the food security issues, and also the results indicate that the proposed model can be efficiently used for developing policy suggestions and for improving decision support to policy makers in food security.

Exercises

Exercise 10.1 Define food security. Discuss the issues of food security in a broad perspective.

Exercise 10.2 Draw the causal loop diagrams of food security based on the FAO definition of food security.

Exercise 10.3 Draw stock–flow diagram of food security based on the FAO definition of food security and simulate the dynamics of food security.

Exercise 10.4 Simulate the model in Exercise 10.3 for different policy options, and make a comparative analysis of the simulated results to search for the best policy option to ensure the optimal food security.

Exercise 10.5 Discuss the policy implication of food security. How the policy of improving food security can be implemented using participatory approach of farmer field schools?

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Modelling of Supply Chain of Rice Milling Systems in Bangladesh

11

In the previous chapters, case studies on system dynamics modelling of boom and bust of cocoa production systems in Malaysia, modelling of hilsa fish population in Bangladesh and modelling of food security in Malaysia have been presented. This chapter presents the application of system dynamics modelling to supply chain of rice milling systems to demonstrate how to construct system dynamics models and simulate these models for policy planning and design. The model presented is an illustration of modelling and simulation of practical problem to provide management scenarios and policy options, and such experiences are essential to face the challenge of modelling and simulation of dynamic systems in practice. To achieve these goals, the model of this case study is organised as follows: (1) introduction, (2) dynamic hypothesis, (3) causal loop diagram, (4) stock–flow diagram, (5) model validation, (6) simulation and policy analysis and (7) conclusion. The model is simulated to address supply chain management scenarios and design the policy options for efficient and sustainable supply chain management of rice milling systems in Bangladesh to ensure the availability of rice to the consumers in an economic manner under uncertainty. The model has the potential to identify and study the critical components of the overall supply chain, allowing for the creation of an efficient and sustainable network.

11.1 Introduction

Rice is the staple food grain in Bangladesh, and it covers almost three quarters of the total cropped area in Bangladesh. Per capita consumption of rice in Bangladesh is one of the highest in the world and it is 188 kg (BBS 2011). The production of rice in Bangladesh has increased significantly over last 40 years, and this success has been strongly related to high yielding varieties triggered by the liberalisation of key input markets such as irrigation and fertilisers (Ahmed 2000; Hossain 1988; Hossain et al. 2006). Although rice production has increased in the recent years with a self-sufficiency in rice food security, the availability of rice to consumers has

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not been stabilised, and hence the changes in the price of rice by days and even by minutes have been common phenomenon. This indicates that it is necessary to identify the appropriate demand and meet them properly in a profitable way, and it is the primary concern of rice supply chain. A proper supply chain management framework is very essential for efficient sourcing, processing, distribution and retailing and hence meeting the customer demands without facing any crisis. Production and business of rice have been one of the most traditional and major concerns of milling industries in Bangladesh. But still no proper supply chain framework has been developed. Of course, dealing with inventory is the major issue in the supply chain management of rice, and it requires that milling, wholesale and retail inventories are properly managed and maintained to ensure the availability of rice to the consumers.

Rice supply chain in Bangladesh is a focus for considerations of food security and climate change impacts. The rice supply chain in Bangladesh is demand driven. Although Bangladesh is self-sufficient in rice, the supply chain does not meet the requirement at the right time at the right place resulting artificial crisis and price volatility. Furthermore, the supply of paddy is also affected by natural calamities such as drought and flood. This requires the supply chain to be more demand driven and all the actors involved in the supply chain to be responsive to the demand information of the ultimate consumers in a timely and cost-effective manner.

Realisation of a demand-driven supply chain is a complex task (Selen and Soliman 2002). Any consumer requirement may trigger execution of different activities by different contributors (Prahalad and Ramswamy 2000), and hence demand-driven supply chains are highly dynamic having different modes of cooperation, control and coordination. This requires that demand-driven supply chains must be modelled and simulated before implementation. Reference process models can be valuable means to support these challenges in the design and implementation of demand-driven supply chains. The reference process models represent specific ordering work activities across time and place (Verdouw et al. 2010; Davenport 1993). Reference process models are predefined models used for the construction of other models (Verdouwa et al. 2010; Thomas 2006). Also the reference process models can be used to construct system dynamics computer models using systems approach developed by Forrester (1968).

Rice milling systems in Bangladesh mainly consist of milling sector, wholesale sector and retail sector. The milling sector procures paddy from the farmers, paddy traders and wholesalers and then prepares the milled rice. The wholesale sector procures the milled rice from this sector and sells the milled rice to the retail sector, while the retail sector sells the milled to the consumer. The product turnover of the retailers is about 22 kg per day. This compares with 10 tons per day for the wholesalers and up to 50 tons per day per mill. In other words, an urban retailer would need on average the sales of 1.5 farmers to assure his rice supplies for the year, whereas a wholesaler would require the sales of 400 farmers and a mill about 2000 farmers (Minten et al. 2013). The supply of paddy to milling sector is seasonal, and there are three seasons of rice production. The main harvesting season is from November to January followed by April to June and July to August. The demand of milled rice to the retail sector depends on the per capita rice consumption and population level. The critical components are supply of paddy in the milling sectors and inventory in the milling, wholesale and retail sector as well as the supply chain costs. Effective management requires timely delivery of rice at right quantity at the right time and right place. The current supply chain of rice milling systems in Bangladesh is lacking efficiency, and this needs reforms. This necessitates a computer model to analyse and support the rice milling systems in Bangladesh. However, for sustainable development of rice supply system in Bangladesh, rice supply chain management must be modelled and simulated for designing policy options before implementation (Bala 1999).

Carter and Easton (2011) reported a systematic review of sustainable supply chain management and demonstrated that it is necessary to develop models. Riddals et al. (2000) reported a critical review of the various mathematical methods used to model and analyse supply chains and concluded that operations research techniques are useful in providing solutions to local tactical problems, but the impact of these solutions on the global behaviour of the whole supply chain can only be assessed using dynamic simulation. System dynamics techniques, a methodology of constructing dynamic simulation model based on feedback concepts incorporating non-linearities and time lags developed by Forrester can be used to model such a dynamic system and analyse performance dynamics of the system (Bala 1999; Forrester, 1968).

Several studies have been reported on system dynamics modelling of supply chain of food industry (Apaiah et al. 2005; Apaiah and Hendrix 2005; Georgiadis et al. 2005). Minegishi and Thiel (2000) developed a system dynamics supply chain model to study the complex logistic behaviour of an integrated food industry and applied it to poultry production and processing to study the influence of different policies like the poultry breeding program and to show the phenomena of instabilities and system controls in supply chains confronted with serious hazards. Vo and Thiel (2008; 2011) reported dynamic behaviour of the entire chicken meat supply chain under bird flu crisis during the period from October 2005 to March 2006 in France, and this model is helpful to decision-makers for other fresh food supply chains when they are facing such crises. Kumar and Nigmatullin (2011) reported a system dynamics model to study the non-perishable product food supply chain performance under a monopolistic environment, and the model was used to study the behaviour and relationships within a supply chain for a non-perishable product and to determine the impact of demand variability and lead time on supply chain performance. The proposed model can be used to analyse 'what if scenarios' of different inventory policies and strategic food supply chain management issues. Also Sachan et al. (2005) reported a system dynamics model of Indian grain supply chain cost to device policies to reduce total supply chain cost and suggested action plans to reduce total supply chain costs.

Several studies have been reported on modelling of food supply chain management (Bosona and Gebresenbet 2013; Dabbene et al. 2008a, b). Dabbene et al. (2008a, b) reported a hybrid model consisting of event-driven dynamics and time-driven dynamics to describe beef meat supply chain, and Bosona and Gebresenbet (2013) conducted route analysis to determine optimal product centres of local food chain. Vo and Thiel (2011) reported an economic simulation of poultry supply chain using system dynamics. More recently detailed frameworks of food supply chain assessment and reference process models for sustainable food supply chain have been reported (Manzini and Accorsi 2013; Verdouw et al. 2010). Although Sachan et al. (2005) reported a system dynamics grain supply chain cost model, it does not include grain supply chain management. Effective and sustainable supply chain management of rice milling systems should not only consider total supply chain cost but also should consider inventory decision and policy development for effective and sustainable management of rice milling systems. To meet this research and literature gap as well the research gap, Bala et al. (2015) and Bhuiyan (2015) motivated us to develop a system dynamics model of rice milling systems that focuses on inventory and policy development. The modelling of the supply chain of the rice milling systems presented here is adopted from Bala et al. (2015) and Bhuiyan (2014).

11.2 Dynamic Hypothesis

The dynamic hypothesis seeks to define the critical feedback loops and stock–flow diagrams that drive the system's behaviour in the reference mode. When the model based on feedback concept is simulated, the endogenous structure of the stock–flow diagram should generate the reference mode behaviour of the system, and thus the endogenous structure causes the changes in dynamic behaviour of the system. In system dynamics modelling, causal loop diagrams and stock–flow diagrams are hypothesised to generate the reference mode of the behaviour over time (Sterman 2000). Supply chain of rice milling systems can be represented by causal loop diagrams and stock–flow diagrams, and the simulation model based on the causal loop diagram and stock–flow diagram would generate dynamic behaviour of the supply chain of the rice milling systems. The supply chain of rice milling systems in the form of causal loop diagram and stock–flow diagram is hypothesised to generate the observed inventory and price in the reference mode. In essence the bullwhip effect in the inventory levels results from the endogenous consequences of the feedback structure of the system.

11.3 Causal Loop Diagram

The causal loop diagram of the supply chain of rice milling systems in Bangladesh is shown in Fig. 11.1. The daily retailer demand is computed from the per capita consumption and population. When the inventory of the retailer reaches the reordering point, the retailer places order to the wholesaler which is equal to economic order quantity. The wholesaler also places order at the reordering point, and the quantity ordered is the economic order quantity. The miller procures the paddy from the farmers, the paddy traders and wholesalers. The rice production is seasonal. The supply chain of the rice milling systems shown in Fig. 11.1 is a multi-loop system having some non-linear cause–effect relationships. For example, three major loops of the milling sector are milling–order for milling–rice inventory–rice for milling–milling; milling–reordering point for milling–milling; and milling–rice for wholesale–wholesale–order for wholesale–milling. Also

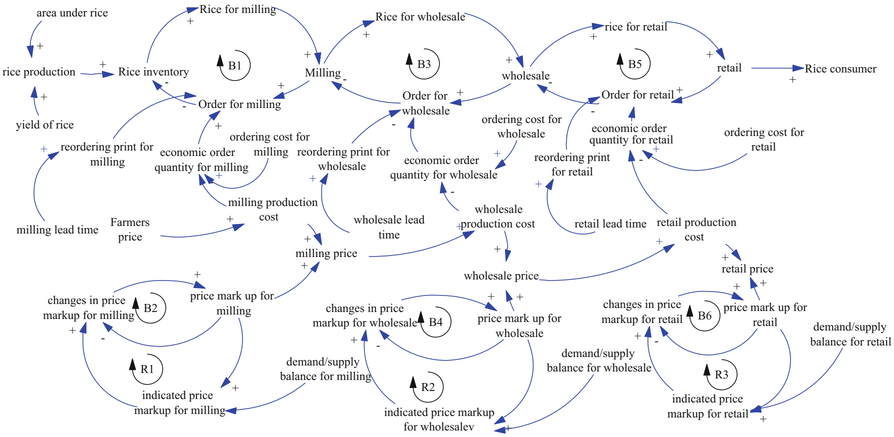

Fig. 11.1 Causal loop diagram of supply chain of the rice milling systems in Bangladesh

demand/supply balance is non-linearly related to price markup. Wholesale and retail also have similar multi-loops and non-linearities.

An economic order quantity could assist in deciding what would be the best optimal order quantity at the lowest cost. Similar to economic order quantity, the reordering point will advise when to place an order for specific products based on the historical demand. The reordering point also allows sufficient stock at hand to satisfy demand while the next order arrives due to the lead time.

The economic order quantity is computed using the following equation (Riggs 1970):

$$Q = \sqrt{\frac{2DS}{H}} \tag{11.1}$$

where

$Q =$ economic order quantity of rice, tons
$D =$ annual demand of rice, tons
$S =$ ordering cost, taka/tons
$H =$ holding and storage cost, taka/ton

and the reordering point for the economic order quantity is computed from the following equation (Riggs 1970):

$$R = d \times L + z \times \sigma_L \times \sqrt{L} \tag{11.2}$$

where

$R =$ reordering point, tons
$d =$ average demand of rice, tons per day

L = lead time, day
z = safety factor
σ_L = standard deviation of average demand, ton

The economic order quantity model gives an optimal solution in closed form, and this model has been effectively employed in automobiles, pharmaceutical industries and retail sectors (Muckstadt and Sapra 2010). Another important technique used along with economic order quantity is the reordering point and safety stock, and this reflects the level of inventory that triggers the placement of an order for another units, whereas the quantity associated with safety stock protects from stock-out (Chen 1998).

The milling price, wholesale price and retail price are determined in this study by change in price markup anchored by demand/supply balance (Kpmaier and Voigt 2013; Teimoury, et al. 2013).

11.4 Stock–Flow Diagram

The detailed STELLA flow diagram of the rice milling systems in Bangladesh is shown in Fig. 11.2. In this study, we consider the simulation of inventories of rice in the milling systems for economic order quantities and different policy options for sustainable optimum operation of the rice milling systems in Bangladesh. The fundamental equations used in this study are as follows.

11.4.1 Rice Milling Sector

Rice inventory is increased by rice production and decreased by sales for milling, and it is computed as

$$\begin{aligned}\text{rice inventory } (t) = \text{ rice inventory } (t-1) \ + \text{rice production rate} \times \Delta t \\ -\text{rice sales for milling} \times \Delta t\end{aligned} \tag{11.3}$$

Rice production depends on area under rice cultivation and yield of rice, and it is calculated as

$$\text{rice production rate} = \text{area under rice} \times \text{yield of rice} \tag{11.4}$$

The rice sales for milling is equal to milling order rate for rice for milling on order and milling received for milling inventory. It is the actual milling placed. When milling on order plus milling inventory is less than milling reordering point, then milling placed is milling reordering point; otherwise, it is zero. This is expressed as

$$\text{milling placed} = \text{IF}(\text{milling on order } + \text{milling inventory}) < (\text{milling reordering point})\text{THEN}(\text{milling to order})\text{ELSE}(0) \tag{11.5}$$

Milling reordering point is defined as the milling demand average over milling lead time plus milling safety stock, and it is computed as

$$\text{milling reordering point} = (\text{milling demand aver} \times \text{milling lead time }) + \text{milling safety stock} \tag{11.6}$$

The safety stock for milling is computes as

$$\text{milling safety stock} = \text{milling safety factor} \times \text{standard deviation of milling demand aver} \times \text{SQRT}(\text{milling lead time}) \tag{11.7}$$

Milling to order, i.e. milling reordering point, is initiated when milling inventory is less than milling reordering point; otherwise, it is zero. This is expressed as

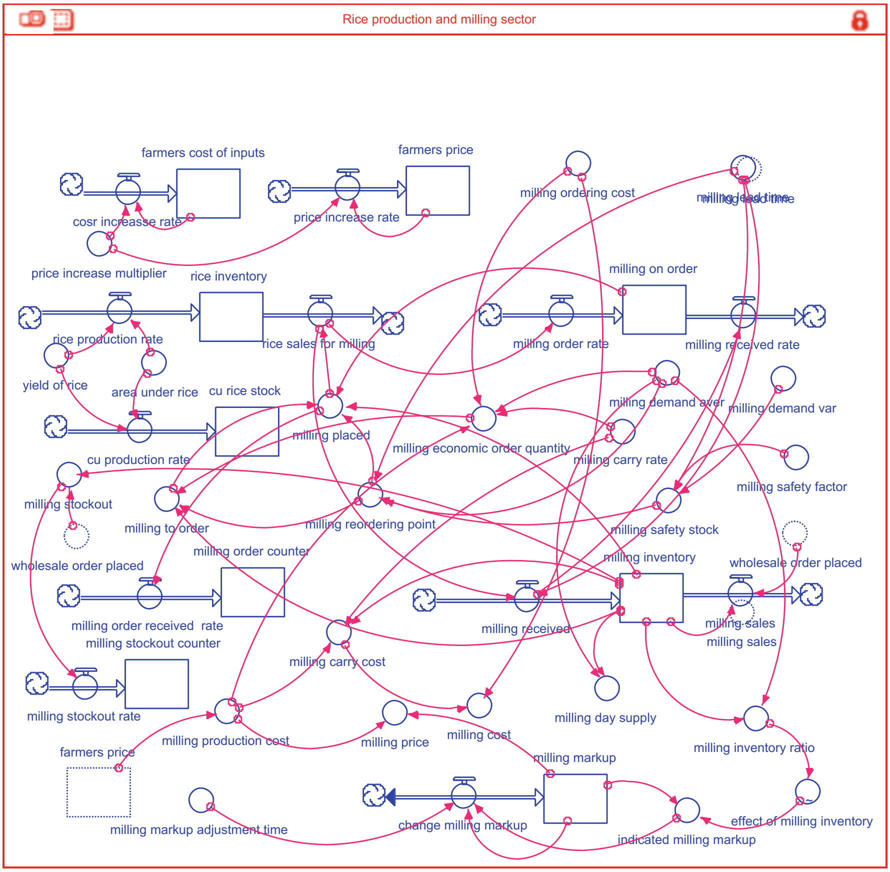

Fig. 11.2 STELLA flow diagram of the rice milling systems in Bangladesh

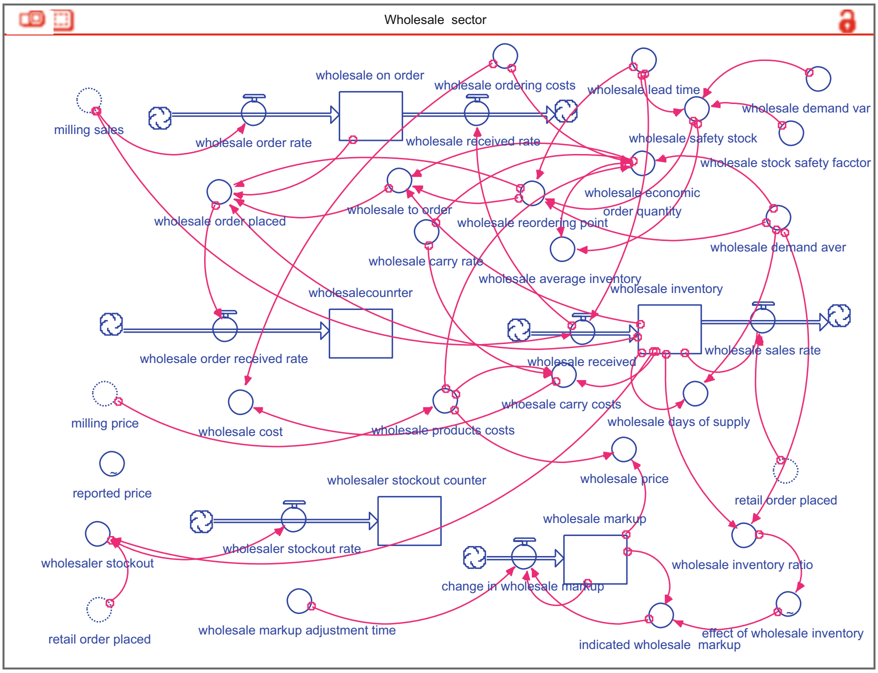

Fig. 11.2 (continued)

$$
\begin{aligned}
&\text{milling to order} = \text{IF}(\text{milling inventory})\\
&< (\text{milling reordering point})\text{THEN}(\text{milling economic order quantity})\text{ELSE}(0)
\end{aligned}
\tag{11.8}
$$

