# 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



B.K. Bala et al., *System Dynamics*, Springer Texts in Business and Economics,
DOI 10.1007/978-981-10-2045-2_2

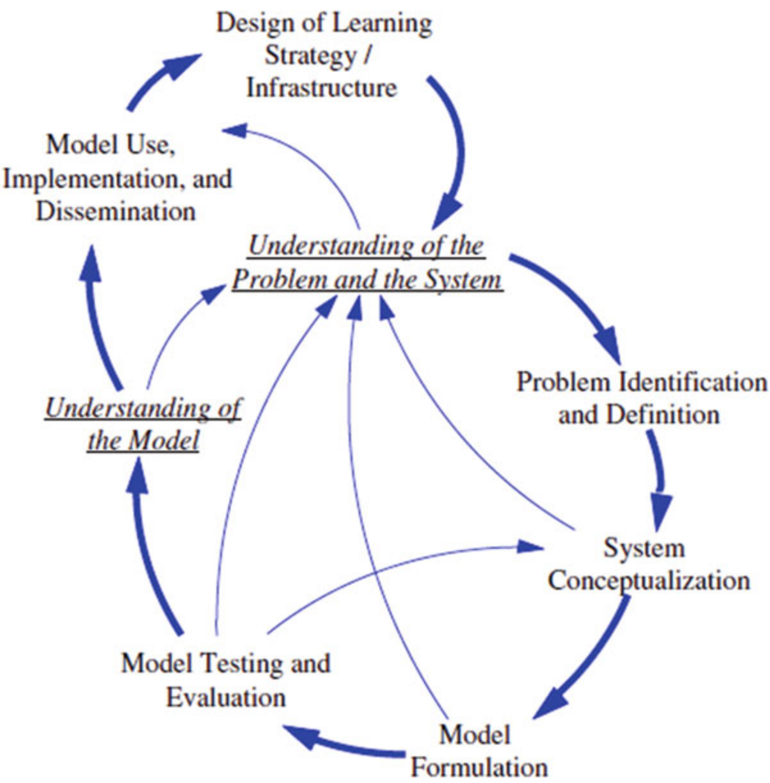


**Fig. 2.1** Overview of the system dynamics modelling approach (Source: Martinez-Moyano and Richardson 2013)

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

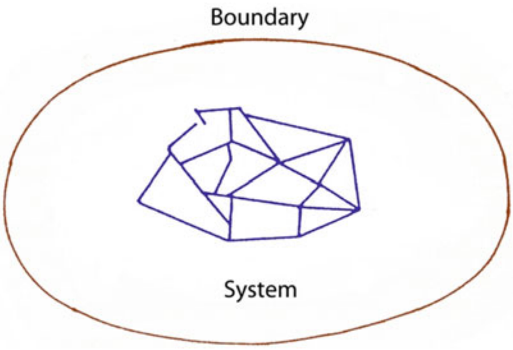


**Fig. 2.2** Closed boundary concept

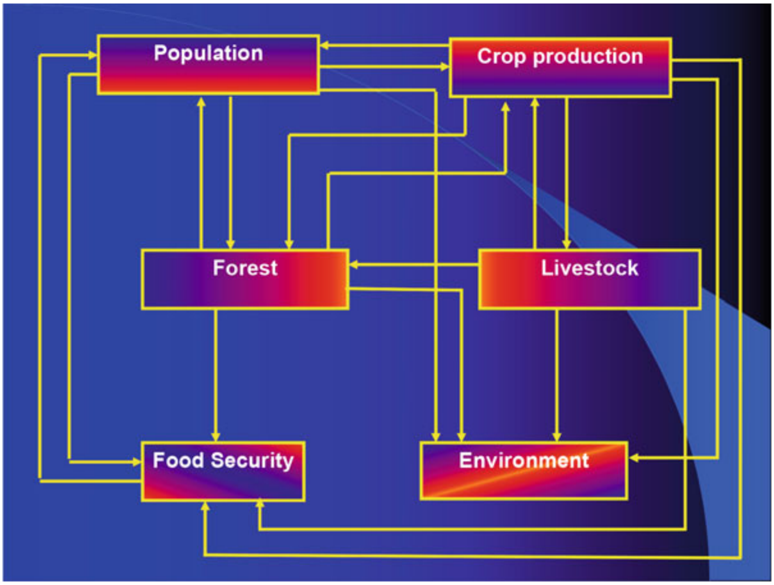


**Fig. 2.3** Structure of food, energy and environment model

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).

