1. PROBLEMS AND SYSTEMS

1.1 Problems and their associated systems

Models are used to solve problems. There is a problem when a **cognitive, volitional, active entity** (person, animal, robot, agent, group or institution) wants to produce a change in itself, or in its environment, or both. A problem solving process may then happen. The types of problems are as diverse as the activities of the active entities (gain in understanding, creation of a new product, change in a situation, self-transformation, inner inspiration to act, amusement). A **rational** procedure of problem solving has the following stages:

1. Precise **definition** of the problem. It is not a trivial task. Early definitions usually have omissions and inaccuracies, which only emerge in the following steps. The aspect of the problem may change. Maybe it can be concluded that there is no problem at all.

2. Definition of the problem leads to the consideration of a part of the universe. It is **the system associated to the problem.** This consideration is an expansion of the vision about the problem. The vision may bring into consideration objects actually related with the actual problem (synchronic) or temporally related in the past or future (diachronic). The study of the associated system (see 1.2 below) can lead to changes in the problem definition. These may be reductions, enlargements, decomposition in sub-problems, integration into higher level problems or the abandonment of the problem if it is recognized as too difficult, insolvable with the available resources or irrelevant. The result of this inquiring process is a conceptual image of the system that can be specified in a **model** that is another system (physical mock-up, verbal description, graphic representation, mathematical description). Obviously it may be different models of the same system. This image of the system depends on the problem, **only the aspects of the system which are relevant for the solution of the problem might be included in the model**. I

Example. If the problem is to increase the safety of operation in a port the associated system will include the reliability of material handling, of personnel and equipment, the safety in the depots, the location of the different type of hazardous materials, the environmental perturbations, the facilities to prevent or control accidents, the alarms, the external safety and health institutions, internal health facilities, attitudes of people about safety, history of past accidents, etc..

If the problem is to increase the throughput of the port (material handling capacity), the system will include the speed and capacity of all the processes, physical, administrative, sanitary, supervisions human relations that made possible the handling of the materials**The coordination and adequate scheduling of these processes is essential.**

The history of variations of throughput is also important.

The system related to the problem is different in both cases and so will be the models.

The model also depend on available information, on the people that create the image (background, intentions, beliefs, situation, capacity of colaboration) on the resources and time available to build the model. In one particular study it may be convenient to build more than one model.

3. Selection or design of a **method of solution.** That is a manipulation of the model that extracts the information to solve the problem. There are a lot of methods to solve standard problems, which are established by experience, common sense, or different branches of science and technology and are known by the corresponding experts. Usually a **discursive manipulation** of a qualitative verbal model is used. However, in many cases complexity and need of accuracy make this informal method inadequate. Formal **mathematical models** are required that may manage multiple ineractions and consider the quantitative and logical aspects.

Mathematical and computational techniques are: Statistical Analysis, Data Bases, Operations Research (Linear and Non Linear Programming, Critical Path methods, Dynamic Programming, Inventory and Queue Theory), Numerical Analysis, Logical Calculus, Control Theory, Stability and Catastrophe Theory, System Dynamics, Expert Systems, Artificial Intelligence techniques, Mathematical Modeling and Simulation, Simulation Games.

It is important to stick to the problem and to avoid distorting the problem to adapt it to a known solution or method.

If no satisfactory method is found, one is to be developed. Techniques of creativity and ideas generation may be used (see 2.9).

The technique depends on the problem. Although each one of the mentioned techniques is the field of a different expert, the system analyst must have some idea of each one to decide what experts to consult.

3. **Application** of the method results in a set of **decisions** that must be **implemented** to solve the problem. This process usually requires resources and creation of auxiliary systems.

Example. In the problem of increasing the throughput of a port, in order to deal with the complexity of the system a **simulation model** may be adopted. Experiments with different alternatives (speed of cranes, use of containers, administrative organizations, addition of piers, increase in the size of deposits) and evaluation of the cost of each alternative, lead to a decision. After this decision is made, the detailed engineering of the implementation must be done.

4. Results are **evaluated**. Difficulties, emergency of new visions, or negative results in one step can require to re-examine and change some previous steps.

Note the special, **indirect approach** to solving problems by means of models. The analysis of the real systems leads to the building of a model. After this, the effort is concentrated in the analysis of the model. The analyst keeps itself separated of the problem. The method enter in some difficulties in social and psychological problems in which the analyst belongs to the system associated to the problem. In other approaches to the problems (conducted by mystics, artists, sportsmen) although some modeling processes also appear, there is a sort of integration with the real objects and intuitive mental processes enter in action (see H. Bergson 1985 and B. Croce 1902). In this text we will not deal with these ideas, except perhaps in some aspects of the reference to creative thinking.