Milling economic order quantity is computed from the following relation:

$$
\begin{aligned}
&\text{milling economic order quantity}\\
&= \text{SQRT}\big((2 \times \text{milling demand aver} \times \text{milling ordering cost})\\
&/((\text{milling carryrate}/365) \times \text{milling production cost})\big)
\end{aligned}
\tag{11.9}
$$

The state variable milling on order is increased by milling order rate and decreased by milling received rate by milling inventory, and it is computed as

$$
\begin{aligned}
&\text{milling on order}(t) = \ \text{milling on order } (t-1) \ + \text{milling order rate} \times \Delta t\\
&-\text{milling received rate} \times \Delta t
\end{aligned}
\tag{11.10}
$$

Rice milling inventory is increased by milling received and decreased by milling sales of rice, and it is expressed as

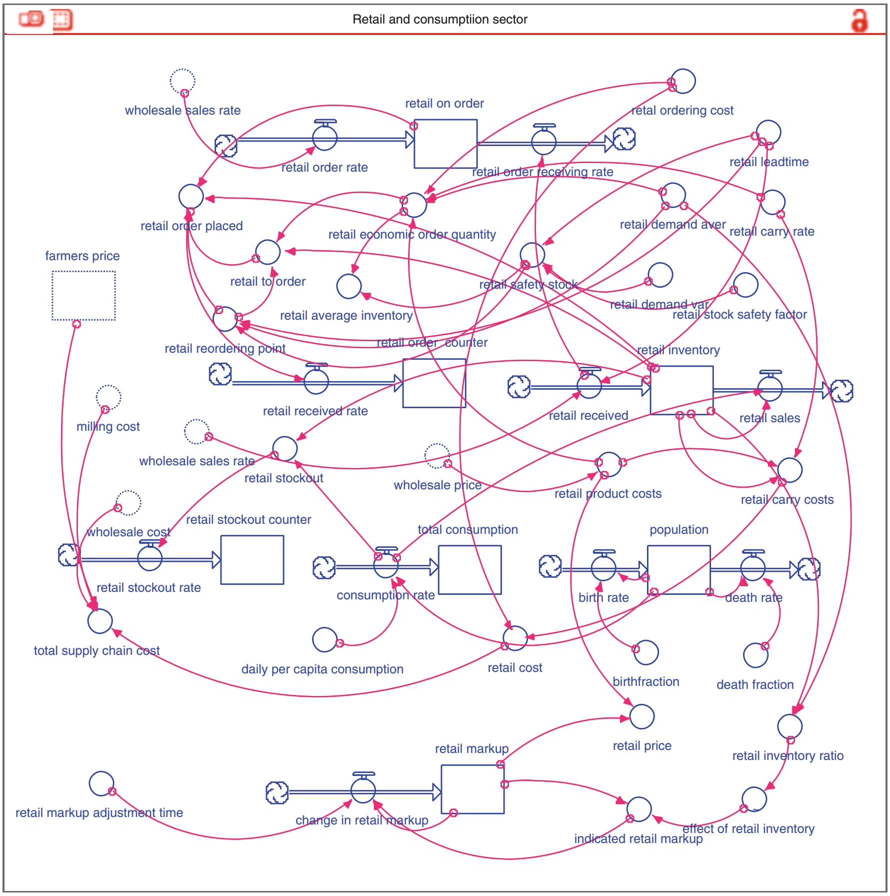

Fig. 11.2 (continued)

$$\text{milling inventory }(t) = \text{ milling inventory }(t-1) \; + \text{milling received} \times \Delta t \\ -\text{milling sales} \times \Delta t \tag{11.11}$$

Milling received is the rice received for milling in the milling inventory with a time delay of milling lead time, and it is expressed as

$$\text{milling received} = \text{DELAY}(\text{rice sales for milling, milling lead time})) \tag{11.12}$$

Milling sales depends on milling inventory and wholesale order placed. When wholesale order placed is greater than milling inventory, then milling sales is equal to milling inventory; otherwise, it is wholesale order placed, and it is expressed as

$$\text{milling sales} = \; \text{IF}(\text{wholesale order placed}) > (\text{milling inventory}) \\ \times\text{THEN}(\text{milling inventory})\text{ELSE}(\text{wholesale order placed}) \tag{11.13}$$

The milling price of rice is computed from cost of milled rice and price markup for milling as

$$\text{milling price} = \text{MAX}\big(\text{milling production cost}\ ,\ (1 + \text{milling markup}) \\ \times \text{milling production cost}\big) \tag{11.14}$$

Price markup for milling of rice depends on change in milling markup, and it is computed as

$$\begin{aligned}\text{milling markup}(t) = {} & \text{milling markup}(t-1) \\ & + \text{change in milling markup} \times \Delta t\end{aligned} \tag{11.15}$$

Change in milling markup depends on milling markup itself, indicated milling markup and milling markup adjustment time, and it is computed as

$$\text{change in milling markup} = (\text{indicated milling markup} - \text{milling markup}) \\ /\text{milling markup adjustment time} \tag{11.16}$$

Indicated price markup for milling of rice is computed from price markup for milling and effect of relative inventory coverage of the milled rice (Sterman 2000; Teimoury et al. 2013), and it is computed as

$$\text{indicated milling markup} = \text{milling markup} \times \text{effect of milling inventory} \tag{11.17}$$

Effect of milling inventory is expressed as a non-linear graphical function of relative inventory coverage of the milled rice. This formulation of price settling essentially consists of expectation adjustment and price adjustment (Sterman 2000). The concept of expectation adjustment was introduced by Nerlove (1958), and subsequently it was used by Meadows (1970) and Bala (1975, 1990) for formulation price setting of agricultural commodities with a reasonably good agreement between the predicted prices and reported values.

11.4.2 Wholesale Sector

Wholesale on order is increased by wholesale order rate and decreased by wholesale received rate, and it is computed as

$$\text{wholesale on order}(t) = \text{wholesale on order }(t-1) + \text{wholesale order rate} \\ \times \Delta t - \text{wholesale received rate} \times \Delta t \tag{11.18}$$

Rice wholesale inventory is increased by wholesale received and decreased by wholesale sales rate of rice, and it is expressed as

$$\text{wholesale inventory } (t) = \text{ wholesale inventory } (t-1) + \text{wholesale received} \times \Delta t \\ -\text{wholesale sales rate} \times \Delta t \tag{11.19}$$

Wholesale received is the rice received for wholesale inventory with a time delay of wholesale lead time, and it is expressed as

$$\text{wholesale received} = \text{DELAY(milling sales, wholesale lead time)} \tag{11.20}$$

Wholesale sales rate depends on wholesale inventory and retail order placed. When retail order placed is greater than wholesale inventory, then wholesale sales rate is wholesale inventory; otherwise, it is retail order placed, and it is expressed as

$$\text{wholesale sales rate} = \text{IF(retail order placed)} \\ > \text{(wholesale inventory)THEN(wholesale inventory)ELSE(retail order placed)} \tag{11.21}$$

When wholesale on order plus wholesale inventory is less than wholesale reordering point, then wholesale order placed is wholesale to order; otherwise, it is zero. This is expressed as

$$\text{wholesale order placed} = \text{IF(wholesale on order } + \text{wholesale inventory)} \\ < \text{(wholesale reordering point)THEN(wholesale to order)ELSE(0)} \tag{11.22}$$

Wholesale reordering point is defined as the sum of wholesale demand average over wholesale lead time and wholesale safety stock, and it is computed as

$$\text{wholesale reordering point} = (\text{wholesale demand aver} \times \text{wholesale lead time}) \\ +\text{wholesale safety stock} \tag{11.23}$$

The safety stock for wholesale is computes as:

$$\text{wholesale safety stock} = \text{wholesale safety factor} \\ \times \text{standard deviation of wholesale demand aver} \times \text{SQRT(wholesale lead time)} \tag{11.24}$$

Wholesale to order, i.e. wholesale reordering point, is initiated as wholesale economic order quantity. When wholesale inventory is less than wholesale reordering point, then wholesale to order is wholesale economic order quantity; otherwise, it is zero. This is expressed as

$$\text{wholesale to order} = \text{IF}(\text{wholesale inventory}) < (\text{wholesale reorderingpoint})\text{THEN}(\text{wholesale economic order quantity})\text{ELSE}(0) \tag{11.25}$$

Wholesale economic order quantity is computed from the following relation:

$$\text{wholesale economic order quantity} = \text{SQRT}\big((2 \times \text{wholesale demand aver} \times \text{wholesale ordering cost})/((\text{wholesale carry rate}/365) \times \text{wholesale product cost})\big) \tag{11.26}$$

The wholesale price of rice is computed from cost of wholesale rice and price markup for wholesale as

$$\text{wholesale price} = \text{MAX}\big(\text{wholesale productscosts}\ ,\ (1 + \text{wholesale markup}) \times \text{wholesale products cost s}\big) \tag{11.27}$$

Price markup for wholesale of rice depends on change in wholesale markup, and it is computed as

$$\text{wholesale markup}(t) = \text{wholesale markup}(t-1) + \text{change in wholesale markup} \times \Delta t \tag{11.28}$$

Change in wholesale markup depends on wholesale markup itself, indicated wholesale markup and wholesale markup adjustment time and it is computed as

$$\text{change in wholesale markup} = (\text{indicated wholesale markup} - \text{wholesale markup})/\text{wholesale markup adjustment time} \tag{11.29}$$

Indicated price markup for wholesale of rice is computed from price markup for wholesale and effect of relative inventory coverage of the wholesale rice (Sterman 2000; Teimoury et al. 2013), and it is computed as

$$\text{indicated wholesale markup} = \text{wholesale markup} \times \text{effect of wholesale inventory} \tag{11.30}$$

Effect of wholesale inventory is expressed as a non-linear graphical function of relative inventory coverage of the wholesale rice.

11.4.3 Retail Sector

Retail on order is increased by retail order rate and decreased by retail received rate, and it is computed as

$$\text{retail on order}(t) = \text{ retail on order } (t-1) \; + \text{retail order rate} \times \Delta t \\ -\text{retail received rate} \times \Delta t \tag{11.31}$$

Rice retail inventory is increased by retail received and decreased by retail sales of rice, and it is expressed as

$$\text{retail inventory } (t) = \text{ retail inventory } (t-1) \; + \text{retail received} \times \Delta t \\ -\text{retail sales} \times \Delta t \tag{11.32}$$

Retail received is the rice received for retail inventory with a time delay of retail lead time, and it is expressed as

$$\text{retail received} = \text{DELAY}(\text{wholesale sales}, \text{retail lead time}) \tag{11.33}$$

Retail sales rate depends on retail inventory and consumption rate. When consumption rate is greater than or equal to retain inventory, then it is retail inventory; otherwise, it is consumption rate, and it is expressed as

$$\text{retail sales} = \text{IF}\big(\text{consumption rate} \\ >= \text{retail inventory}\big)\text{THEN}(\text{retailinventory})\text{ELSE}(\text{consumption rate}) \tag{11.34}$$

When retail on order plus retail inventory is less than retail reordering point, then retail placed is retail to order; otherwise, it is zero. This is expressed as

$$\text{retail placed} = \text{IF}(\text{retail on order } \; + \text{retail inventory}) \\ < (\text{retail reordering point})\text{THEN}(\text{retail to order})\text{ELSE}(0) \tag{11.35}$$

Retail reordering point is defined as the sum of retail demand average over retail lead time and retail safety stock, and it is computed as

$$\text{retail reordering point} = (\text{retail demand aver} \times \text{retail lead time }) \\ +\text{retail safety stock} \tag{11.36}$$

The safety stock for retail is computed as

$$\text{retail safety stock} = \text{retail safety factor} \\ \times\text{standard deviation of retail demand aver} \times \text{SQRT}(\text{retail lead time}) \tag{11.37}$$

Retail to order, i.e. retail reordering point, is initiated as retail economic order quantity. When retail inventory is less than retail reordering point, then retail to order is retail reordering quantity; otherwise, it is zero. This is expressed as

$$\text{retail to order} = \text{IF}(\text{retail inventory}) \\ < (\text{retail reorderingpoint})\text{THEN}(\text{retail economic order quantity})\text{ELSE}(0) \tag{11.38}$$

Retail economic order quantity is computed from the following relation:

$$\text{retail economic order quantity} = \text{SQRT}\big(\big(2 \times \text{retail demand aver} \times \text{retail ordering cost}\big)/\big((\text{retail carry rate}/365) \times \text{retail product cost}\big)\big) \tag{11.39}$$

The retail price of rice is computed from cost of retail rice and price markup for retail as

$$\text{retail price} = \text{MAX}(\text{retail productcosts}\ ,\ (1 + \text{retail markup}) \times \text{retail product cost s}) \tag{11.40}$$

Price markup for retail of rice depends on change in retail markup, and it is computed as

$$\text{retail markup}(t) = \text{retail markup}(t-1) + \text{change in retail markup} \times \Delta t \tag{11.41}$$

Change in retail markup depends on retail markup itself, indicated retail markup and retail markup adjustment time, and it is computed as

$$\text{change in retail markup} = (\text{indicated retail markup} - \text{retail markup}) /\text{retail markup adjustment time} \tag{11.42}$$

Indicated price markup for retail of rice is computed from price markup for retail and effect of relative inventory coverage of the retail rice (Sterman 2000; Teimoury et al. 2013), and it is computed as

$$\text{indicated retail markup} = \text{retail markup} \times \text{effect of retail inventory} \tag{11.43}$$

Effect of retail inventory is expressed as a non-linear graphical function of relative inventory coverage of the retail rice.

These equations were solved numerically using Runge–Kutta fourth-order method, and the solution interval dt was taken to be 0.25 which is less than half of the shortest first-order delay.

11.5 Model Validation

Initial values and the parameters were estimated from the primary and secondary data (BBS 2011; Bhuiyan 2014). The data on milling inventory, wholesale inventory and retail inventory used for simulation of supply chain of the rice milling systems in Bangladesh are shown in Table 11.1.

To build up confidence in the predictions of the model, various ways of validating a model such as checking the structure of the model, comparing the model predictions with historic data, checking whether the model generates plausible behaviour and checking the quality of the parameter values were considered. Time series data of wholesale prices of rice in Bangladesh in 2011 were compared with the simulated wholesale rice prices to build up confidence in the model, and

Table 11.1 Data used for the simulation of rice supply chain in Bangladesh

Item	Initial value, tones	Lead time, days	Demand average, tonnes	Ordering cost, taka[a]	Carry rate, fraction of product cost (1/year)
Milling inventory	2,500,000	7	950,000	500,000	0.15
Wholesale inventory	1,500,000	7	950,000	500,000	0.15
Retail inventory	2,500,00	7	95,000	50,000,000	0.15

Sources: BBS (2011) and Bhuiyan (2014)
[a]1 US dollar = 78.30 Bangladeshi taka

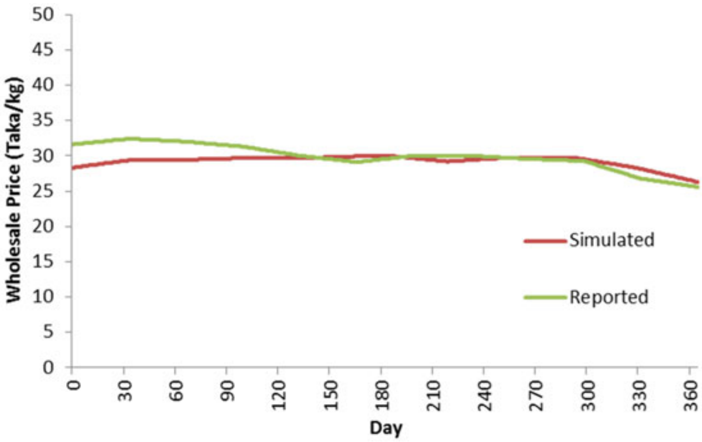

Fig. 11.3 Comparisons of the predicted and reported values of wholesale price in Bangladesh in 2011

this is shown in Fig. 11.3. The model-simulated prediction agrees reasonably well with historical behaviour. Also the model was tested for extreme conditions to detect the defect in the model structure and enhance the usefulness of the model for policy analysis. Figure 11.4 shows simulated milling inventory, wholesale inventory and retail inventory under extreme condition of crop failure, i.e. zero crop production. Under this condition, the milling inventory and then wholesale inventory and retail inventory are reduced to zero since the rice production is zero. The model results confirmed to the expected patterns of results and realities. This model complied with the basic principles of supply chain management and was consistent with supply chain theory and research results. The model is able to provide qualitative and quantitative understanding of the supply chain performances of rice milling systems. Hence, the model is reliable, and the validated model was used for policy analysis.