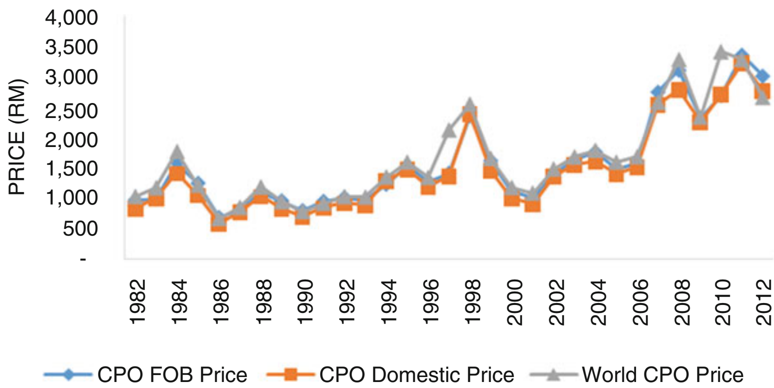


**Fig. 2.4a** CPO FOB Price, CPO Domestic Price and World CPO Price (1982–2012) (Source: MPOB 2012)

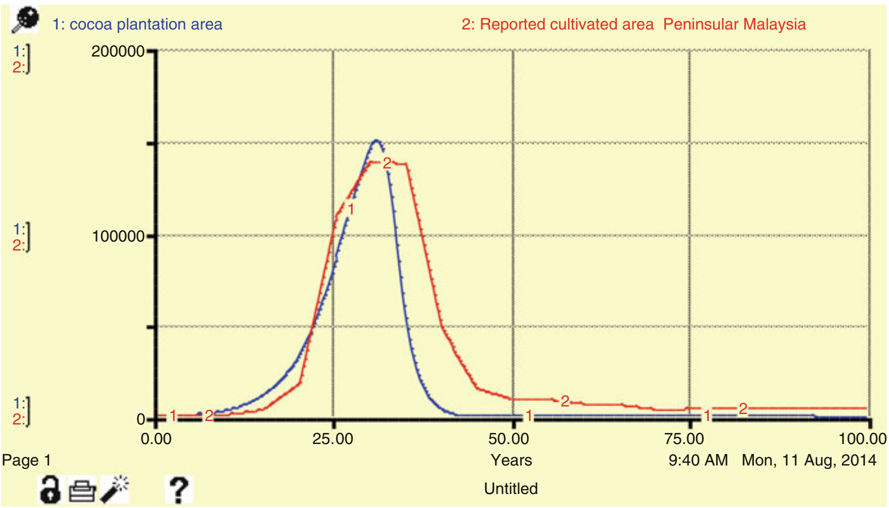


**Fig. 2.4b** Observed and simulated reference mode behaviour of cocoa production systems in Malaysia (Source: Fatimah et al. 2015)

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.

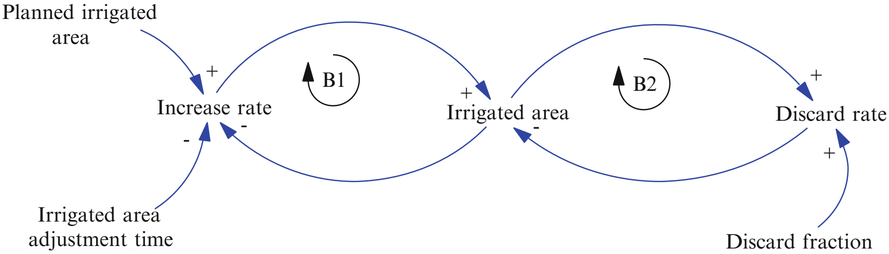


**Fig. 2.5** Causal loop diagram of a simple irrigation model

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.