1.2 System analysis

The objective of system analysis is to get knowledge about the system. The result is, as it was said, a conceptual image or **model of the system** that may be handled to learn about the behavior of the system. Two processes alternate in the study of a system and the model definition**:**

1. Delimitation and determination of the system, i.e. decisions about which are its components and the relations among them and with the environment. That means the **building of the model.**

2. Information gathering and processing to do that delimitation and determination.

It is useless to discuss what process is more important or must be the first. Every information search assumes a certain previous knowledge of the system structure (model) which points to what information to look for. All knowledge of the system components and relations is based in previous information. The important issue is to decide correctly, in a state of the research, which kind of step, the speculative or the informative, will be the following one. The usual procedure is: if there is some immediately available information, build a preliminary image of the system (model), whose imperfections, inconsistencies and deficiencies would indicate the needed information. If the initial information is not enough to build that image, an initial informative general exploration must be done.

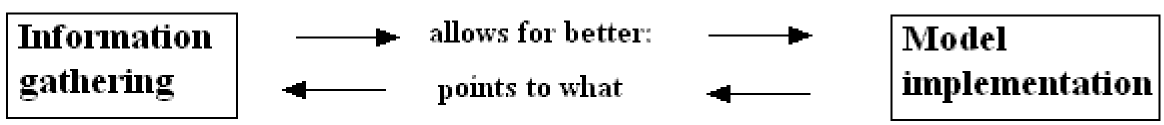


Figure 1-1 Relation between Information Gathering and Model Implementation.

These processes must be conducted keeping in mind the inquiry's main target: that is, **the problem to solve**. However, in both processes some exploration, aloof of the target, speculation and information getting, may be allowed. They may lead to discover additional aspects of the associated system that may be key elements of the research.
Exploration and representation techniques have been developed for both processes. In this chapter, system specification techniques are discussed, leaving for the next the problems of gathering and organizing information.
The analysis of the system may procced in three stages: input/output analysis, state analysis and system decomposition. See Fig.1-1.

1.2.1 Input/Output analysis. When **a part of the universe** that is supposed to be associated with the problem **is isolated** to be analyzed, an artificial segregation is done. In fact, the rest of the universe, or at least a part of it, acts on the system. That is called the **input**. The system, in turn, acts on the rest of the universe. That is the **output**. The part of the universe that sensibly affects or is affected by the system is called its **environment**. In the I/O analysis the following rules are useful:

If there are **many inputs and outputs as compared with internal relations** among the elements of the system, this means that the system **is not well delimited**. Some elements or relations must be included or excluded in the model. See Exercise 1

Outputs should not be related with inputs. If this is the case, the links and elements that connect them should be included in the system. Otherwise, if some values are given to the inputs these values may be altered by the output and the true input may remain unknown. See Exercises 2 and 3.

It is desirable that **the different inputs to be independent**. If they are not, when the change in one of them is taken into account, the change of others must also be considered and estimated from a known relation. It is better to include the relation explicitly in the model of the system. See Exercise 4.

The outputs should also be independent. If they are related the final action on the environment has to be additionally estimated. It is better to include this estimation in the model of the system. See Exercise 5.

A frequent error is to omit **inputs and outputs that are undesirable**, **accidental** or **useless** for the operation of the systems. Pollution, robberies, power failures, sabotage, aliens action, poisons, diseases, catastrophes are examples of these. See Exercise 6.

The knowledge of the inputs and outputs **and their relations** seems to exhaust the knowledge of the system. This is all the knowledge needed to **use or handle** the system: what actions (inputs) are required to obtain certain outputs. Who uses an automobile or a TV set do not care about what happens inside. It is said that the system is a **black box** for the user.
However, this level of analysis is not enough to predict the system behavior. There might be too many combinations of inputs and outputs making the system difficult to handle. A most serious problem is that **to the same set of inputs may correspond different outputs**. One morning you apply the usual inputs to your car and it does not start.
Mathematically: there is **not a function** that gives the outputs when the inputs are put as the values of its argument. It is only a mathematical **relation**, in which to the same input would correspond different outputs. This situation is managed introducing the concept of **state**.