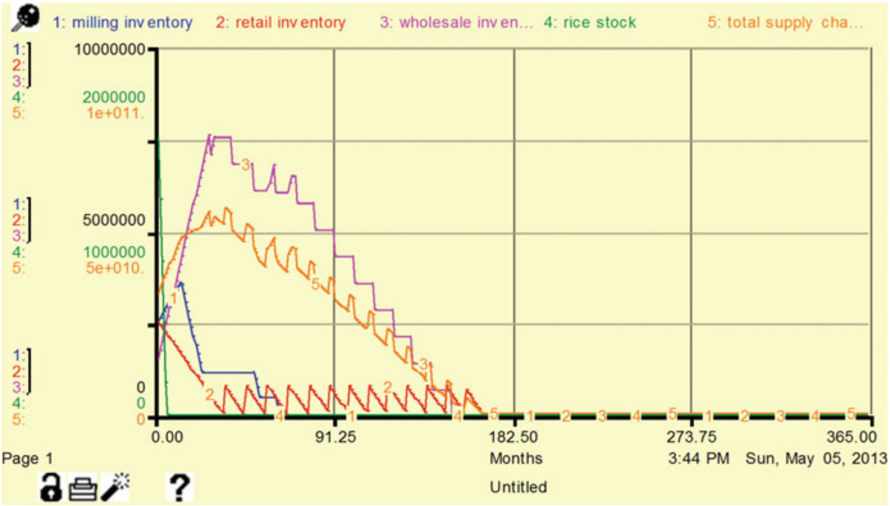

Fig. 11.4 Simulated rice stock, total supply chain cost, milling inventory, wholesale inventory and retail inventory under extreme condition of total crop failure

11.6 Simulation and Policy Analysis

Figure 11.5 shows the simulated milling inventory, wholesale inventory and retail inventory for economic order quantity and reordering point operation of the order rate of milling, wholesale and retail. Economic order quantity and reordering point operation of the order rate of milling, wholesale and retail of the supply chain of rice milling systems stabilises the retail inventory and retail supply of the rice for consumption is ensured. However, there is a bullwhip or Forrester effect due to economic order quantity and reordering point operation of the milling, wholesale and retailing. Four major causes of bullwhip effect are demand updating, order batching, price fluctuation and rationing and shortage gaming. In this study, mainly the demand updating and order batching in the form of economic order quantity and reordering point operation, respectively, caused this bullwhip effect. Ideally inventory level should be as low as possible, but increased inventory is justified to meet the increased demand if the cost is low, and stock-out means failure to meet consumer demand. The milling and wholesale inventories fluctuate due to seasonal supply of rice, and this causes the rice milling industries to starve for rice for milling during the off-season of rice production. The milling inventory reduces to zero during the off-season of rice production, while the wholesale inventory accumulates rice from the harvesting season and reaches the peak at early part of the year to maintain the supply to the retailer for sustainable availability of rice to the consumers during the off-season, and then it decreases until rice from new

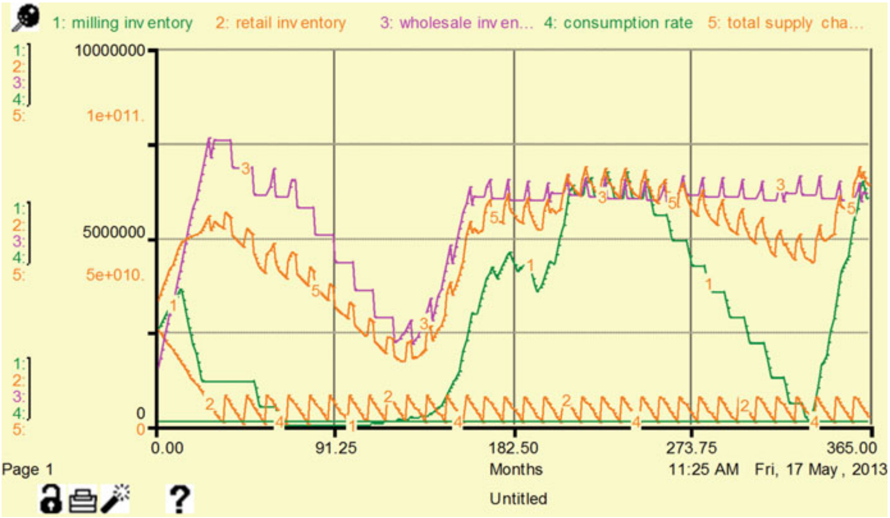

Fig. 11.5 Simulated milling, wholesale and retail inventory, daily rice requirement and total supply chain costs for economic order quantity and reordering point operation of the order rate of milling, wholesale and retailing

harvest is available. Then it increases and remains stable for rest of the period of the year.

To assess how the supply chain of the rice milling systems in Bangladesh would behave for any other ordering policies, the model was simulated for lead time average demand (demand average × lead time) policy. Although lead time average demand (demand average × lead time) order quantity and reordering point operation policy stabilises the retail inventory in a pattern similar to the economic order quantity policy, it increases the bullwhip effect and total supply chain cost. The annual total supply chain cost increases by 2.64 times the annual total supply chain cost of economic order quantity and reordering point operation of the milling, wholesale and retailing. This demonstrated the potentiality of using economic order quantity operation policy for supply chain management of rice milling systems.

The model was also simulated to address the impacts of rice productivity on the supply chain performances. Here the rice productivity is the yield of rice per ha. Rice productivity may be reduced from crop damage due to floods or pest infestation, and also it can be increased by development of higher yield hybrid rice through research and development. Rice productivity for this policy is defined as

$$\text{rice production rate} = \text{area under rice} \times \text{yield of rice} \tag{11.44}$$

$$\text{yield of rice} = 1.81, 2.81 \text{ and} 3.81 \text{ tons/ha} \tag{11.45}$$

Simulated milling inventory, wholesale inventory, retail inventory and total supply chain cost for rice productivity of 1.81 tons per ha, 2.81 tons per ha (present average rice productivity) and 3.81 tons per ha are shown in Figs. 11.6a, 11.6b, 11.6c and

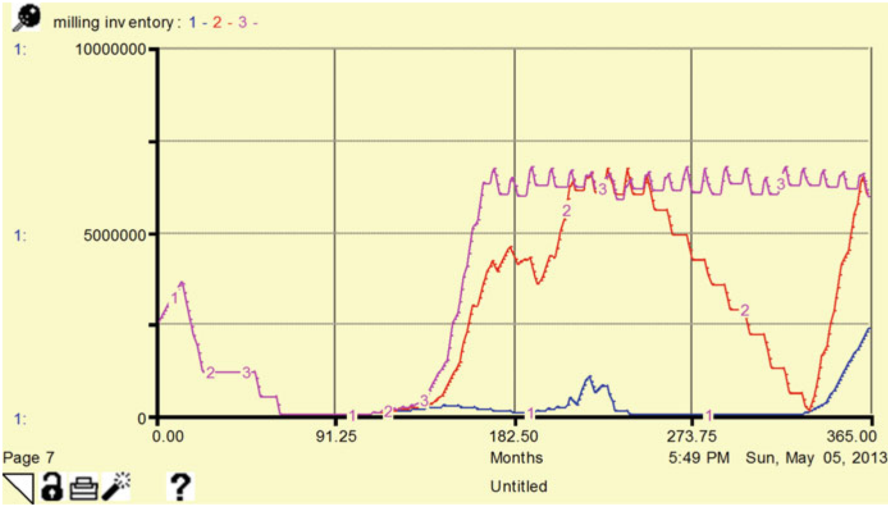

Fig. 11.6a Simulated milling inventory for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

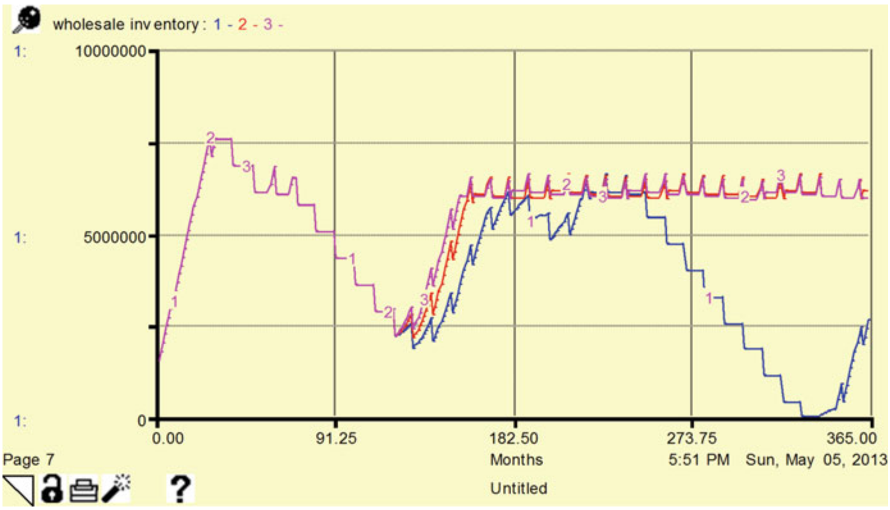

Fig. 11.6b Simulated wholesale inventory for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

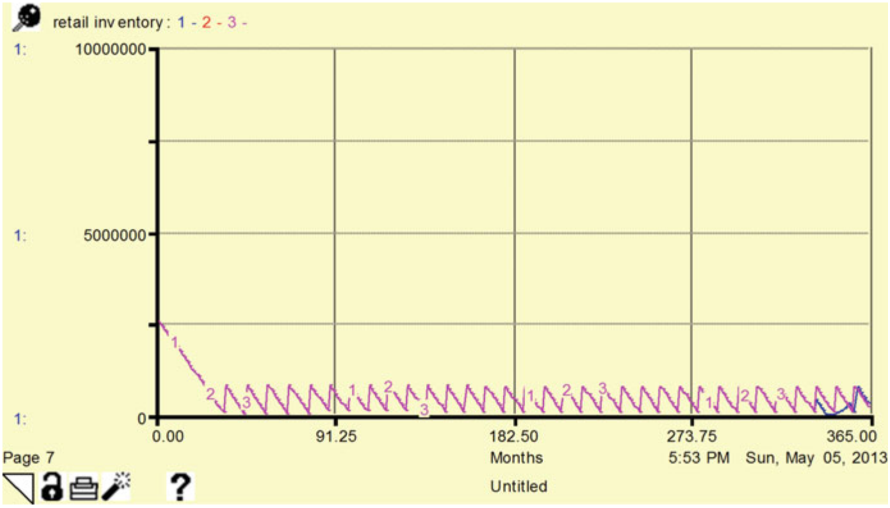

Fig. 11.6c Simulated retail inventory for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

11.6d, respectively. Milling inventory is reduced to zero for most of the period of the reduced productivity of rice (1.81 tons per ha), while it is high for bumper production of rice (3.81 tons per ha) (Fig. 11.6a). Wholesale inventory is reduced significantly in the fourth quarter of the year for reduced rice productivity (1.81 tons per ha) (Fig. 11.6b). Total supply chain cost is also reduced in the third and fourth quarter of the year for reduced rice productivity (Fig. 11.6d). However, in all the cases, the retail inventory is almost the same except towards the end of the year when both milling and wholesale inventories are empty for reduced productivity (Fig. 11.6c). Thus, increased wholesale inventory is a possible solution for the retail inventory to face the shortage of rice during the off-peak harvesting season of rice production. This implies that as long as wholesale inventory is available, the retail inventory is stabilised based on economic order quantity and reordering point operation of milling, wholesale and retail inventory. This demonstrates that the policy based on economic order quality and reordering point can ensure the availability of rice even under reduced production of rice, i.e. during crop damage/failure unless both wholesale and milling inventories are empty.

The model was also simulated to assess the impacts of lead times on the supply chain performances. Lead time can be defined as the time it takes from when first a need for a product is determined until it arrives on the doorstep and the reordering point and safety stock depend the lead time. Reordering point and safety stock for milling, wholesale and retailing for this policy are defined as

$$\text{reordering point} = (\text{ demand aver} \times \text{lead time }) + \text{safety stock} \qquad (11.46)$$

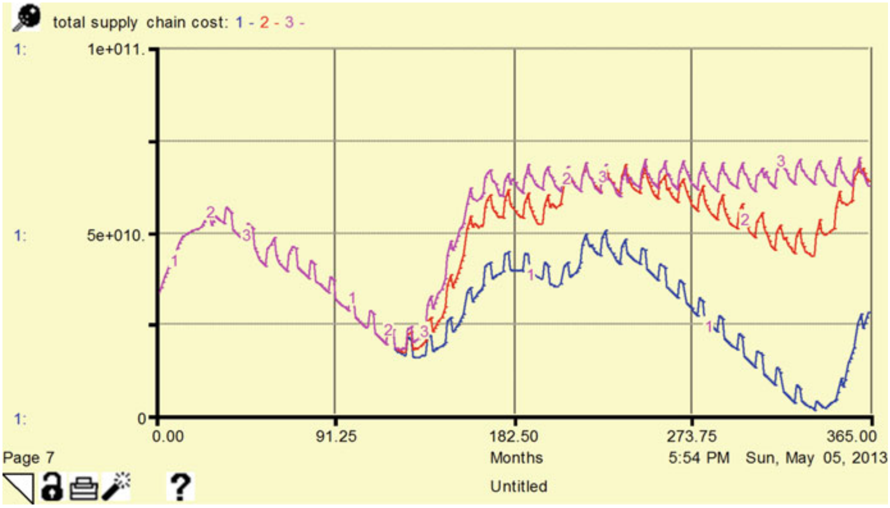

Fig. 11.6d Simulated total supply chain cost for rice productivity of 1.81 tons per ha, 2.81 tons per ha and 3.81 tons per ha

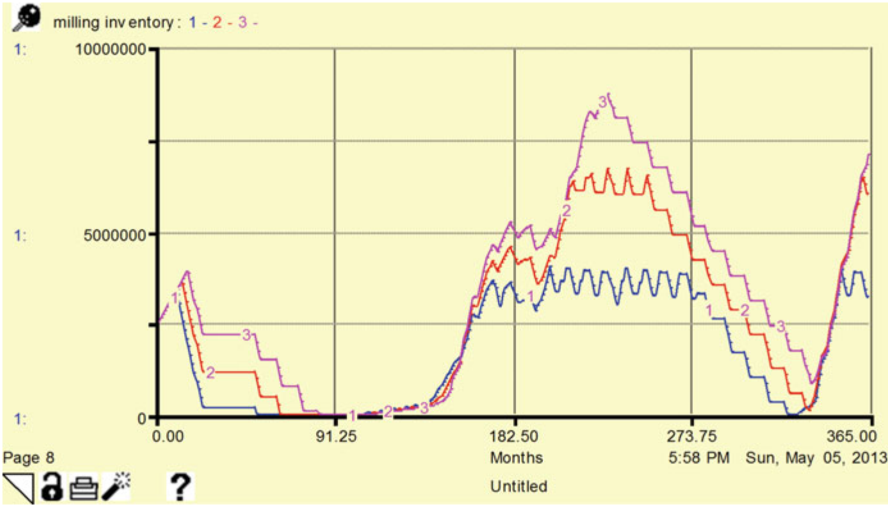

Fig. 11.7a Simulated milling inventory for milling lead time of 4 days, 7 days and 10 days

$$\text{safety stock} = \text{safety factor} \times \text{standard deviation of demand aver} \times \text{SQRT}(\text{ lead time}) \tag{11.47}$$

$$\text{lead time} = 4,\ 7 \text{ and } 10 \text{ days} \tag{11.48}$$

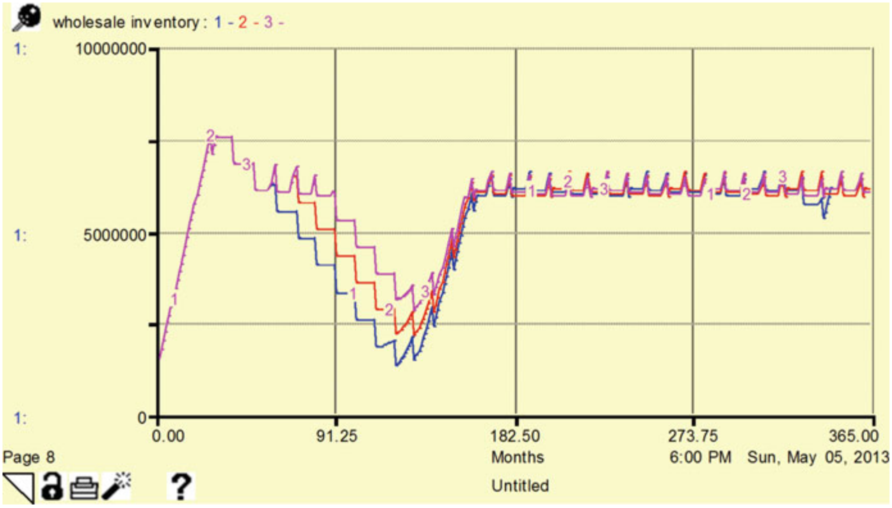

Fig. 11.7b Simulated wholesale inventory for milling lead time of 4 days, 7 days and 10 days

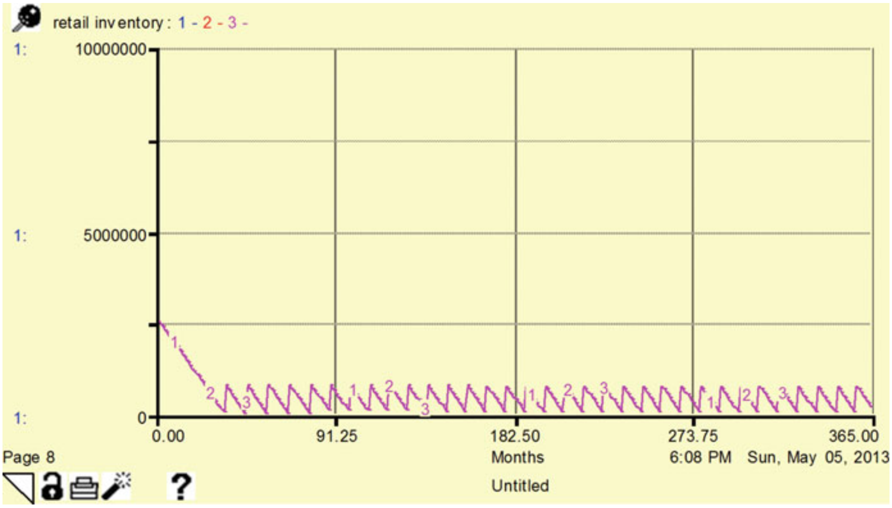

Fig. 11.7c Simulated retail inventory for milling lead time of 4 days, 7 days and 10 days

Simulated milling inventory, wholesale inventory, retail inventory and total supply chain cost for milling lead time (4, 7 and 10 days), wholesale lead time (4, 7 and 10 days) and retail lead time (4, 7 and 10 days) are shown in Figs. 11.7a, 11.7b, 11.7c, 11.7d, 11.8a, 11.8b, 11.8c, 11.8d, 11.9a, 11.9b, 11.9c and 11.9d, respectively.

