

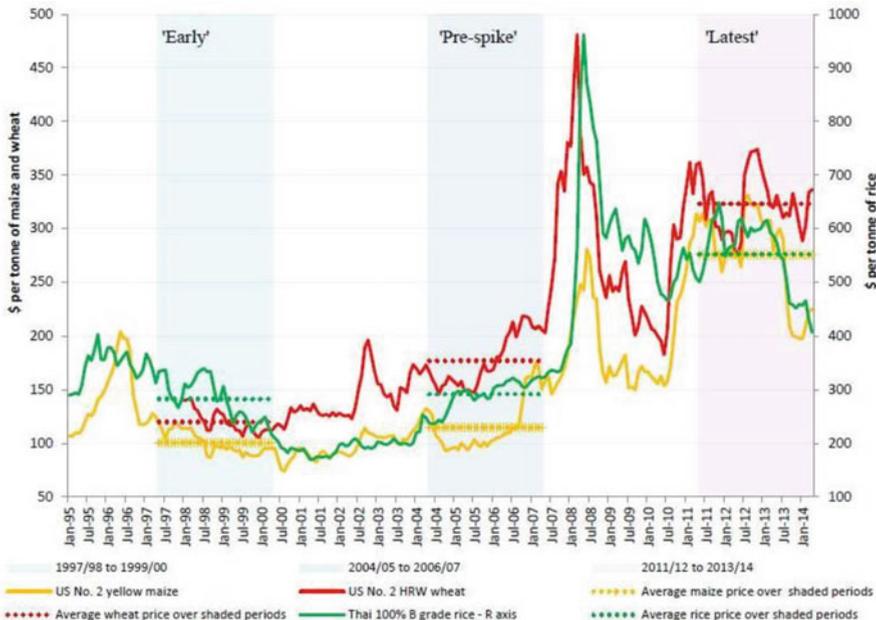
This chapter introduces the complexity and change of the dynamic systems, systems thinking and system dynamics as a methodology of systems thinking. Feedback system concepts and mode of behaviour of dynamic systems are highlighted. Model and simulation are defined, systems thinking methodology outlined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

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## 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



**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.

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## 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.

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## 1.3 Open and Feedback Systems

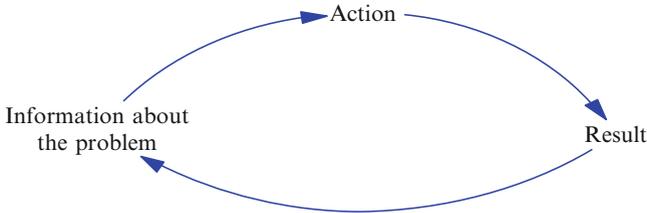
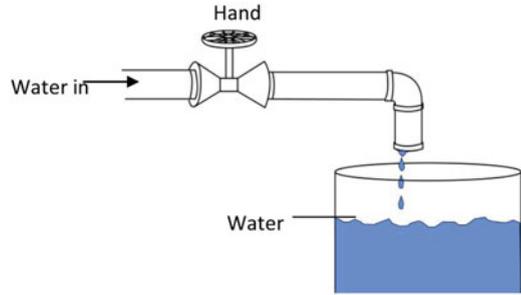
We have discussed about some complex and dynamic systems in Sect. 1.1. What is meant by a system? Here system means a grouping of parts that operate together for a common purpose. For a simple example, a tractor is a system of components that work together for providing cultivation. A system may include 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).