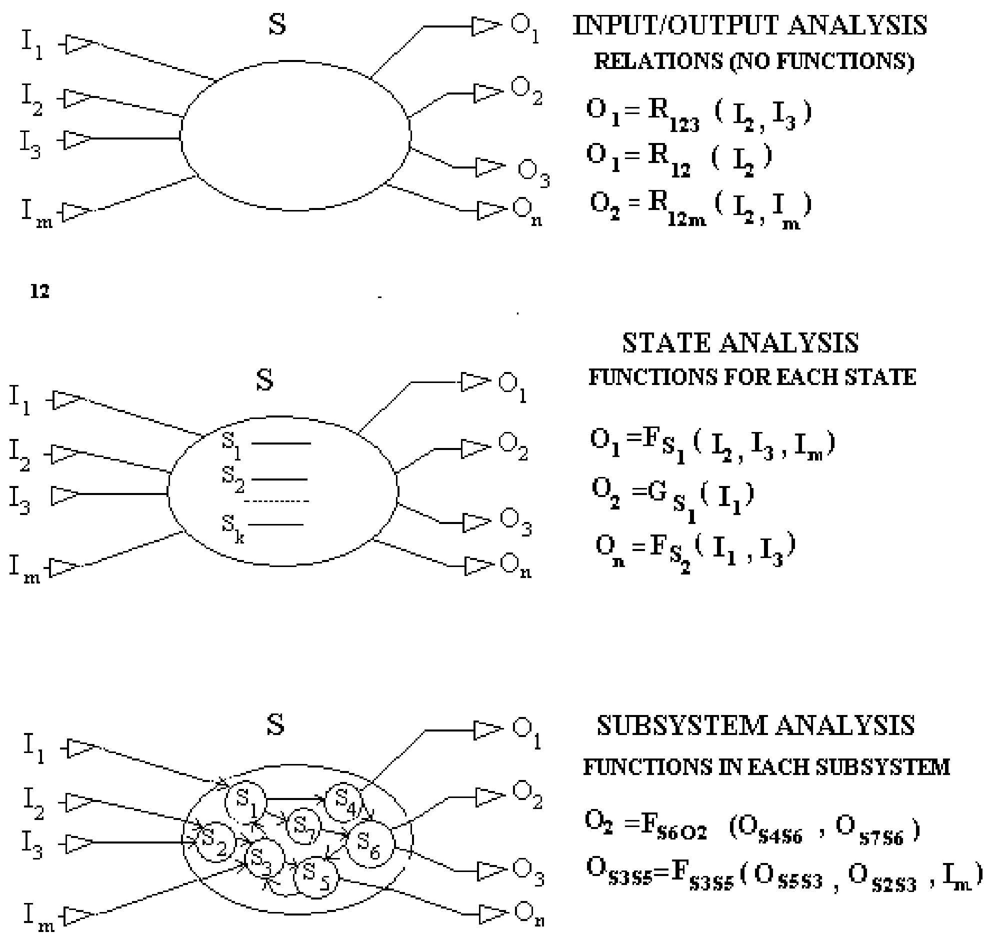


Figure 2-1 System analysis techniques

1.2.2. State Analysis. It is a common experience to verify that applying the same input to a system the output is different. That may seem a violation of the **principle of causality**. The principle “is saved” accepting that the system is in different states and that in each state there are different relations between input and output, these relations being each one a true function. The procedure could not be seeing as a trick to save the principle of causality. Many years of scientific experience have shown that this hypothesis not only have been verified, by finding real differences inside the system in the case of different behaviors, but the search for such differences has been one of the most successful guides to produce new knowledge. The exceptions to these deterministic explanations using states will be discussed below when dealing with stochastic models (Chapter 6). The state analysis reduces the knowledge to a set of functions: $O_e(I)$ that for each input vector I and state e, give the output vector O_e.

However in many situations this reduction to a deterministic unambiguous dependence of inputs of the outputs is not possible. It may be very difficult to get, or it is not necessary. In this cases, as is discussed in Chapter 6, a probabilistic relation is assumed. It is yet possible to extract interesting consequences of this class of models.

It seems that now a system may be specified by the set of its states and the I/O function for each state. However, this specification has two drawbacks: it may be **too complex** for large systems **and it does not constitute an explanation** of the behavior of the system in which the behavior might be deduced from general laws and principles. Even if one know for each state of a car the relations between all possible inputs and outputs this may be enough to use it, but it is of not use at all to understand its functioning and to diagnose and repair a failure, (See Exercises 7 and 8) let alone to build a car with only this type of specification.

1.2.3. Decomposition and integration. The system can be decomposed into semi-independent parts called **subsystems**. They are parts of the system whose components have more relations among them than with the rest to the system and the environment. Each subsystem can be further decomposed into subsystems. The analysis stops when the subsystem is simple enough to be easily understood and its outputs (actions on the rest of the system and environment) are **a function** of its inputs (actions of the environment and the rest of the system on it). Usually these functions can be defined by general scientific laws or can be determined by special scientific research. **Putting together these laws of the parts, the system analyst expects to explain the properties of the whole system**. The method of decomposition and integration, stated explicitly by Descartes and other scientists and philosophers of the late Renaissance, has been very successful in many physical systems. The first problem with the method appears when the existing theory about the subsystem cannot determine its I/O function but only **some possible outputs and their probabilities**. This situation precludes the building of a deterministic model. As will be seen in chapter 6 **stochastic models** may be developed. The method also enters into difficulties in very complex systems in which the behavior of some subsystems depends on the processes of many other subsystems. Or when the relation of elements originate a whole with new properties difficult to predict from the properties of the parts. The Systems Approach was developed to cope with these difficulties (see Exercise 9).