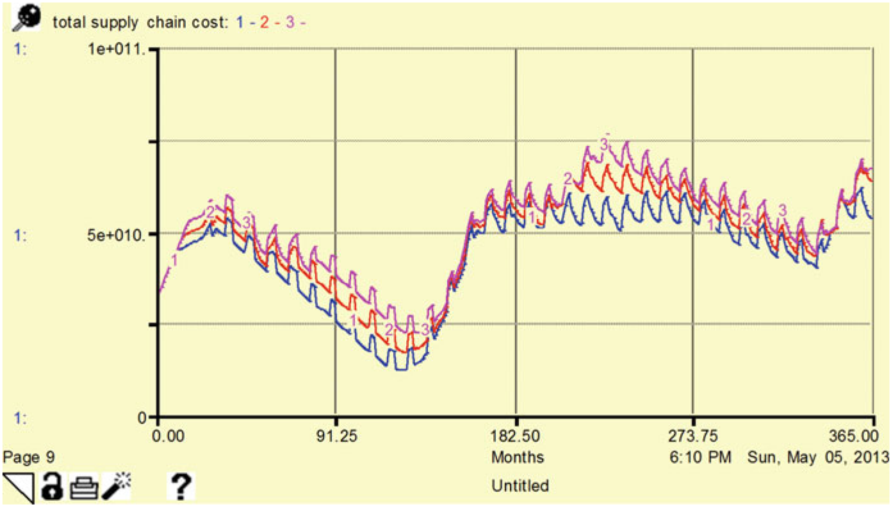

Fig. 11.7d Simulated total supply chain cost for milling lead time of 4 days, 7 days and 10 days

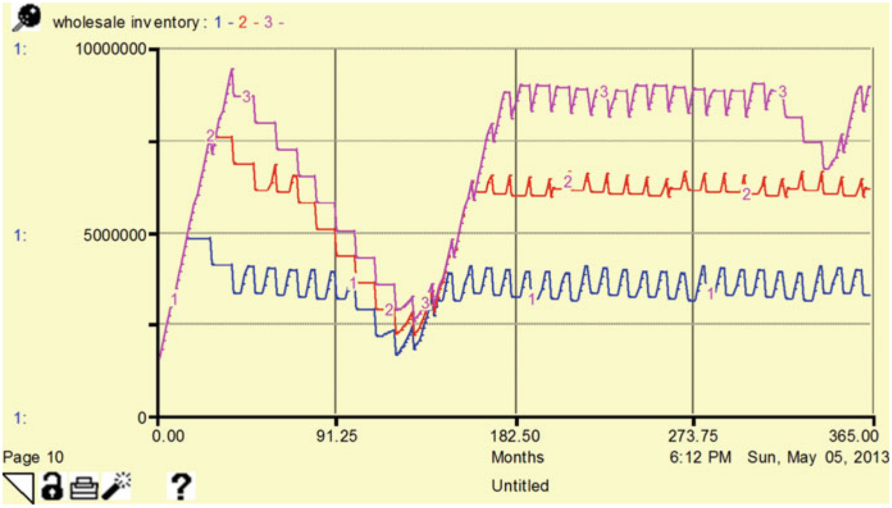

Fig. 11.8a Simulated wholesale inventory for wholesale lead time of 4 days, 7 days and 10 days

Firstly let us consider the impacts of milling lead time on supply chain performances for milling lead time of 4 days, 7 days and 10 days. Milling inventory increases considerably with the increase in the milling lead time (Fig. 11.7a). Wholesale inventory and total supply chain cost increase little with the increase of milling lead time (Figs. 11.7b and 11.7d), but the retail inventory remains almost

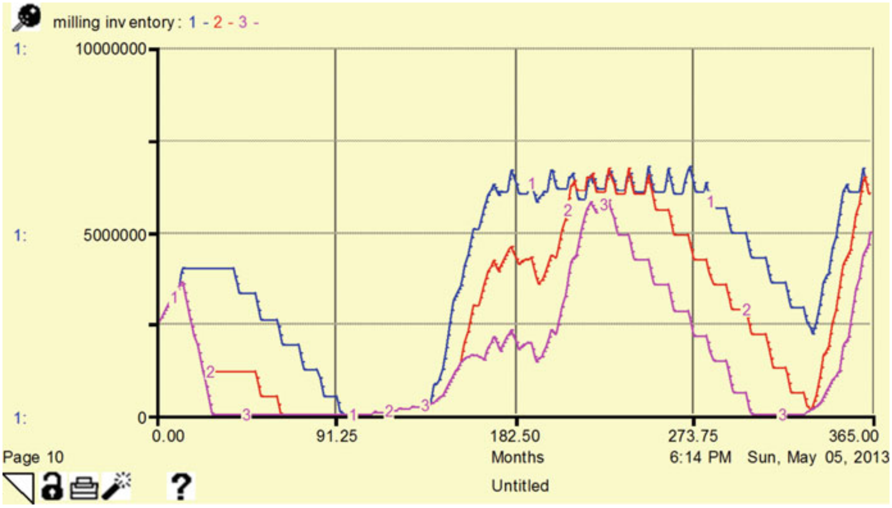

Fig. 11.8b Simulated milling inventory for wholesale lead time of 4 days, 7 days and 10 days

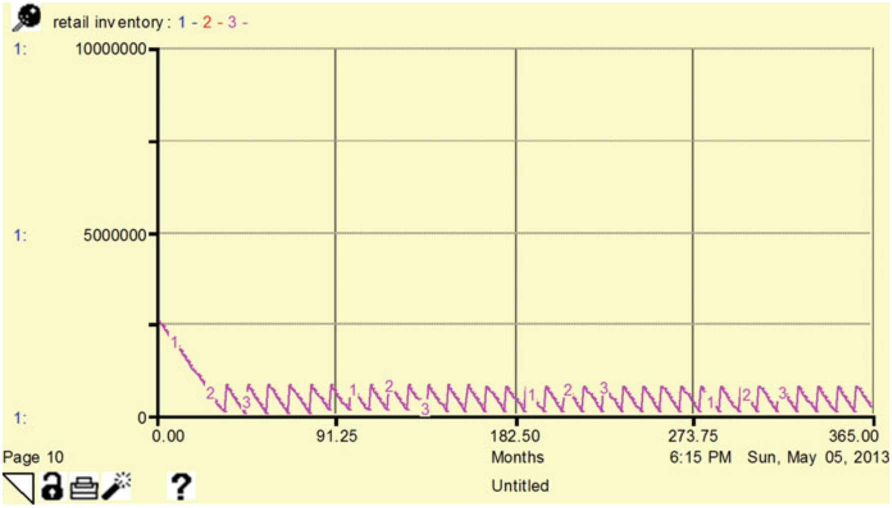

Fig. 11.8c Simulated retail inventory for wholesale lead time of 4 days, 7 days and 10 days

unchanged (Fig. 11.7c). In essence the major impact of the changes in milling lead time is reflected on the milling inventory, but the impact on the retail inventory is a minimum.

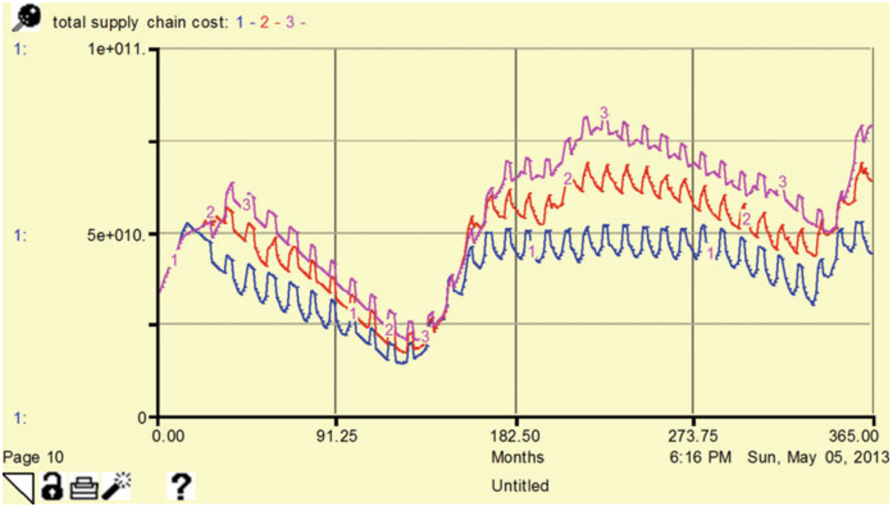

Fig. 11.8d Simulated total supply chain cost for wholesale lead time of 4 days, 7 days and 10 days

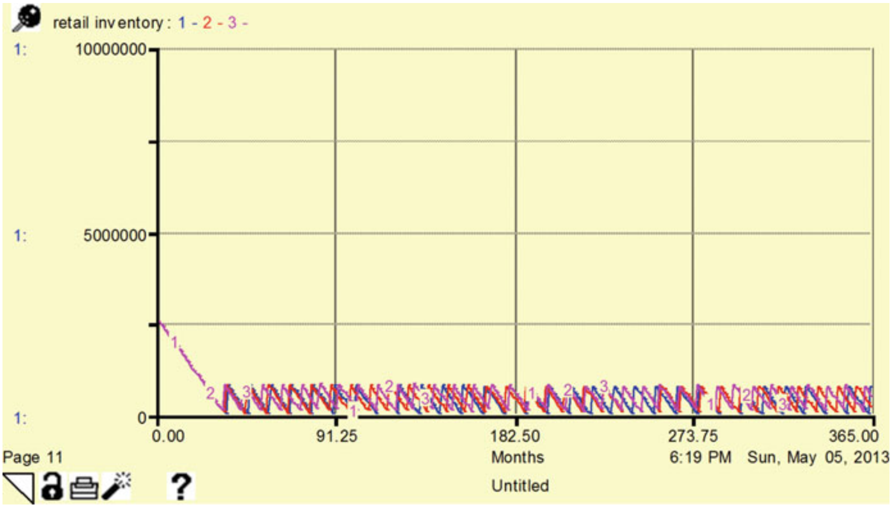

Fig. 11.9a Simulated retail inventory for retail lead time of 4 days, 7 days and 10 days

Secondly let us consider the impacts of wholesale lead time on supply chain performances for wholesale lead time of 4 days, 7 days and 10 days. Simulated wholesale inventory, milling inventory, retail inventory and total supply chain cost for wholesale lead time of 4 days, 7 days and 10 days are shown in Figs. 11.8a,

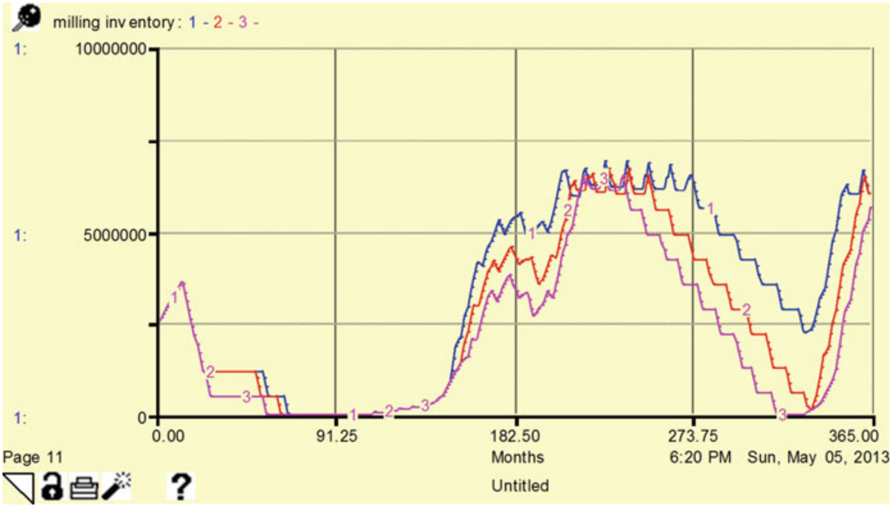

Fig. 11.9b Simulated milling inventory for retail lead time of 4 days, 7 days and 10 days

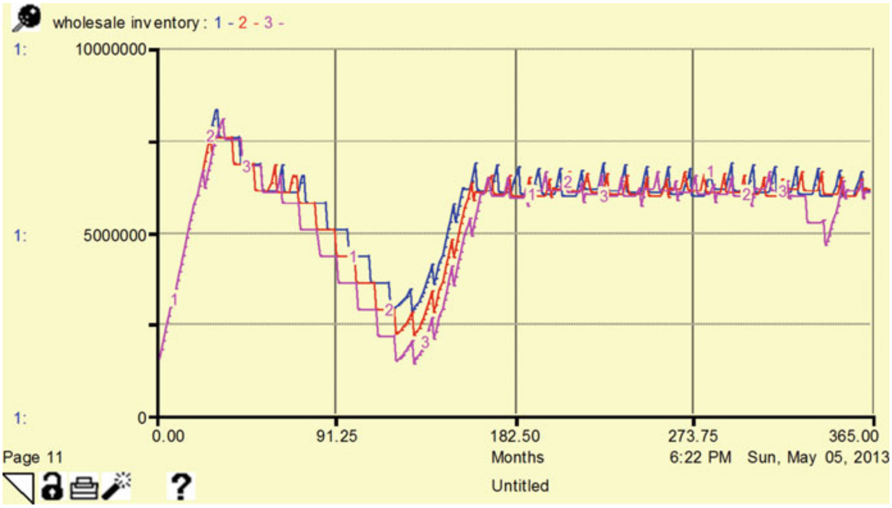

Fig. 11.9c Simulated wholesale inventory for retail lead time of 4 days, 7 days and 10 days

11.8b, 11.8c, and 11.8d, respectively. Wholesale inventory and total supply chain cost increase with the increase of wholesale lead time (Figs. 11.8a and 11.8d), while milling inventory decreases (Fig. 11.8b), and the changes are relatively large, but the retail inventory remains almost unchanged (Fig. 11.8c). In essence the major impacts of the changes in wholesale lead time are reflected not only on the changes

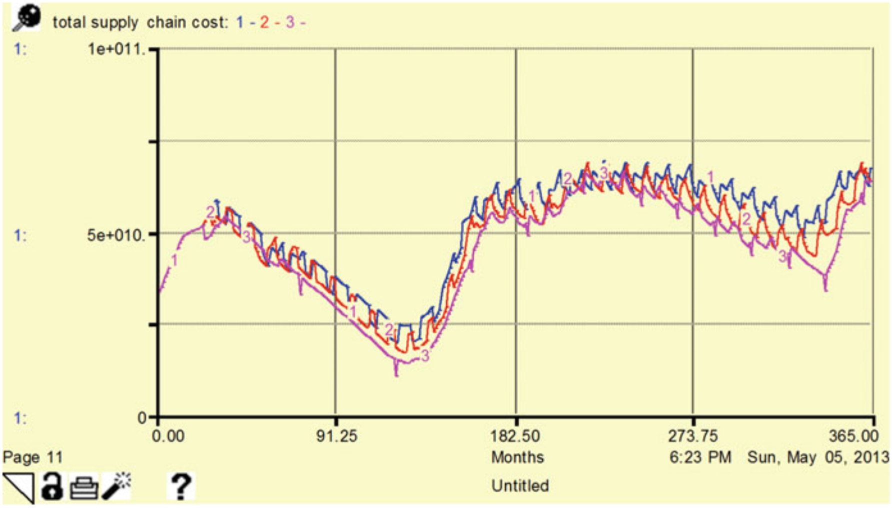

Fig. 11.9d Simulated total supply chain cost for retail lead time of 4 days, 7 days and 10 days

of wholesale inventory but also on the milling inventory and total supply chain costs. However, the impact on the retail inventory is a minimum.

Thirdly let us consider the impacts of retail lead time on supply chain performances for retail lead time of 4 days, 7 days and 10 days. Simulated retail inventory, milling inventory, wholesale inventory and total supply chain cost for retail lead time of 4 days, 7 days and 10 days are shown in Figs. 11.9a, 11.9b, 11.9c and 11.9d, respectively. Retail inventory increases very little with the increase of retail lead time (Fig. 11.9a). But the effects of lead time changes are more prominent in the second half of the simulated period, and the milling inventory decreases with the increase in retail lead time (Fig. 11.9b). The wholesale inventory and total supply chain cost show small changes for changes in retail lead time, but each category follows similar patterns with time within a narrow band (Figs. 11.9c and 11.9d).