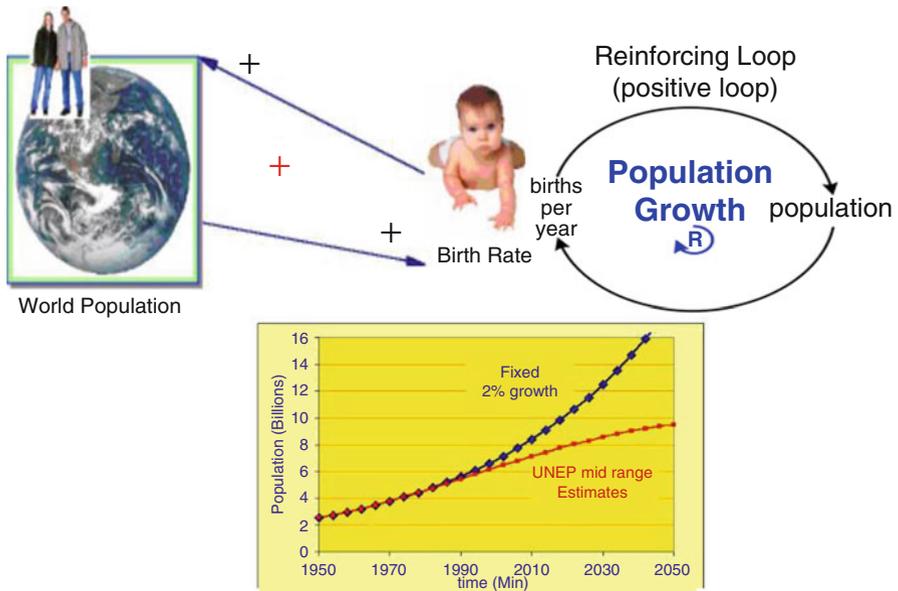


Fig. 1.5 Population growth system

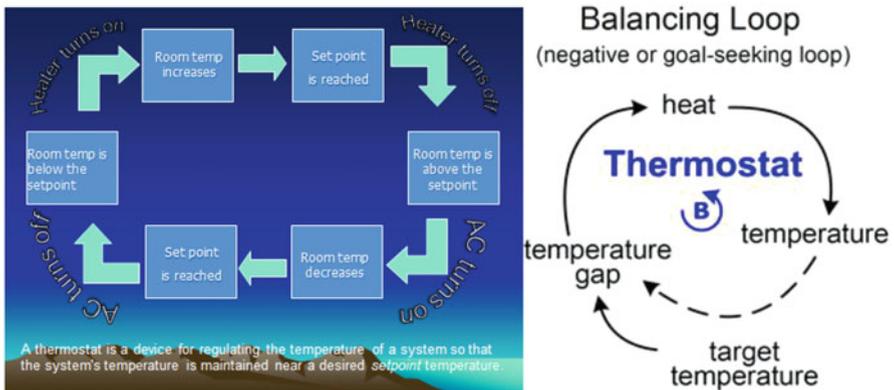
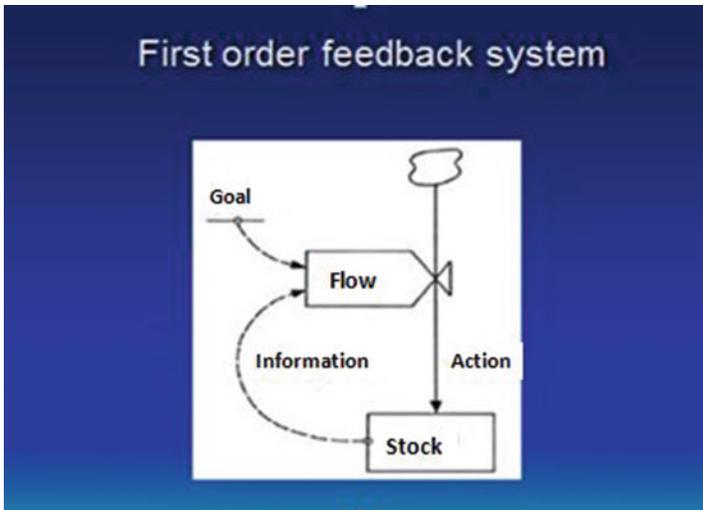


Fig. 1.6 Temperature control system in a room

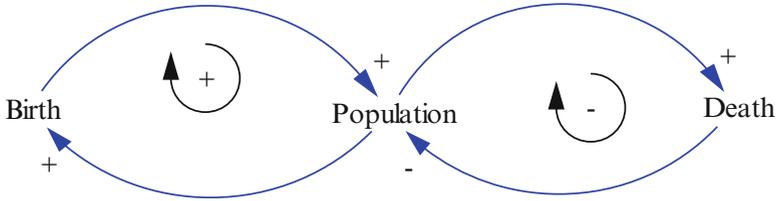
## 1.4 Modes of Behaviour of Dynamic Systems

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.

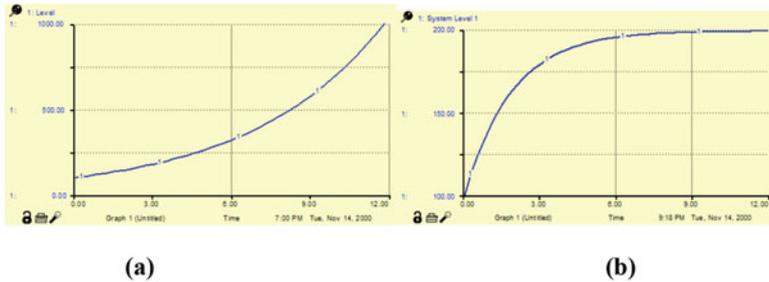
Feedback loop structure of a system simulates dynamic behaviour, and all the dynamics arises from the interactions of two types of feedback loops: positive feedback loops and negative feedback loops. Positive feedback loop generates growth, i.e. self-reinforcing and the causal loop consisting of population, 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.