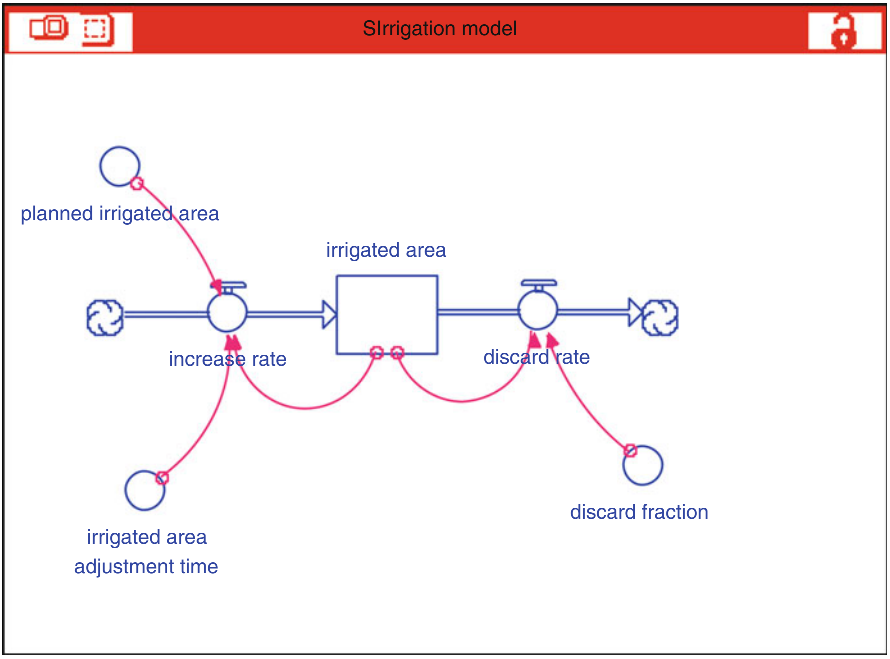


**Fig. 2.6** Stock–flow diagram of the irrigation model

## 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).

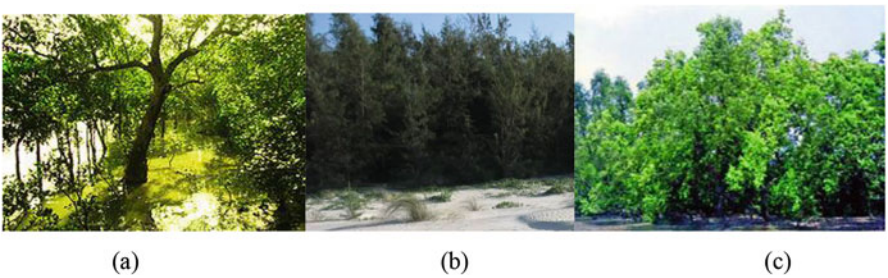


**Fig. 2.7** (a) Sundari, (b) Gewa and (c) Keora trees of the Sundarbans

## 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 $V_{\mathrm{P}}$ at time t is calculated from the maximal volume $V_{\mathrm{mat,P}}$, time t and constant $K_{\mathrm{M}}$. 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:

$$\frac{dV_\mathrm{P}}{dt} = \frac{1}{K_\mathrm{M}} V_\mathrm{P} \left( \frac{V_\mathrm{P}}{V_\mathrm{mat,P}} - 2 \right) + \frac{V_\mathrm{mat,P}}{K_\mathrm{M}} C_\mathrm{P} \tag{2.3}$$

with

$$C_\mathrm{P} = 1 - \frac{\omega_\mathrm{IP}}{\omega_\mathrm{IP} + \omega_\mathrm{CP}} \frac{V_\mathrm{I}}{V_\mathrm{mat,I}} - \frac{\omega_\mathrm{CP}}{\omega_\mathrm{IP} + \omega_\mathrm{CP}} \frac{V_\mathrm{C}}{V_\mathrm{mat,C}}$$

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 $\omega_{IP}$ and $\omega_{CP}$ 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:

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

$$\frac{dV_\mathrm{C}}{dt} = \left(a_\mathrm{input} + g_\mathrm{C} V_\mathrm{C}\right) \times \left(1 - \frac{\omega_\mathrm{IC}}{\omega_\mathrm{IC} + \omega_\mathrm{CC}} \frac{V_\mathrm{I}}{V_\mathrm{mat,I}} - \frac{\omega_\mathrm{CC}}{\omega_\mathrm{IC} + \omega_\mathrm{CC}} \frac{V_\mathrm{C}}{V_\mathrm{mat,C}}\right) \tag{2.5}$$

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:

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

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

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.