It is demonstrated that the policy based on economic order quantity and reordering point can ensure the availability of rice even under changes in lead time and demand average in the supply chain of the rice milling systems. However, the bullwhip or Forrester effect remains present in the system. Forrester (1961) and Sterman (1989) ascribe behavioural causes to the bullwhip effect, where Lee et al. (1997a, b) suggest that the bullwhip effect also occurs due to operational causes. The lack of supply chain coordination results in bullwhip effect which distorts the demand information in the supply chain and increases the supply chain cost. The most obvious remedy to counter demand signal processing is collaboration, but it generally does not completely eliminate the problem (Moll 2013). The largest increase in total supply chain cost occurs for the increase in the wholesale

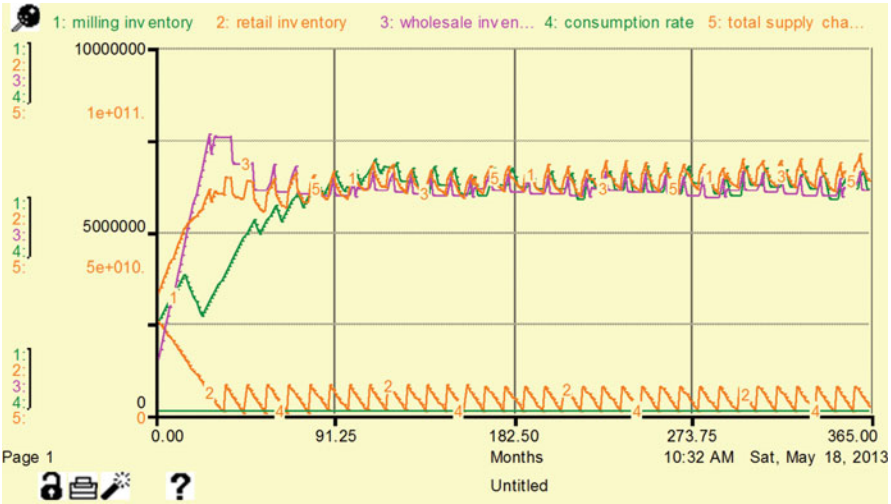

Fig. 11.10 The impacts of the round-the-year supply of rice to the milling industries on wholesale inventory, retail inventory and total supply chain costs

demand average, and this indicates that supply chain cost increases at the wholesale stage of the supply chain. In essence the major influence of the retail lead time and demand average is on the milling inventory.

The model was also simulated to assess the impacts of the round-the-year supply of rice to the milling industries on wholesale inventory, retail inventory and total supply chain costs. Round-the-year equal amount of supply of rice is ensured by the round-the-year equal amount of release of rice from the storage for sales for milling. The rice supply to milling industries is defined as

$$\begin{aligned} &\text{rice inventory } (t) = \text{ rice inventory } (t-1) \ + \text{rice supply rate} \times \Delta t \\ &-\text{rice sales for milling} \times \Delta t \end{aligned} \tag{11.49}$$

$$\text{rice suply rate} = 97955 \text{ tons/day} \tag{11.50}$$

Figure 11.10 shows the impacts of the round-the-year supply of rice to the milling industries on wholesale inventory and retail inventory. The simulated results show that round-the-year supply and the use of rice to the milling industries not only stabilise the milling inventory but also the whole system. This implies that if rice is dried initially for safe storage and then used round the year, the whole system can be stabilised. However, the bullwhip or Forrester effect remains present in the stabilised system.

The simulated results of the model demonstrate that the economic order quantity and reordering point for milling, wholesale and retail inventories not only ensure the availability of rice to the consumers during poor harvest (as long as stock is available from wholesale inventory) but also near optimal order quantities. Annual total supply chain cost for economic order quantity is 2.64 times less than the total supply chain cost for lead time demand average, and a major share of this cost is for transportation which requires fossil fuels. Hence economic operation results in less fuel consumption and hence less contribution to global warming.

Sustainability in three dimensions is widely accepted, and this allows easy comprehension of the integration of economic, environmental and social issues (Seuring 2013). Economic order quantity and sustainable supply of rice to consumers in this study address the economic and food security issues while less contribution to global warming addresses the environmental issue.

This study brings systems approach to understanding and managing the different activities needed to coordinate the rice milling systems to best serve the ultimate customer of rice in Bangladesh. With the proposed model planners and plant managers can visualise the milling, wholesale and retail inventories and the supply chain costs as well as even can be used to determine the storage facilities needed to ensure the availability of rice to the consumers. The actors in the rice supply chain make decisions individually and collectively such as milling and ordering activities. Some of these decisions influence the capabilities and effectiveness of the supply chain. Also Seuring and Müller (2008) emphasise the need of increasing cooperation along the supply chain, if sustainability goals are to be reached. Participatory system dynamics modelling uses system dynamics perspective in which stakeholders or clients participate to some degree in different stages of the modelling process, including problem definition, system description, identification of policy levers, model development and/or policy analysis. Participatory system dynamics/multi-agent system modelling of the rice milling supply chain involving all the stakeholders is recommended for future study. This model can be used for participatory modelling of rice milling systems. Overall, the proposed model can be used to study and analyse 'what if' scenarios of the supply chain of the rice milling systems.

11.7 Conclusion

A system dynamics model of supply chain of rice milling systems in Bangladesh is developed for policy analysis, and the retail inventory is fully stabilised for economic order quality and reordering point resulting in an efficient and sustainable supply chain network. Productivity reduction of seasonal production of rice causes changes in the milling inventory, wholesale inventory and total supply chain cost, but the retail inventory remains constant as long as the wholesale inventory is not empty. Lead time changes have positive influences on the directly related inventory level, and the changes are more pronounced in the milling and wholesale inventories. Also the influence of the demand average is dominant on the milling inventory. Round-the-year operation of the milling industries increases the stability of the whole system. Also the less total supply chain cost from economic operation results in less fuel consumption and hence less contribution to global warming. This model facilitates identification and study of the critical components of the overall supply chain, allowing for the creation of an efficient and sustainable supply chain network. This model also provides greater insight and better understanding of the supply chain of rice milling systems, and it can be used as a computer laboratory for developing scenarios for policy analysis

Exercises

Exercise 11.1 Why a computer model is a necessity to analyse and support rice milling systems. Discuss where to use operations research and system dynamics in supply chain management.

Exercise 11.2 Draw the causal loop diagram of the supply chain of rice milling systems. Draw another causal loop diagram for sustainable supply chain management.

Exercise 11.3 Draw stock–flow diagrams of both the causal loop diagrams in exercise 11.2 and compare the simulated results of retail inventory and retail price.

Exercise 11.4 Draw causal loop and stock–flow diagrams of supply chain of rice milling systems incorporating economic order quantity and reordering point for sustainable development. Simulate the retail inventory, retail price and contribution to global warming.

Exercise 11.5 Simulate both the models in exercise 11.2 to assess the impacts of round-the-year supply of rice to the milling industries and also assess the contribution to global warming.

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12 Modelling of Solid Waste Management Systems of Dhaka City in Bangladesh

In the previous chapters of this part, case studies on system dynamics modelling and simulation of some practical problems have been presented. This chapter presents a case study of environmental management of solid waste management system of Dhaka City, Bangladesh. The model of this case study is organised as (1) introduction, (2) dynamic hypothesis, (3) causal loop diagram, (4) stock–flow diagram, (5) model validation, (6) simulation and policy analysis and (7) conclusion to illustrate the system dynamics applications in environmental management based on systems thinking. Population, uncleared waste, untreated waste, composite index and public concern are projected to increase with time for Dhaka City. Simulated composts, CO_2 total, CH_4 and BOD from energy, leachate production and BOD from leachate over a period of 30 years are also presented. Simulated results also show that increasing the budget for collection capacity alone does not improve environmental quality; rather an increased budget is required for both collection and treatment of solid wastes of Dhaka City. This model can be used as a tool to assess and design policy options of solid waste management.

12.1 Introduction

Solid waste consists of the highly heterogeneous mass of discarded materials from the urban community, as well as the more homogeneous accumulation of agricultural, industrial and mining wastes. The principal sources of solid wastes are residences, commercial establishments, institutions and industrial and agricultural activities. Domestic, commercial and light industrial wastes are considered together as urban wastes. The main constituents of urban solid wastes are similar throughout the world, but the quantity generated, the density and the proportion of constituents vary widely from country to country and from town to town within a country according to the level of economic development, geographic location, weather and social conditions. In general, it has been found that as the personal income

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rises, kitchen wastes decline but the paper, metal and glass wastes increase; the total weight generated increases but the density of the wastes declines (Rao 1992).

Several disposal methods are being used in various parts of the world, and the most prominent of these are open dumping, sanitary landfilling, incineration and composting. Sanitary landfilling is the main method used in industrialised countries, and open dumping is very common in developing countries like Bangladesh and India.

Open dumping of solid wastes is practised extensively in Bangladesh because it is cheap and requires no planning. Generally, the low-lying areas and outskirts of the towns and cities are used for this purpose.

Sanitary landfilling is a controlled engineered operation, designed and operated according to acceptable standards. It may be defined as a controlled method of disposing of refuse onto or into land while minimising nuisances or hazards to public health or safety. The operation is carried out without environmental damage and in areas already spoiled or in need of restoration.

Incineration involves the burning of solid wastes at high temperatures. If incineration is to become an economical method for solid waste disposal, useful materials and energy must be recovered by the process. Heat can be recovered by putting a waste heat boiler or some other recovery devices on an existing solid waste incinerator. The heat so recovered can be utilised for generating electricity or for space heating purposes. In general, solid waste has about one-third the heating value of coal, but unlike coal it has a very low sulphur content. All types of incinerators produce air pollution. The contributions to global warming by incineration are much less than those of landfill but comparable to those by composting. Yongfeng (2005) reported that municipal solid waste incineration has recently emerged as the method of choice for the primary treatment of municipal solid wastes in many cities in China. Alam and Bole (2001) and Sufian and Bala (2006) reported that there exists high electrical energy recovery potential from urban solid waste of Dhaka City.

In contrast to a sanitary landfill, composting of refuse is an aerobic method of decomposing solid waste. Many types of microorganisms already present in the waste biostabilise the organic matter in the waste and produce a soil conditioner as a result of the process. The organisms include bacteria, which predominate at all stages; fungi, which often appear after the first week; and actinomycetes, which assist during the final stages. Zurbrugg et al. (2002) reported a success story of decentralised collection and composting scheme in Mirpur, Dhaka, Bangladesh. The case of Mirpur shows that composting can be a good alternative to conventional solid waste management options, reducing the amount of waste to be transported and dumped by producing a valuable raw material for fertilisers.

Solid wastes contain significant amounts of valuable materials like steel, aluminium, copper and other metals which, if they are recovered and reused, would reduce the volume of the wastes to be collected and at the same time would yield significant salvage and resale income. In addition, better reclamation techniques will help to save valuable natural resources and turn wastes, which could be dangerous, into useful products. Some important solid wastes that have been successfully reclaimed are paper, plastics, glass and metals.

Solid waste generation of the Dhaka metropolitan area in 1998 was 3944 tons/day and 4750 tons/day in 2000. Solid waste generation in Dhaka City is increasing rapidly with rapidly growing population and GDP, and the Japan International Cooperation Agency (JICA) (2005) predicted solid waste generation to increase from 3200 tons/day in 2004 to 4634 tons/day in 2015. Of the total waste produced, nearly 20 % is used for recovery and recycling and about 37 % remains scattered laying around on roadsides, open spaces or drains. The remaining 43 % of the wastes are deposited together in some primary depots from where about 45 % is finally disposed of either by the DCC or community-based organisations (CBOs) in the open landfill sites.

Many studies have been reported on strategies to achieve municipal solid waste management (Pawan et al. 1997; Salvato 1992; Kum et al. 2005). Linear programming, input–output analysis, expert system (a methodology that uses expert knowledge to solve problems of a complex system) and system dynamics have been applied to aid decision-makers in planning and management of solid waste management systems (Everett and Modak 1996; Clayton and McCarl 1979; Barsi 2000; Ming et al. 2000; Heikki 2000; Mashayekhi 1992; Sudhir et al. 1997). Several studies have been reported on life cycle assessment (LCA) of municipal solid waste management systems (Consonni et al. 2005a, b; Velumani and Meenakshi 2007). Consonni et al. (2005a, b) examined environmental impacts and economics of the various strategies using life cycle assessment starting from heat and mass balances. Velumani and Meenakshi (2007) reported life cycle inventory analysis for three different municipal solid waste management scenarios: (i) open landfill; (ii) generation, collection, transportation and sanitary land filling; and (iii) generation, collection, transportation, segregation, incineration, recycling and sanitary land filling for Coimbatore City, India, to aid the decision-makers and planners for integrated management of solid waste management for sustainable development.

Dyson and Chang (2005) emphasised the capability of system dynamics for prediction of solid waste generation, and Sufian and Bala (2006, 2007) and Bala and Sufian (2006) successfully applied system dynamics to model and analyse the policy options of solid waste management system.

Solid waste crisis is emerging in Bangladesh and the majority of the cities are severely affected. The disposal problem is more serious for Dhaka City, the capital of Bangladesh. There is a large gap between the waste generation and management system which results in environmental pollution. To meet this gap, there is a need of a model for solid waste management systems of Dhaka City, Bangladesh. Here the system dynamics model of solid waste management adopted from Sufian and Bala (2006, 2007) is presented, and it has been designed to predict solid waste generation, scientific landfill, incineration, composting and life cycle assessment.

12.2 Dynamic Hypothesis

The dynamic hypothesis is a conceptual model which seeks to define the critical feedback loops and system structure that drive the system's behaviour in the reference mode. When the model based on feedback concept is simulated, the endogenous structure of the model should generate the reference mode behaviour of the system, and thus, the endogenous structure causes the changes in the dynamic behaviour of the system. In system dynamics modelling, causal loop diagrams identify the principal feedback loops of a system, and the causal loop diagram and stock–flow diagram are used to describe the basic cause–effect relationships hypothesised to generate the reference mode of the behaviour over time (Sterman 2000). Solid waste management systems can be represented by causal loop diagram and stock–flow diagram, and the simulation model based on the causal loop diagram and stock–flow diagram would generate dynamic behaviour of the solid generation, uncleared wastes and untreated wastes and composting in the reference mode. The solid wastes and its present management systems in the form of causal loop diagram and stock–flow diagram are hypothesised to generate the observed solid waste generation, uncleared wastes and untreated wastes in the reference mode. In essence there is piling up of uncleared wastes and untreated wastes from the lack of management strategies and fund; this dynamics results from the endogenous consequences of the feedback structure of the solid waste management systems.

12.3 Causal Loop Diagram

Causal loop diagram of solid waste management systems of Dhaka City, Bangladesh, is shown in Fig. 12.1. Municipal solid wastes increase with population (R1) and solid generation creates public concern and pressure to mitigate the waste (B1). The solid wastes are separated into recyclable wastes and nonrecyclable wastes. Both the uncollected waste and unhygienic disposal of waste create environmental pollution, which gives rise to increase public annoyance and anger, and hence public concern develops to reduce waste generation (B2 and B3). Also, the untreated wastes create public concern and pressure (B4). A higher composite index increases management perception which increases fund allocation for solid waste management (B5). The composite index is defined as

$$\text{Composite Index} = (w_1 \times \text{UNCL} + w_2 \times \text{UNTR}) \times \text{POPR} \tag{12.1}$$

where

w_1, w_2 = weighting factor ($w_1 = 0.5$ and $w_2 = 0.5$)
UNCL = the ratio of the uncleared waste at any point of time to the base value
UNTR = the ratio of the untreated waste at any point of time to the base value
POPR = the ratio of the population at any point of time to the base value

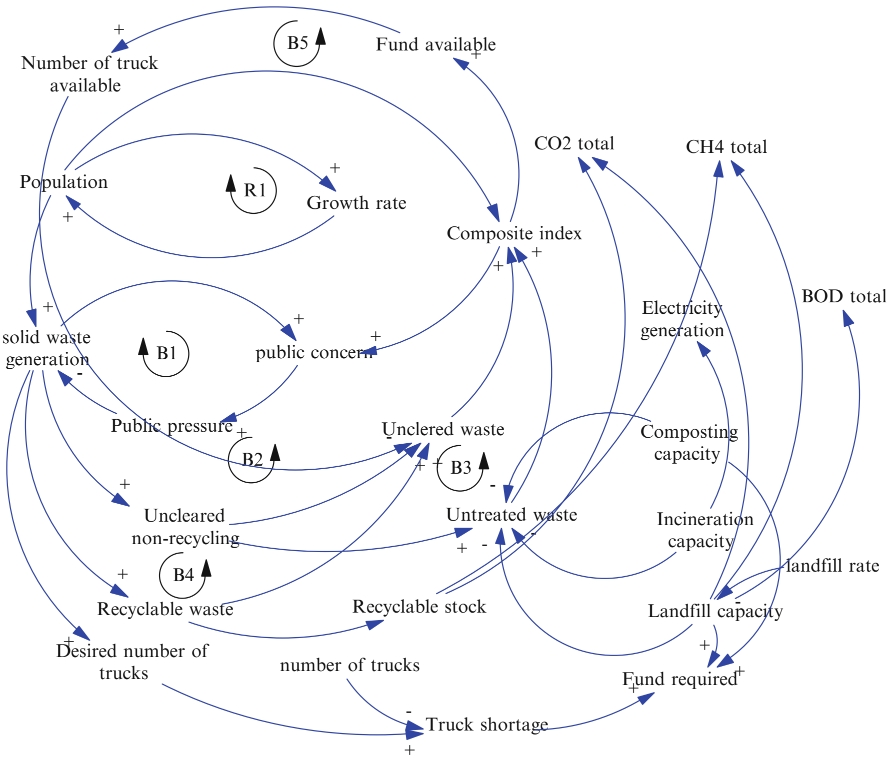

Fig. 12.1 Causal loop diagram of solid waste management systems of Dhaka in Bangladesh

A higher value of composite index indicates a progressive deterioration in health and environmental quality. A fraction of organic solid wastes from the municipal solid wastes is used for composting, and the remaining portion of the nonrecyclable wastes is used for sanitary landfill and incineration.

Life cycle assessment (LCA) of municipal solid waste management of the Dhaka City is also included in this model. The scope of life cycle assessment is to account for all possible environmental impacts 'from cradle to grave', i.e. along the whole sequence of actions required to bring about and later terminate a given product or an activity. Life cycle assessment of municipal solid wastes starts just at the moment when it is put into the waste bin and ends up when it is disposed. Life cycle assessment assesses the use of resources and releases of emissions to air, water and land and the generation of useful products from the wastes. This is done here by compiling an inventory of relevant inputs and outputs of the system and evaluating the potential impacts of those inputs and outputs in relation to the objectives of the study. To evaluate properly the global warming potential, CO_2 emissions are broken down into a fraction originated by fossil carbon (plastics, rubber or fossil fuel) and a renewable fraction originated from biogenic materials (paper, wood or organic fractions).