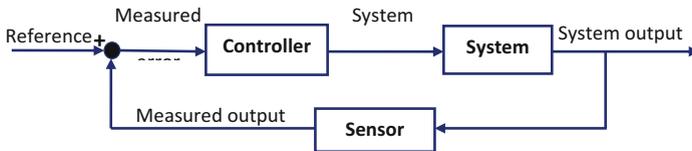
**Fig. 1.7** Feedback loop



**Fig. 1.8** Causal loop



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



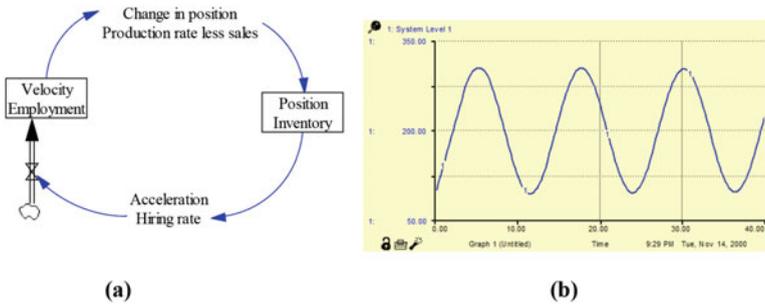
**Fig. 1.10** Control theory block diagram of a negative feedback system

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.

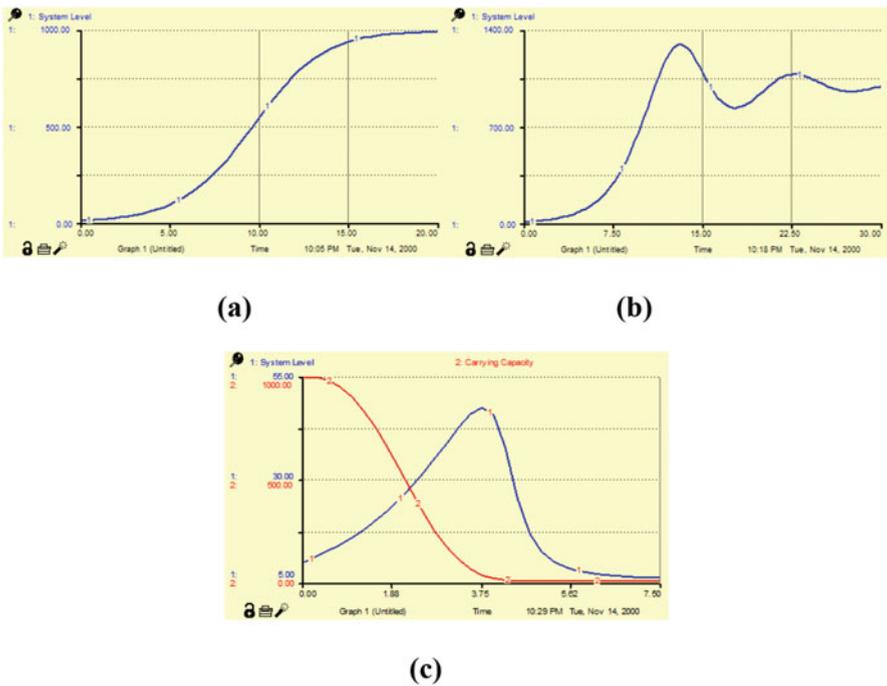
Figure 1.12 represents the responses of some complex systems. Figure 1.12a shows s-shaped growth, Fig. 1.12b shows s-shaped growth with overshoot and Fig. 1.10c shows overshoot and collapse of complex systems. First order and higher order positive feedback systems generate growth. First order negative 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



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



**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.

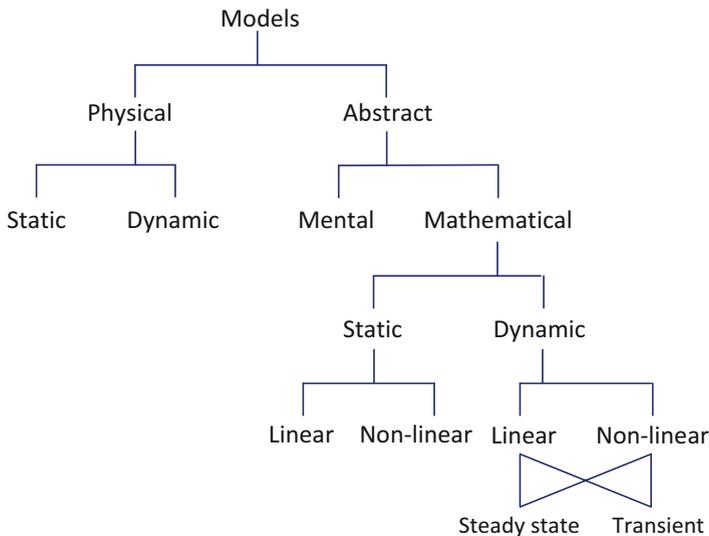
A model may be defined as a substitute of any object or system. Everyone uses models in their daily life. A mental image used in thinking is a model, and it is not

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.

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## 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.

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## 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.

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## 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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