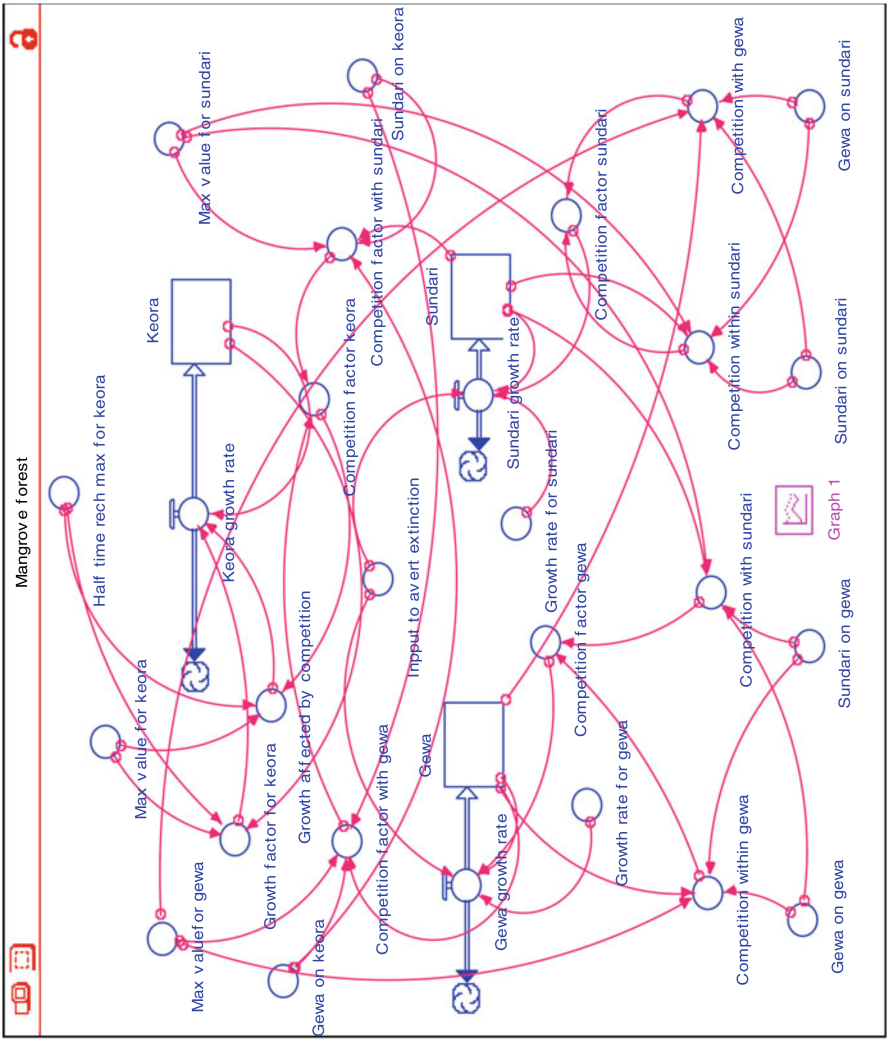


**Fig. 2.8** Stock–flow diagram for undisturbed mangrove forest model

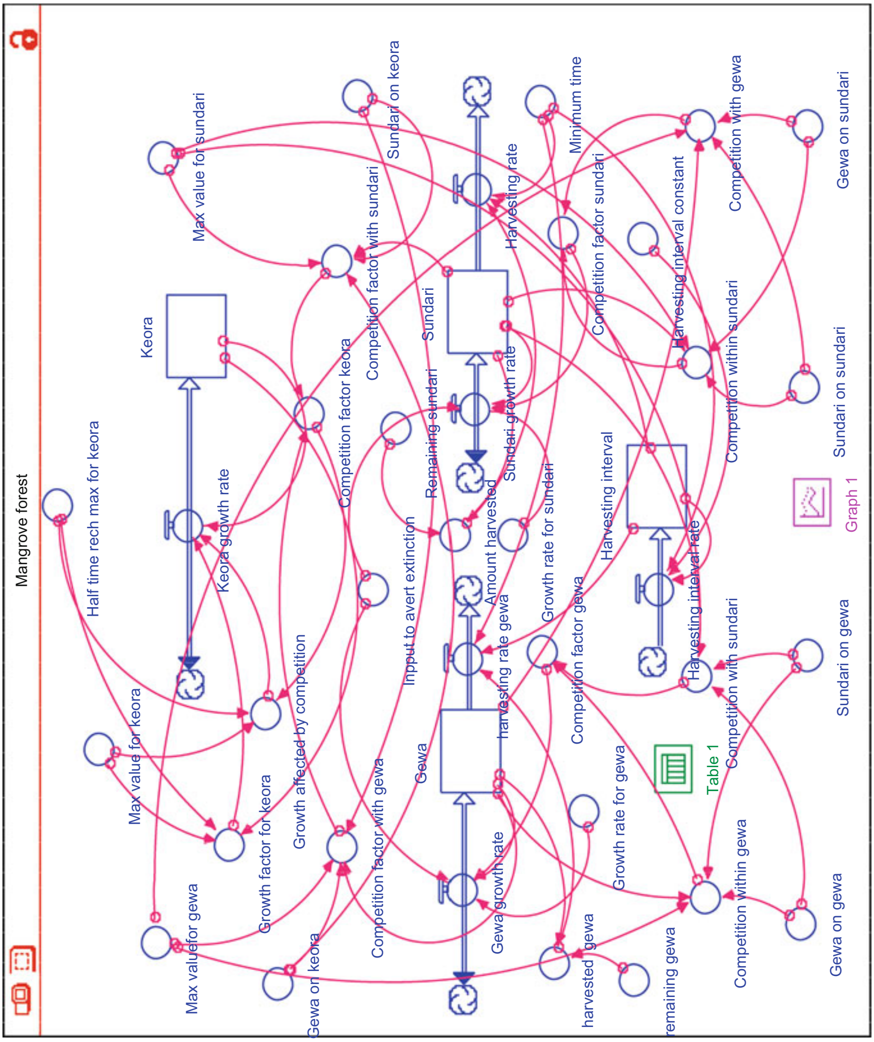


**Fig. 2.9** Stock–flow diagram for mangrove forest model with logging operations

**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 |

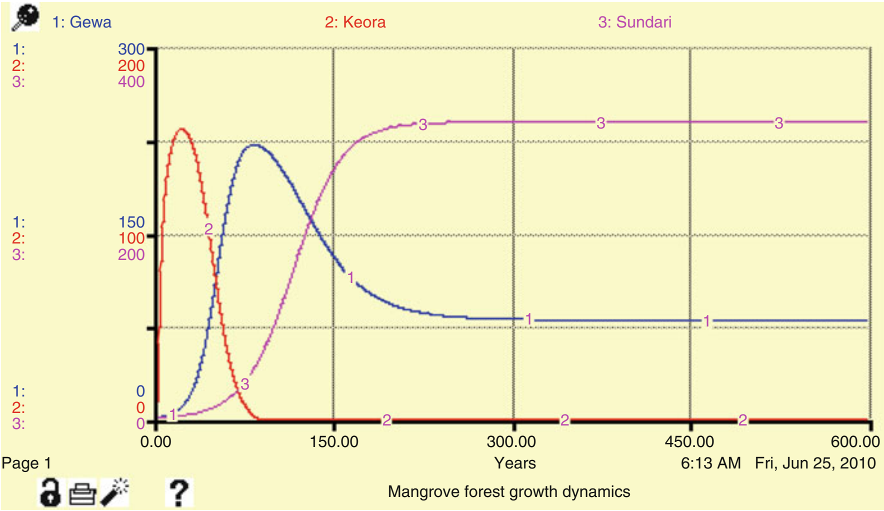