12.4 Stock Flow Diagram

The flow diagram of the model was constructed using icon-operated stock and flow symbols of STELLA software. The STELLA flow diagram of the urban solid waste management system is shown in Figs. 12.2a, 12.2b, 12.2c and 12.2d. Fundamental equations that correspond to the major state variable are as follows:

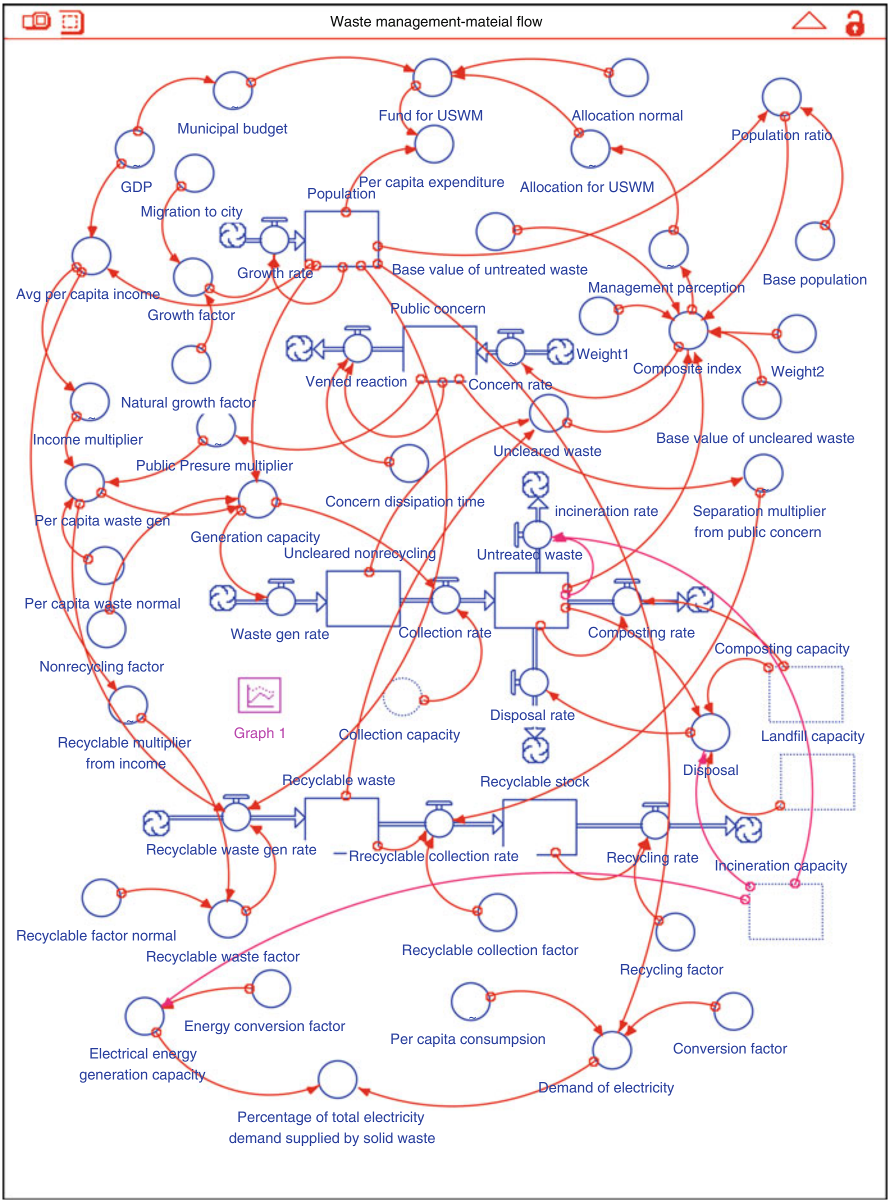

Fig. 12.2a STELLA flow diagram of solid waste management system dynamics—material flow

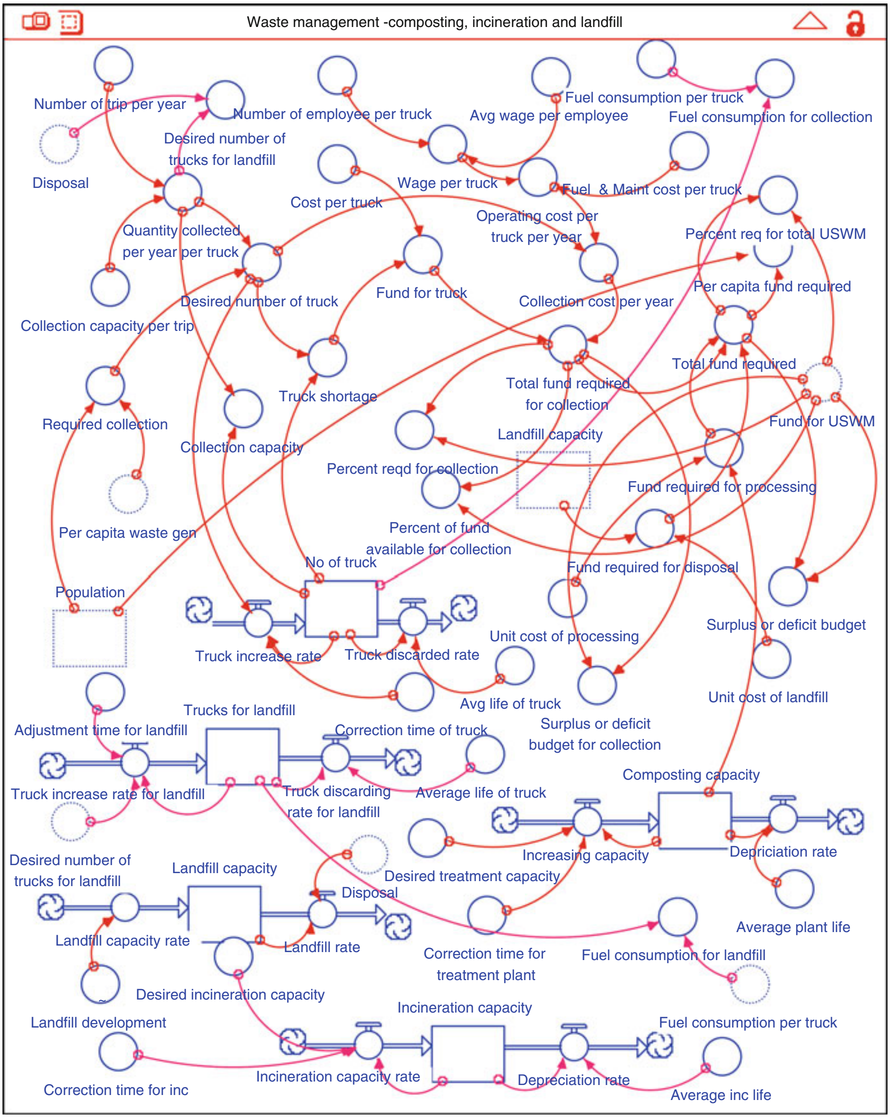

Fig. 12.2b STELLA flow diagram of solid waste management system dynamics—composting, incineration and landfill

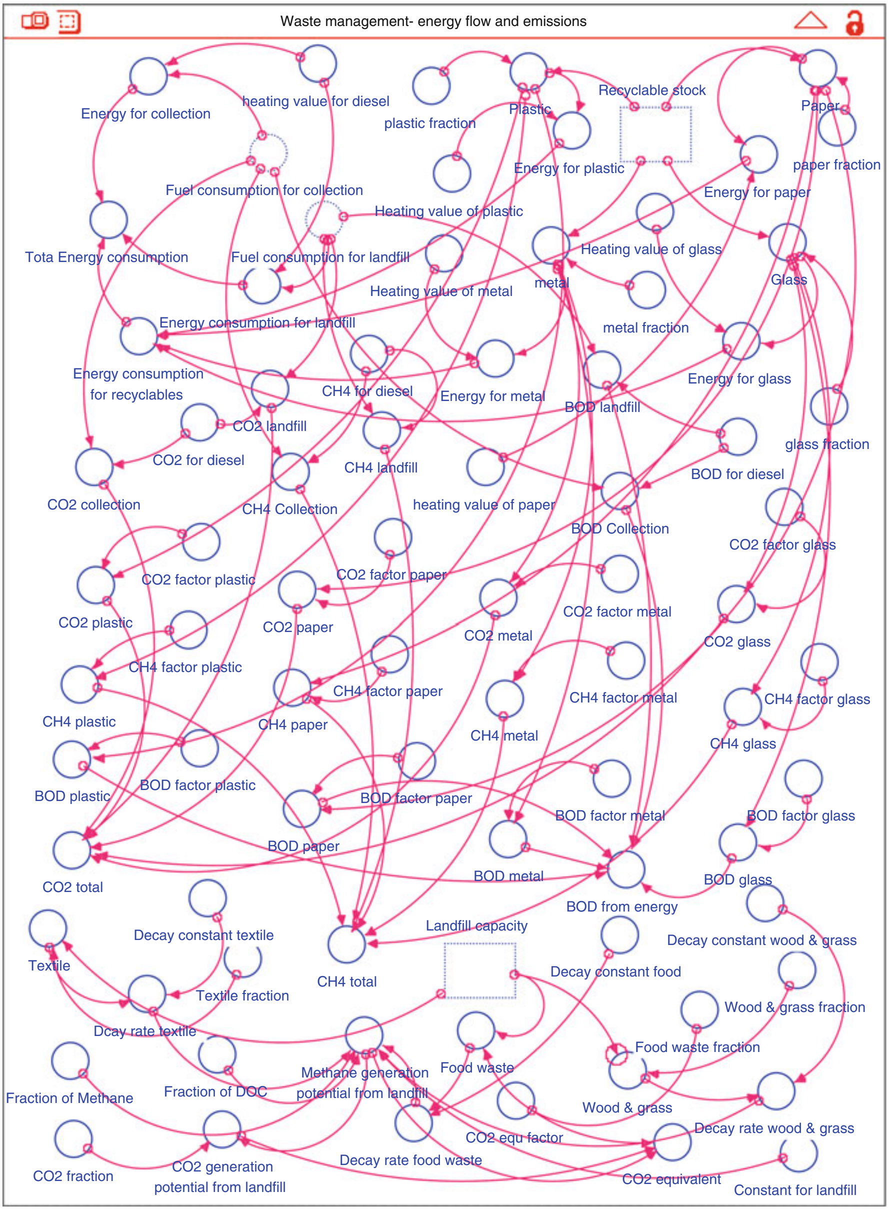

Fig. 12.2c STELLA flow diagram of solid waste management system dynamics—energy flow and emissions

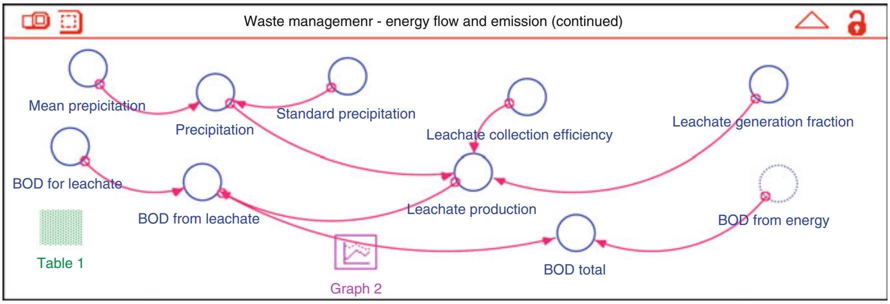

Fig. 12.2d STELLA flow diagram of solid waste management system dynamics—energy flow and emissions

12.4.1 Waste Management–Material Flow

The generated solid wastes consist of uncleared nonrecycling wastes and recyclable wastes.

Uncleared nonrecycling waste is increased by waste generation rate and decreased by collection rate, and it is expressed as

$$\begin{aligned}\text{Uncleared\_nonrecycling}(t) &= \text{Uncleared\_nonrecycling}(t - dt) \\ &\quad + (\text{Waste\_gen\_rate} - \text{Collection\_rate}) * dt \end{aligned} \tag{12.2}$$

Nonrecyclable waste generation depends on the population, per capita income and GDP. The nonrecyclable waste generation rate, i.e. waste capacity, is computed from population, per capita waste generation and nonrecycling factor as

$$\text{Generation\_capacity} = \text{Population*Nonrecycling\_factor*Per\_capita\_waste\_gen} \tag{12.3}$$

The waste collection rate depends on collection capacity and generation capacity. IF generation capacity is greater than collection capacity THEN collection rate is collection capacity ELSE it is generation capacity, and it is expressed as

$$\begin{aligned}\text{Collection\_rate} = \; & \text{IF}(\text{Generation\_capacity} > \text{Collection\_capacity}) \\ & \text{THEN}(\text{Collection\_capacity})\text{ELSE}(\text{Generation\_capacity})\end{aligned} \tag{12.4}$$

Recyclable waste is increased by recyclable waste generation rate and decreased by recyclable collection rate, and it is expressed as

$$\begin{aligned}\text{Recyclable\_waste}(t) = \; & \text{Recyclable\_waste}(t - dt) \\ & + (\text{Recyclable\_waste\_gen\_rate} \\ & - \text{Recyclable\_collection\_rate}) * dt\end{aligned} \tag{12.5}$$

The recyclable waste generation rate is computed from population, average per capita income and recyclable waste factor as

$$\begin{aligned}&\text{Recyclable\_waste\_gen\_rate}\\&= \text{Population*Per\_capita\_waste\_gen*Recyclable\_waste\_factor}\end{aligned} \tag{12.6}$$

The recyclable collection rate depends on recyclable waste, recyclable collection factor and separation multiplier from public concern, and it is computed as

$$\begin{aligned}&\text{Recyclable\_collection\_rate}\\&= \text{Recyclable\_waste*Recyclable\_collection\_factor*Separation\_multiplier\_from\_public\_concern}\end{aligned} \tag{12.7}$$

The portion of the uncleared nonrecycling wastes and recyclable wastes that are not collected is termed as uncleared wastes. Uncleaned and untreated wastes create nuisance which causes public concern. This concern is reduced by vented reaction. The public concern is expressed as

$$\begin{aligned}\text{Public\_concern}(t) = {} & \text{Public\_concern}(t - dt)\\&+ (\text{Concern\_rate} - \text{Vented\_reaction}) * dt\end{aligned} \tag{12.8}$$

Concern rate increases with composite index and it is non-linearly related with composite index. This relationship is expressed by a graphical function:

Concern_rate = GRAPH(Composite_index)
(0.00, 1.00), (25.0, 1.11), (50.0, 1.25), (75.0, 1.35), (100, 1.42), (125, 1.47), (150, 1.50)

Concern decreases with time and it is expressed as

$$\text{Vented\_reaction} = \text{Public\_concern/Concern\_dissipation\_time} \tag{12.9}$$

Public concern in turn creates public pressure to reduce the waste generation, and the effect of public pressure resulting from public concern is expressed as a multiplier. The public pressure multiplier is non-linearly related to public concern, and it is expressed as

Public_pressure_multiplier = GRAPH(Public_concern)
(1.00, 1.01), (2.50, 1.04), (4.00, 1.08), (5.50, 1.15), (7.00, 1.25), (8.50, 1.35), (10.0, 1.50)

Untreated waste is increased by collection rate and decreased by composting rate, disposal rate and incineration rate, and it is expressed as

$$\begin{aligned}&\text{Untreated\_waste}(t) = \text{Untreated\_waste}(t - dt)\\&+ (\text{Collection\_rate} - \text{Composting\_rate} - \text{Disposal\_rate} - \text{incineration\_rate}) * dt\end{aligned} \tag{12.10}$$

IF untreated waste is greater than composting capacity THEN composting rate is composting capacity ELSE it is untreated waste, and it is expressed as

$$\begin{aligned}\text{Composting\_rate} = \;& \text{IF}(\text{Untreated\_waste} > \text{Composting\_capacity})\\&\times\text{THEN}(\text{Composting\_capacity})\text{ELSE}(\text{Untreated\_waste})\end{aligned} \tag{12.11}$$

IF untreated waste plus incineration capacity is greater than composting capacity THEN disposal rate is the MIN of (i) (untreated waste plus incineration capacity >composting capacity) and (ii) (landfill capacity) ELSE it is zero, and it is expressed as

$$\begin{aligned}&\text{Disposal\_rate}\\&= \text{IF}((\text{Untreated\_waste} + \text{Incineration\_capacity}) > \text{Composting\_capacity})\\&\;\text{THEN}(\text{MIN}((\text{Untreated\_waste} + \text{Incineration\_capacity} - \text{Composting\_capacity}),\\&\qquad\qquad \text{Landfill\_capacity})) \times \text{ ELSE}(0)\end{aligned} \tag{12.12}$$

IF untreated waste is greater than incineration capacity THEN incineration rate is incineration capacity ELSE it is untreated waste, and it is expressed as

$$\begin{aligned}\text{incineration\_rate} = \;& \text{IF}(\text{Untreated\_waste} > \text{Incineration\_capacity})\\& \text{THEN}(\text{Incineration\_capacity})\text{ELSE}(\text{Untreated\_waste})\end{aligned} \tag{12.13}$$

Both uncleared wastes and untreated wastes create nuisance and increase environmental concern. Composting index is an environmental indicator and it is defined by the following expression:

$$\begin{aligned}&\text{Composite\_index}\\&= (\text{Weight1*Uncleared\_waste/Base\_value\_of\_uncleared\_waste}\\&+ \text{Weight2*Untreated\_waste/Base\_value\_of\_untreated\_waste})\text{*Population\_ratio}\end{aligned} \tag{12.14}$$

Recyclable stock increases by recyclable collection rate and decreases by recycling rate. It is expressed as

$$\text{Recyclable\_stock}(t) = \text{Recyclable\_stock}(t-dt) + (\text{Recyclable\_collection\_rate} - \text{Recycling\_rate}) * dt \tag{12.15}$$

Recycling rate is a fraction of recyclable stock and it is expressed as

$$\text{Recycling\_rate} = \text{Recyclable\_stock}*\text{Recycling\_factor} \tag{12.16}$$

12.4.2 Waste Management: Composting, Incineration and Landfill

Composing capacity is increased by increasing capacity and decreased by depreciation and it is expressed as

$$\text{Composting\_capacity}(t) = \text{Composting\_capacity}(t-dt) + (\text{Increasing\_capacity} - \text{Depriciation\_rate}) * dt \tag{12.17}$$

Increasing capacity is computed from desired treatment capacity, existing composting and correction time, and it is expressed as

$$\text{Increasing\_capacity} = (\text{Desired\_treatment\_capacity} - \text{Composting\_capacity}) / \text{Correction\_time\_for\_treatment\_plant} \tag{12.18}$$

Depreciation rate is computed from composting capacity and its average life, and it is computed as

$$\text{Depriciation\_rate} = \text{Composting\_capacity}/\text{Average\_plant\_life} \tag{12.19}$$

Incineration capacity is increased by incineration capacity rate and decreased by depreciation, and it is expressed as

$$\text{Incineration\_capacity}(t) = \text{Incineration\_capacity}(t-dt) + (\text{Incineration\_capacity\_rate} - \text{Depreciation\_rate}) * dt \tag{12.20}$$

Incineration capacity rate is computed from desired incineration capacity, existing incineration capacity and correction time, and it is expressed as

$$\text{Incineration\_capacity\_rate} = (\text{Desired\_incineration\_capacity} - \text{Incineration\_capacity}) / \text{Correction\_time\_for\_inc} \tag{12.21}$$

Depreciation rate is computed from incineration capacity and its average life, and it is computed as

$$\text{Depreciation\_rate} = \text{Incineration\_capacity}/\text{Average\_inc\_life} \tag{12.22}$$

Landfill capacity is increased by landfill capacity rate and decreased by landfill rate, and it is expressed as

$$\begin{aligned}\text{Landfill\_capacity}(t) = {} & \text{Landfill\_capacity}(t - dt) \\ & + (\text{Landfill\_capacity\_rate} - \text{Landfill\_rate}) * dt\end{aligned} \tag{12.23}$$

Landfill capacity rate is the landfill development and it is expressed as

$$\text{Landfill\_capacity\_rate} = \text{Landfill\_development} \tag{12.24}$$

IF Disposal is less than Landfill capacity THEN Landfill rate is Disposal ELSE it is Landfill capacity, and it is expressed as

$$\begin{aligned}\text{Landfill\_rate} = {} & \text{IF}(\text{Disposal} < \text{Landfill\_capacity})\text{THEN}(\text{Disposal}) \\ & \text{ELSE}(\text{Landfill\_capacity})\end{aligned} \tag{12.25}$$

The landfill development is non-linearly related to time and it is expressed as

Landfill_development = GRAPH(TIME)
(0.00, 175500), (3.00, 252000), (6.00, 366750), (9.00, 460250), (12.0, 558000), (15.0, 647250), (18.0, 732250), (21.0, 791750), (24.0, 855500), (27.0, 893750), (30.0, 915000)

The number of trucks for collection of wastes increases with increase rate and decreases by discard rate, and it is expressed as

$$\begin{aligned}\text{No\_of\_truck}(t) = {} & \text{No\_of\_truck}(t - dt) \\ & + (\text{Truck\_increase\_rate} - \text{Truck\_discarded\_rate}) * dt\end{aligned} \tag{12.26}$$

The truck increase rate is computed from the desired number of trucks, number of trucks and correction time as

$$\begin{aligned}\text{Truck\_increase\_rate} = {} & (\text{Desired\_number\_of\_truck} - \text{No\_of\_truck}) \\ & /\text{Correction\_time\_of\_truck}\end{aligned} \tag{12.27}$$

The truck discard rate is calculated from number of trucks and average life of a truck:

$$\text{Truck\_discarded\_rate} = \text{No\_of\_truck}/\text{Avg\_life\_of\_truck} \tag{12.28}$$

The number of trucks for landfill increases with increase rate for landfill and decreases by discard rate for landfill, and it is expressed as

$$\begin{aligned}&\text{Trucks\_for\_landfill}(t) = \text{Trucks\_for\_landfill}(t - dt)\\&+ (\text{Truck\_increase\_rate\_for\_landfill} - \text{Truck\_discarding\_rate\_for\_landfill}) * dt\end{aligned} \tag{12.29}$$

The truck increase rate for landfill is computed from the desired number of trucks for landfill, number of trucks for landfill and adjustment time for landfill as

$$\begin{aligned}&\text{Truck\_increase\_rate\_for\_landfill}\\&= (\text{Desired\_number\_of\_trucks\_for\_landfill} - \text{Trucks\_for\_landfill})\\&/\text{Adjustment\_time\_for\_landfill}\end{aligned} \tag{12.30}$$

The truck discard rate for landfill is calculated from the number of trucks for landfill and average life of a truck:

$$\text{Truck\_discarding\_rate\_for\_landfill} = \text{Trucks\_for\_landfill}/\text{Average\_life\_of\_truck} \tag{12.31}$$

The total fund required is computed from the fund required for disposal, processing and collection as

$$\begin{aligned}\text{Total\_fund\_required} &= \text{Fund\_required\_for\_disposal}\\&+ \text{Fund\_required\_for\_processing}\\&+ \text{Total\_fund\_required\_for\_collection}\end{aligned} \tag{12.32}$$

The total fund required for collection is the sum of collection cost and cost of the truck, and it is expressed as

$$\begin{aligned}\text{Total\_fund\_required\_for\_collection} &= \text{Collection\_cost\_per\_year}\\&+ \text{Fund\_for\_truck}\end{aligned} \tag{12.33}$$

12.4.3 Waste Management: Energy Flow and Emissions

BOD total is the sum of BOD from energy and BOD from leachate, and it is expressed as

$$\text{BOD\_total} = \text{BOD\_from\_energy} + \text{BOD\_from\_leachate} \tag{12.34}$$

BOD from energy is the sum of BOD collection, BOD from the glass, BOD from the landfill, BOD from the metal, BOD from the paper and BOD from the plastic, and it is expressed as

$$\begin{aligned}\text{BOD\_from\_energy} &= \text{BOD\_Collection} + \text{BOD\_glass} + \text{BOD\_landfill}\\ &\quad + \text{BOD\_metal} + \text{BOD\_paper} + \text{BOD\_plastic}\end{aligned} \tag{12.35}$$

where

$$\text{BOD\_Collection} = \text{Fuel\_consumption\_for\_collection*BOD\_for\_diesel} \tag{12.36}$$

$$\text{BOD\_glass} = \text{Glass*BOD\_factor\_glass} \tag{12.37}$$

$$\text{BOD\_landfill} = \text{Fuel\_consumption\_for\_landfill*BOD\_for\_diesel} \tag{12.38}$$

$$\text{BOD\_metal} = \text{metal*BOD\_factor\_metal} \tag{12.39}$$

$$\text{BOD\_paper} = \text{Paper*BOD\_factor\_paper} \tag{12.40}$$

$$\text{BOD\_plastic} = \text{Plastic*BOD\_factor\_plastic} \tag{12.41}$$

BOD from leachate is computed from leachate and BOD for leachate as

$$\text{BOD\_from\_leachate} = \text{Leachate\_production*BOD\_for\_leachate} \tag{12.42}$$

where

$$\begin{aligned}&\text{Leachate\_production}\\ &= \text{Leachate\_collection\_efficiency*Leachate\_generation\_fraction*Precipitation}\end{aligned} \tag{12.43}$$

CH_4 total is the sum of CH_4 from collection, CH_4 from the glass, CH_4 from the metal, CH_4 from the paper, CH_4 from the plastic and CH_4 from the landfill, and it is computed as

$$\begin{aligned}\text{CH}_4\text{\_total} &= \text{CH}_4\text{\_Collection} + \text{CH}_4\text{\_glass} + \text{CH}_4\text{\_metal} + \text{CH}_4\text{\_paper}\\ &\quad + \text{CH}_4\text{\_plastic} + \text{CH}_4\text{\_landfill}\end{aligned} \tag{12.44}$$

where

$$\text{CH}_4\text{\_Collection} = \text{Fuel\_consumption\_for\_collection*CH}_4\text{\_for\_diesel} \tag{12.45}$$

$$\text{CH}_4\text{\_glass} = \text{Glass*CH}_4\text{\_factor\_glass} \tag{12.46}$$

$$\text{CH}_4\text{\_landfill} = \text{Fuel\_consumption\_for\_landfill*CH}_4\text{\_for\_diesel} \tag{12.47}$$

$$\text{CH}_4\text{\_metal} = \text{metal*CH}_4\text{\_factor\_metal} \tag{12.48}$$

$$\text{CH}_4\text{\_paper} = \text{Paper*CH}_4\text{\_factor\_paper} \tag{12.49}$$

$$CH_4\_plastic = Plastic*CH_4\_factor\_plastic \tag{12.50}$$

CO_2 total is the sum of CO_2 from collection, CO_2 from the glass, CO_2 from the landfill, CO_2 from the metal, CO_2 from the paper and CO_2 from the plastic, and it is expressed as

$$\begin{aligned} CO_2\_total = {} & CO_2\_collection + CO_2\_glass + CO_2\_landfill + CO_2\_metal \\ & + CO_2\_paper + CO_2\_plastic \end{aligned} \tag{12.51}$$

where

$$CO_2\_collection = Fuel\_consumption\_for\_collection*CO_2\_for\_diesel \tag{12.52}$$

$$CO_2\_glass = Glass*CO_2\_factor\_glass \tag{12.53}$$

$$CO_2\_landfill = Fuel\_consumption\_for\_landfill*CO_2\_for\_diesel \tag{12.54}$$

$$CO_2\_metal = metal*CO_2\_factor\_metal \tag{12.55}$$

$$CO_2\_paper = Paper*CO_2\_factor\_paper \tag{12.56}$$

$$CO_2\_plastic = Plastic*CO_2\_factor\_plastic \tag{12.57}$$

12.5 Model Validation

The various ways of validating a system dynamics model, such as comparing the model results with historical data, checking whether the model generates plausible behaviour and checking the quality of parameter values, were considered. Some of the parameters have been derived from studies in other areas and some were the results of expert guesswork. To judge the plausibility of the model, the behaviour of the key variables in the base run was examined.

12.6 Simulation and Policy Analysis

Computer projections of population, solid waste generation, uncleared waste and untreated waste for Dhaka City are shown in Fig. 12.3. Dhaka City had a population of 4.375 million in 1995 and approaching 12.082 million by 2025. The population growth rate of the city is higher than the average value of the whole country. This might be due to the fact that for job opportunities or other attractive factors, there is a rapid population inflow into the city. More population means more waste, and more waste means more resources needed for waste management. The waste generation increases from 1.027 million tons in 1995 to 4.257 million tons in 2025. An estimate of waste generation is crucially important to collection services and disposal facilities. It is clear from the figure that uncleared waste increases from

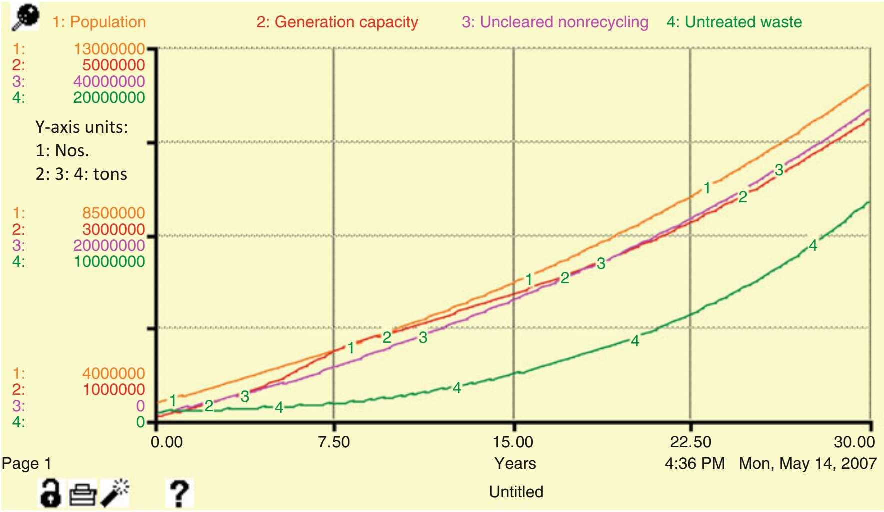

Fig. 12.3 Population, solid waste generation, uncleared waste and untreated waste of Dhaka City for a time horizon of 30 years

519,681 tons in 1995 to 33.183e + 006 tons in 2025, and untreated waste increases from 376,321 tons in 1995 to 11.65e + 006 tons in 2025. The uncleared waste of Dhaka City is increasing with time because of an inadequate collection capacity to transport the wastes to the dumpsites. Untreated waste is also increasing with time due to the lack of treatment facilities.

Figure 12.4 shows simulated incineration capacity, composting capacity, landfill capacity, electrical energy generation potential and composite index for a time horizon of 30 years. For a policy of introduction of incineration plant, composting and sanitary landfill, the landfill capacity increases from 150,000 tons in 1995 to 907,729 tons in 2025, incineration capacity increases from 150,000 tons in 1995 to 0.190e + 006 tons in 2025, corresponding electrical energy generation capacity increases from 66,750 MWh in 1995 to 84,556 MWh in 2025 and composting plant capacity increases up to 15 years, and then it becomes almost constant. The electrical energy recovery from urban solid waste generation of Dhaka City can supply a significant portion of the consumption requirement of electrical energy of the city. Hence, adoption of the policy for electricity from urban solid waste of Dhaka City should be dictated by the economy of adoption of the technology of electricity generation from the solid waste and environmental implications. The composite index increases from 0.86 in 1995 to 101.47 in 2025. The rapid increase in composite index with time means that the quality of the environment is deteriorating rapidly with time. In the early period (0–7.5 years), the composite index is very low with a very small growth rate, while in the later period, it increases very rapidly. The rapid increase in the composite index with time means that the quality of the environment is deteriorating rapidly with time.

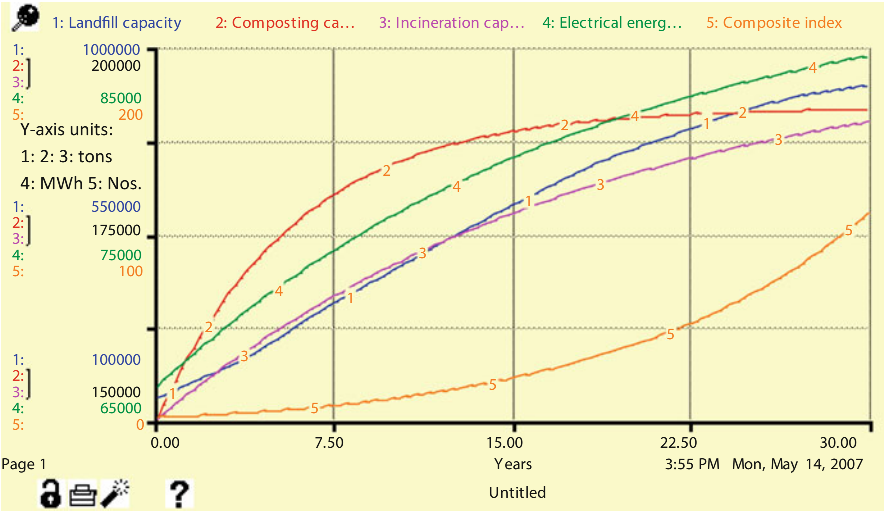

Fig. 12.4 Simulated landfill capacity, composting capacity, incineration capacity and electricity generation potential from solid waste and composite index for a time horizon of 30 years

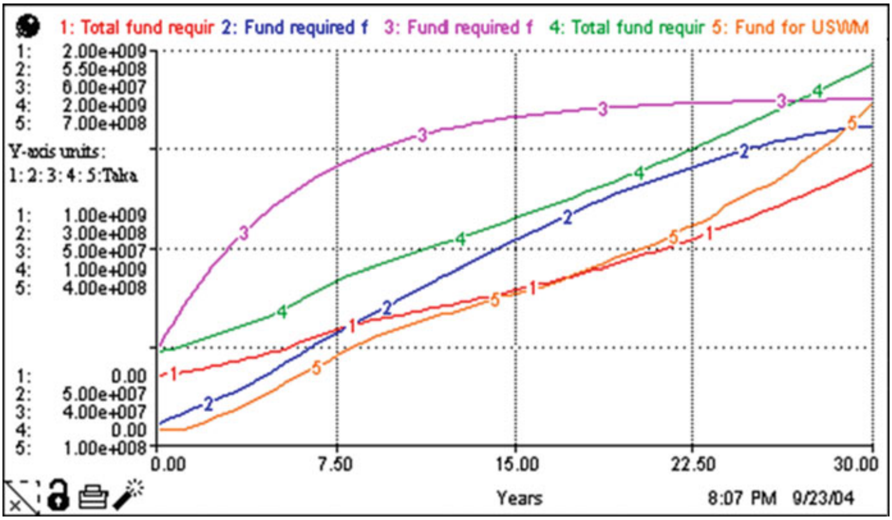

Fig. 12.5 Simulated total fund required for collection, fund required for disposal, fund required for processing, total fund required and fund for USWM for a time horizon of 30 years (one US $ = Taka 70.00)

Thus, solid waste management system is sustainable in the short run and becomes unsustainable in the long run.

Figure 12.5 shows the simulated total funds required for collection, landfill and treatment, total fund required and fund for USWM for a time horizon of 30 years.