**Fig. 2.10** Simulated volume for undisturbed mangrove forest (Keora, pioneer; Gewa, intermediate; Sundari, climax)

## 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

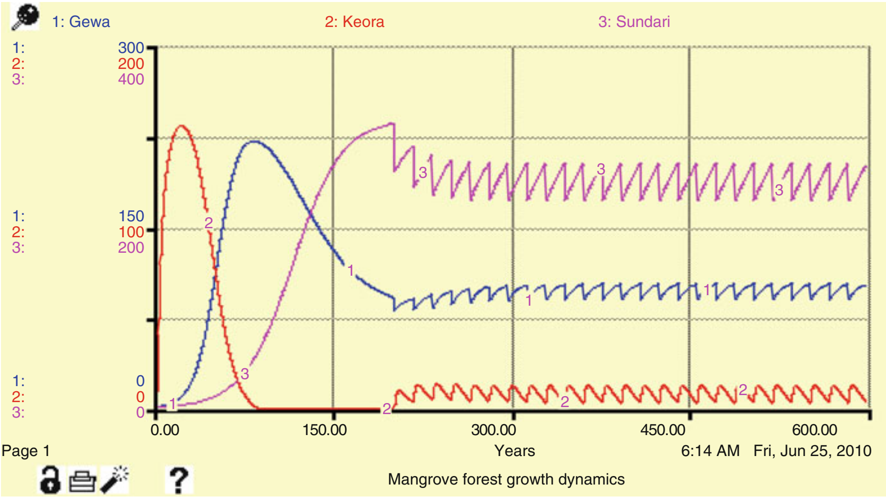


**Fig. 2.11** Simulated volume of mangrove forest for 16 years logging cycle (Keora, pioneer; Gewa, intermediate; Sundari, climax)

(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.