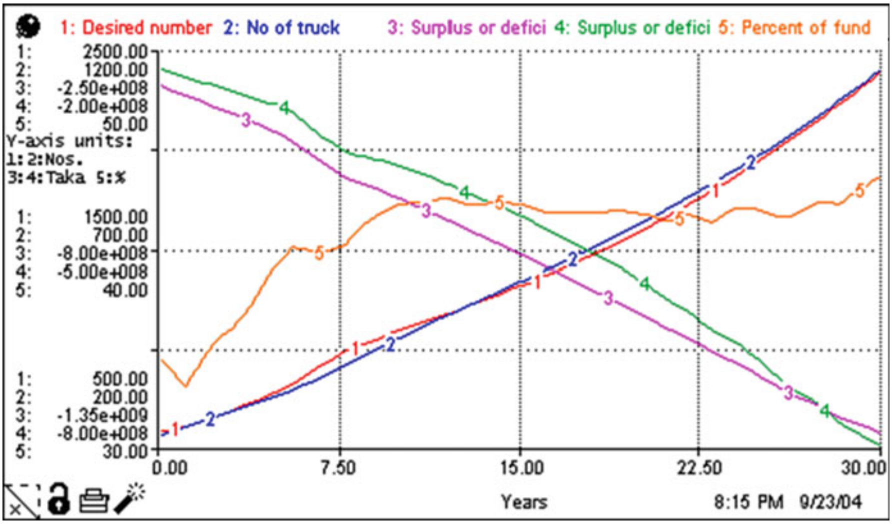

Fig. 12.6 Simulated desired number of trucks, number of trucks used, surplus or deficit budget, surplus or deficit budget for collection and percent of fund available for collection for a time horizon of 30 years

The simulated total fund required for collection, total fund required and fund for USWM are increasing with time. The fund required for collection increases from Tk 3.46e + 008 in 1995 to Tk 14.15e + 008 in 2025 since the generation of solid waste increases. The fund required for disposal also increases from Tk 7.50e + 007 in 1995 to Tk 45.38e + 007 in 2025. The fund required for waste treatment is increasing up to 15 years. After 15 years, the fund required for treatment is more or less constant at a value of Tk 5.70e + 007. This is because of the fact that the capacity utilisation of the treatment plant is fulfilled. The fund required for landfill is also increasing until towards the end of the simulated period. These are due to the facts that treatment capacity and landfill capacity are approaching the proposed desired treatment capacity and proposed desired landfill capacity, respectively. Logically, the total fund required increases from Tk 4.660e + 008 in 1995 to Tk 19.27e + 008 in 2005, and the total fund required for solid waste management increases from Tk 1.18e + 008 in 1995 to Tk 6.16e + 008 in 2005. Thus, increased funds are needed for both collection and solid waste management.

Figure 12.6 shows the simulated desired number of trucks, number of trucks used, surplus or deficit total budget, surplus or deficit budget for collection and percent of fund available for collection for a time horizon of 30 years. The desired number of trucks increases from 575 in 1995 to 2384 in 2025, whereas the number of trucks used increases from 230 in 1995 to 1148 in 2025. There is always a gap between the desired number of trucks and number of trucks used. Thus, the collection service at Dhaka City is deteriorating rather than improving. Moreover, the transportation of the waste to the dumpsite is not properly managed. Wastes are seen flying from the trucks during transport. Since the population and wastes generated are increasing with time, the desired number of trucks is also increasing. The number of trucks never equals the desired number of trucks, since the policy was to reduce the shortage in number of trucks which is dynamic. This indicates that more funds are required to mitigate the shortage of trucks and to meet the collection cost. The patterns of the change of deficit of the budget and the budget for collection decrease with time, but the percent of fund available for collection increases from almost 34 % in 1995 to 39 % in 2000 and then gradually increases to 43.5 % in 2005 and then almost remains constant. Thus, there is high shortage of fund for collection particularly for trucks for collection.

Figure 12.7 shows the simulated percent of fund increase required for only total waste collection and total USWM for a time horizon of 30 years. Initially the required budget for collection is 291 %. The budget requirement for collection decreases from 291 to 254 % sharply within 5 years; then it gradually decreases to a constant value of 238 % within 10 years and it continues up to 25 years. After 25 years, it decreases gradually. But for total urban solid waste management, the required budget for total waste management is 415 %. Then, the budget requirement decreases gradually from 415 % to an almost constant value of 340 % within 10 years. The initial jumps of the budgets for total waste collection and total urban solid waste management are due to the introduction of treatment plant and landfills for solid waste disposal.

Figure 12.8 shows simulated composts, i.e. nitrogen, potassium and phosphorus, and composite index. Composts available from solid waste increase from 0.150e + 006 tons in 1995 to 0.191e + 006 tons in 2025. Nitrogen, potassium and phosphorus increase from 3600 tons in 1995 to 4602 tons in 2025, from 2550 tons in 1995 to 3260 tons in 2025 and from 1800 tons in 1995 to 2301 tons in 2025, respectively,

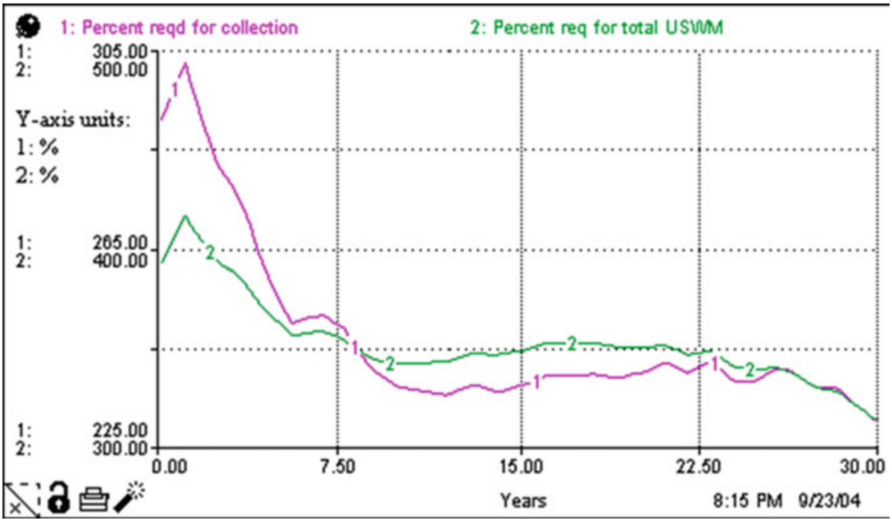

Fig. 12.7 Simulated percent of fund increased required for only total waste collection and total USWM for a time horizon of 30 years

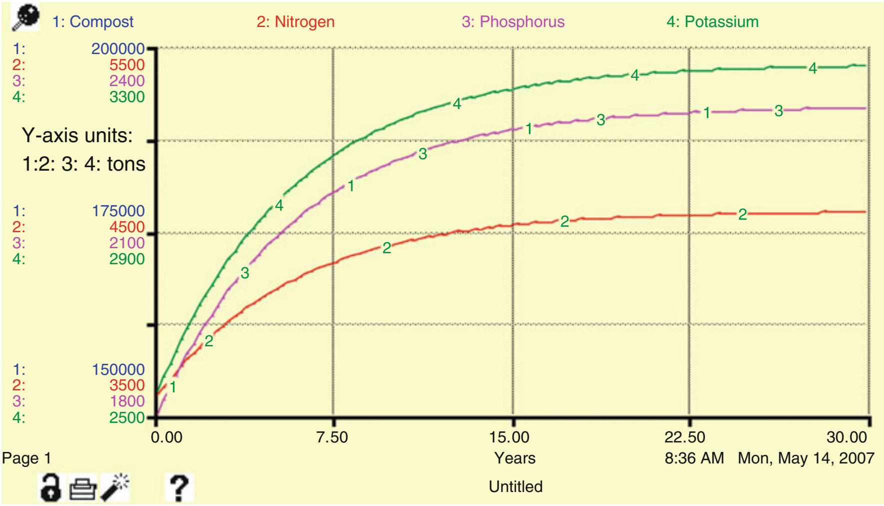

Fig. 12.8 Simulated compost, nitrogen, phosphorus and potassium for a time horizon of 30 years

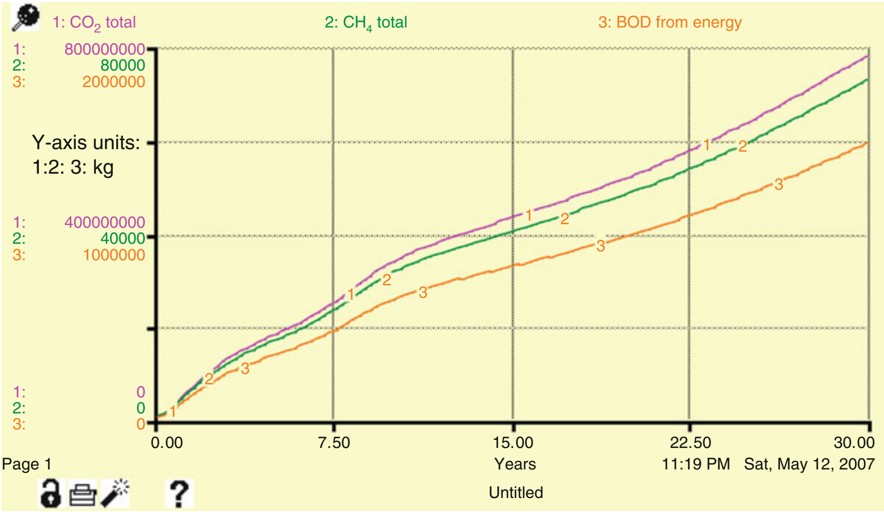

Fig. 12.9 Simulated CO_2 total, CH_4 total and BOD from energy for a time horizon of 30 years

and follow the production pattern of the composts. There is a significant contribution of organic fertilisers from the compost from composting of solid waste. This compost is a good-quality organic fertiliser for garden vegetables and other crops, and it is approved by the Bangladesh Agricultural Research Council (BARC).

Figure 12.9 shows simulated CO_2 total, CH_4 and BOD from energy. Simulated CO_2 total increases from 5.153e + 006 kg in 1995 to 78.112e + 007 kg in 2025. CH_4

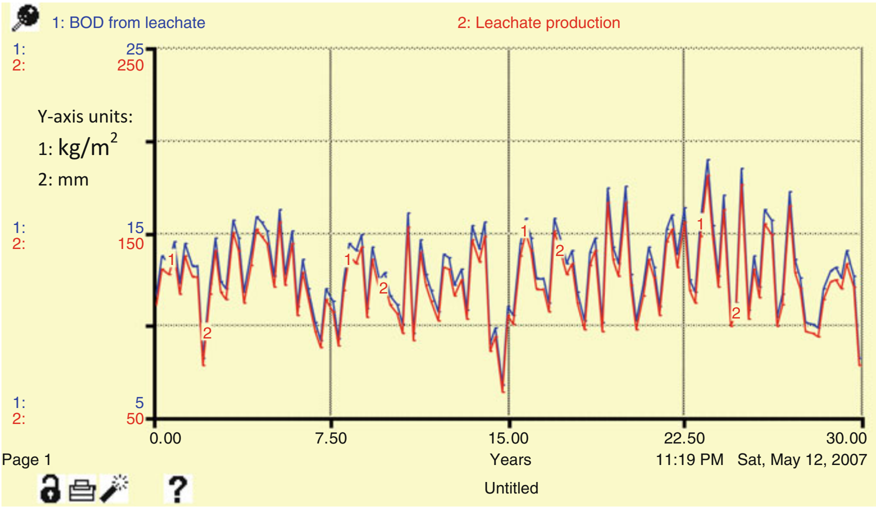

Fig. 12.10 Simulated leachate production (mm) and BOD (kg/m^2) from leachate for a time horizon of 30 years

total increases from 412 kg in 1995 to 72,884 kg in 2005 and BOD from energy increases from 8136 kg in 1995 to 1.48e + 006 kg in 2025. The increase of these emissions with time is due to the increase in solid waste generated. However, the intensity of production of these emissions is moderately low due to the proposed introduction of the composting, incineration plant and sanitary landfill.

Figure 12.10 shows the simulated leachate production and BOD from leachate for a time horizon of 30 years. The simulated leachate production shows fluctuations which are mainly due to the fluctuation in the annual rainfall. BOD from leachate follows the pattern of leachate production. However, BOD from leachate lies between 100 mm and 150 mm.

In order to obtain insight into the effect of the alternative policy options, the following two policy options are considered:

Policy 1: Increasing the collection capacity and assessing its impact on uncleared waste, untreated waste, number of trucks and composite index.

Policy 2: Increasing the collection capacity, treatment capacity and landfill capacity and assessing its impact on uncleared waste, untreated waste, number of trucks and composite index.

Policy 1: Figure 12.11 shows the simulated uncleared waste, untreated waste, number of truck and composite index for increase in collection capacity for a time horizon of 30 years. From the figure it is observed that if we increase the collection capacity by doubling the truck increase rate, the uncleared waste decreases and untreated waste increases, but the composite index remains unchanged as compared with the base scenarios discussed earlier. This means

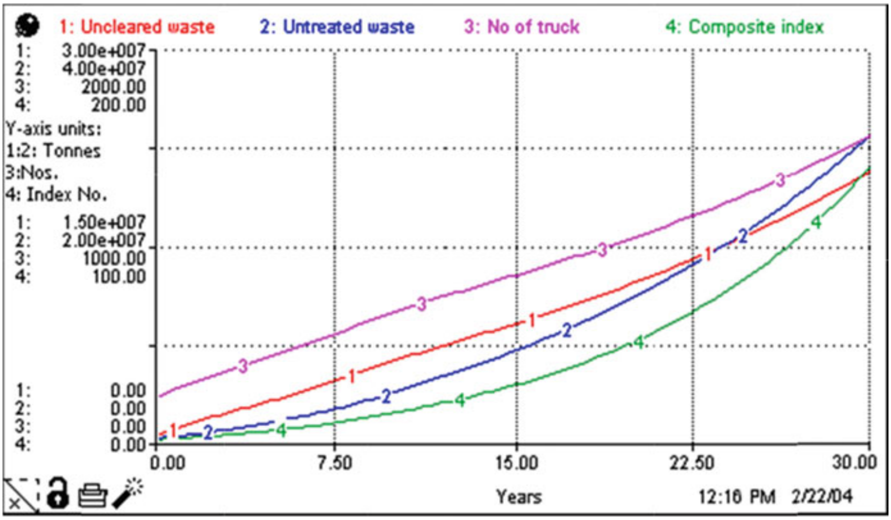

Fig. 12.11 Simulated uncleared waste, untreated waste, number of trucks and composite index with increase in collection capacity for a time horizon of 30 years

that increasing collection capacity alone does not improve the environmental quality because composite index is the indicator of environmental quality.

Policy 2: Figure 12.12 shows the simulated uncleared waste, untreated waste, number of trucks used and composite index with increase in collection capacity, treatment capacity and landfill capacity for a time horizon of 30 years. From Fig. 12.12, it is observed that if we increase collection capacity, treatment capacity and landfill capacity by doubling the truck increase rate, treatment capacity increase rate and landfill capacity increase rate, respectively, the uncleared waste decreases in a similar fashion as in policy 1, but the untreated waste and the composite index also decrease as compared to policy 1. Increased composite index is the sign of environmental quality deterioration, and decreased composite index is the sign of environmental quality improvement. This implies that the increased budget allocation for both clearing and treating the wastes is essential for improving the environmental quality of Dhaka City.

Energy from the waste as well as from the incineration reduces greenhouse gas emission. An analysis of CO_2 equivalent emission per kWh of electricity produced by energy from waste showed that global warming potential of emission from waste is less than coal, fuel and even natural gas.

Finally, in the short run the proposed policy is for sustainable development. But in the long run, it appears to be a dream unless population control within the carrying capacity of the city is achieved, and the treatment plants with energy and material recovery are realised.

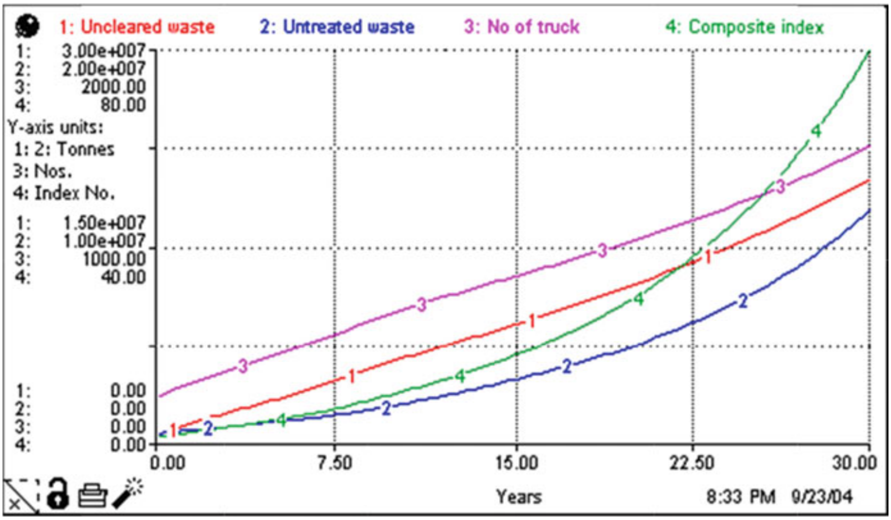

Fig. 12.12 Simulated uncleared waste, untreated waste, number of trucks and composite index with increased collection capacity, treatment capacity and landfill capacity for a time horizon of 30 years

12.7 Conclusions

Population, solid waste generation and electrical energy generation possibility from the solid waste for Dhaka City are increasing with time. The electrical energy recovery from urban solid waste generation of Dhaka City can supply a significant portion of the consumption requirement of electrical energy of the city. Adoption of the policy for electricity from urban solid waste should be dictated by the economy of adoption of the technology of electricity generation from the waste and environmental implications. There exists a potential for organic fertilisers for composting of solid waste, and this compost is a good-quality organic fertiliser for garden vegetables. A policy of introduction of incineration, composting and sanitary landfill is assessed. The intensity of production of the emissions is moderately low due to the proposed introduction of the composting, incineration plant and sanitary landfill. The proposed system is sustainable in the short run but becomes unsustainable in the long run. This model can be used as a tool to assess and design policy options.

Exercises

Exercise 12.1 What is meant by solid waste? Why modelling and simulation of solid waste management systems is important?

Exercise 12.2 Draw the causal loop diagrams of solid waste management systems consisting of solid waste generation and disposal in the form of limited landfill, composting and open dumping.

Exercise 12.3 Draw stock–flow diagram of solid waste management systems consisting of solid waste generation and disposal in the form of limited landfill, incineration, composting and open dumping and simulate the model for solid waste generation, landfill, composting and open dumping.

Exercise 12.4 Simulate the model in Exercise 12.3 for increasing collection and treatment capacity and also analyse the simulated results.

Exercise 12.5 Simulate the model including incineration in the model in Exercise 12.3 and assess the contribution of CO_2, CH_4 and BOD from the solid waste management system.

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