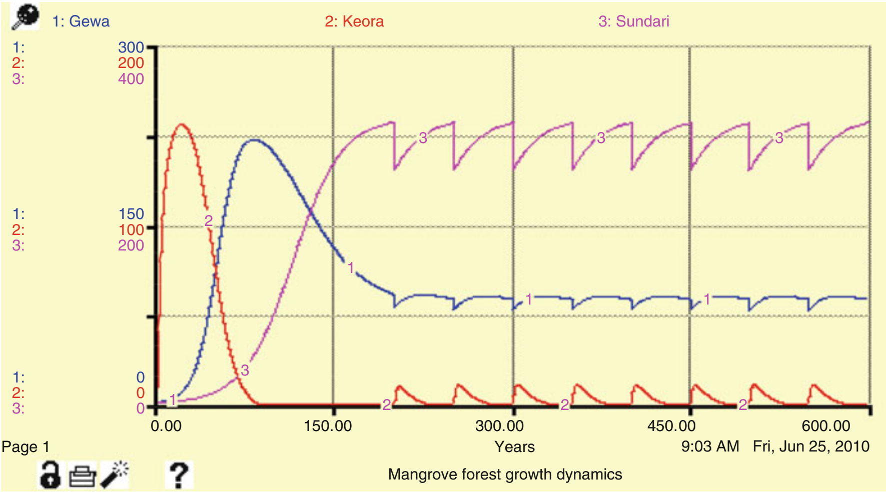


**Fig. 2.12** Simulated volume of mangrove forest for 50 years logging cycle (Keora, pioneer; Gewa, intermediate; Sundari, climax)

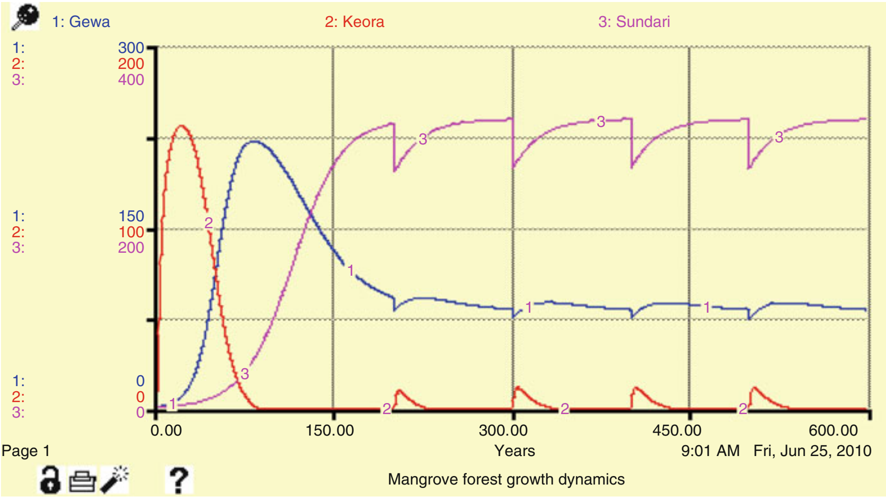


**Fig. 2.13** Simulated volume of mangrove forest for 100 years logging cycle (Keora, pioneer; Gewa, intermediate; Sundari, climax)

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.

## References

Andersen DF, Richardson GP (1997) Scripts for group model building. Syst Dyn Rev 13:107–129

Arquitt S, Hongang X, Johnstone R (2005) A system dynamics analysis of boom and bust in the shrimp aquaculture industry. Syst Dyn Rev 21:305–324

Bossel H (1994) Modeling and simulation. K.Peters, Wellesley, 484 pp

de Gooyert V, Rouwette FAJA, van Kranenburg HI (2012) A typology of stakeholder involvement in group model building. In: Proceeding of the 30th international conference of the System Dynamics Society

Elias AA, Cavana RY, Jackson LS (2000) Linking stakeholder literature and system dynamics: opportunities for research. In 1st international conference on systems thinking in management, pp 174–179

Fatimah MA, Bala BK, Alias EF, Abdulla I (2015) Modeling boom and bust of cocoa production systems in Malaysia. Ecol Model 310:22–32

Forrester JW (1961) Industrial dynamics. MIT Press, Cambridge, MA

Forrester JW (1968) Principles of system dynamics. MIT Press, Cambridge, MA

Gardiner PC, Ford A (1980) Which policy run is best, and who says so. TIMS Stud Manag Stud 14:241–257

Haefner JW (1996) Modeling biological systems: principles and applications. Kluwer Academic Publishers, New York, 473 pp
Hsiao N (1998) Conflict analysis of public policy stakeholders combining judgment analysis and system dynamics modeling. In: Proceeding of the 16th international conference of the System Dynamics Society
Maani KE, Cavana RY (2000) Systems thinking and modelling: understanding change and complexity. Prentice Hall, Auckland
Manetsch TJ, Park GL (1982) Systems analysis and simulation with applications to economic and social systems. Department of Electrical Engineering and System Science, Michigan State University, USA
Martinez-Moyano IJ, Richardson IJG (2013) Best practices in system dynamics modelling. Syst Dyn Rev 29(2):102–123
MPOB (Malaysian Palm Oil Board) (2012) Prices of palm oil products. Economics and Industry Development Division, Malaysian Palm Board, Kuala Lumpur
Rouwette EAJA, Korzilius H, Vennix JAM, Jacobs E (2011) Modeling as persuasion: the impact of group model building on attitudes and behavior. Syst Dyn Rev 27(1):1–21
Sterman JD (2000) Business dynamics: systems thinking and modeling for a complex world. McGraw-Hill Higher Education, Boston
Tàbara D, Pahl-Wostl C (2007) Sustainability learning in natural resource use and management. Ecological Society, 12, 3. Available online: http://www.ecologyandsociety.org/vol12/iss2/art12/. Accessed on 17 Apr 2010
Tietjen B, Huth A (2006) Modelling dynamics of managed tropical rainforests – an aggregated approach. Ecol Model 199:421–432
Vennix J (1996) Group model building. Irwin McGraw-Hill, New York
Vennix JAM (1999) Group model-building: tackling messy problems. Syst Dyn Rev 15 (4):379–402
Voinov A, Gaddis EJB (2008) Lessons for successful participatory watershed modeling: a perspective from modeling practitioners. Ecol Model 216:197–207

## Bibliography

Bala BK (1999) Principles of system dynamics. Agrotech Publishing Academy, Udaipur
Cavana RY, Maani KE (2000) A methodological framework for systems thinking and modelling (ST&M) interventions. Ist international conference on systems thinking in management. Internet
Mohapatra PKJ, Mandal P, Bora MC (1994) Introduction to system dynamics modelling. Universities Press, Hyderabad
Yadama GN, Hovmand PS, Chalise, N (2010) Community driven modeling of social-ecological systems: lessons from Andhra Pradesh, India. In: Proceedings of the 28th international conference of the System Dynamic Society. Seoul, South Korea