Example. Consider a brick in isolation, for example in a gravity free region of space. If a force is applied in one of its faces as input, the output will be an accelerated movement. On the other hand the brick does not produce elastic forces on the other faces. If the brick is put as component of a system, for example a wall on the earth, the property of being accelerated under a force disappears. Besides new elastic forces appear as outputs acting on the surrounding bricks. So the study of the parts of a system in isolation cannot predict its behavior when they are integrated in a system.

Chaotic systems, which are non linear systems (in the equations that represent their behavior appear products and /or powers of the variables) may show a behavior highly sensitive to imperceptible changes in conditions. They are intractable by the decomposition integration approach. The same happens with systems that show creative or undetermined behavior (as systems that include human beings or elementary particles). All these processes are now the object of an active research in the so called Complexity Theory and Structural Change theory. See Exercise 10.

It is necessary to realize that in complex and complex changing systems the designed model may depend on the initial approach and the background and beliefs of the people involved in the design. The consideration of **different models for the same problem** or situation may be important in these cases. This is related with the **scenario** techniques that will be considered later on.

The above analysis often requires simultaneous handling of information about many elements and relationships. This is not possible by the unaided human mind and discursive expression. Many techniques have been developed to represent the information in such a way that facilitates the analysis. The main techniques are described in the following.

1. Lists. The simple expedient of putting in a list all the elements of an aspect of the system may be very useful. Lists containing the elements, inputs, outputs, related systems, bibliography, sources of information, isolated ideas and suggestions, dangers and opportunities perceived, possible changes, and many other types of information may be done. The important attitude is not to relay in simple memory. It does not work when dealing with complex systems. See Exercise 9.

2. Images. Mock-ups**,** schemata, pictures, films, maps, videos, are increasingly important by the introduction of graphic processing and Geographic Information Systems.

3. Graphs. Mathematical graphs consist in points (or geometrical units) called **nodes**, united by lines or **arcs.** There are many types or graphs. The nodes may represent subsystems, operations, decisions, beginning and end of activities, processes, variables, concepts. The arcs may represent relations among these entities. Some graphic types are mentioned in the following.

System graphs. The nodes may indicate components or subsystems, the arcs, relationships or interactions. In directed graphs (digraphs) each arc has an arrow that may show the direction of the interaction. A **trajectory** is a set of successive arcs. **Closed cycles** can be formed in which the end of a trajectory coincides with the beginning. The nodes may be geometrical figures (rectangles, ovals) called **boxes**, in which the names and some information about the components can be written. Some information can also be written on the arcs. The system graph allows perceiving at a glance the general structure of the system.

See Exercise 11, Fig.7.

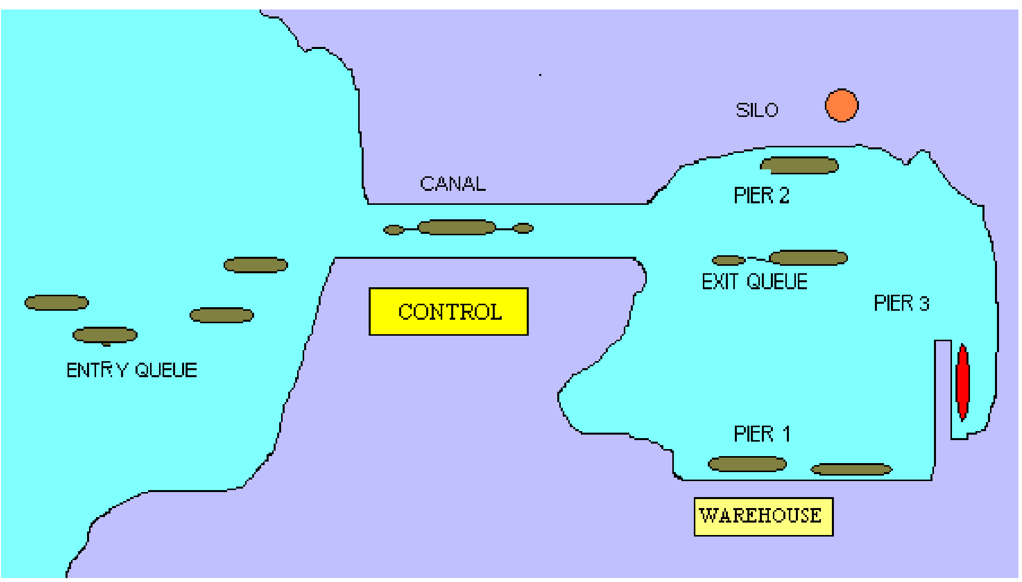


Figure 3-1 Port with three piers. Schema

Sequential procedure graphs (flow charts). They are widely used to represent **diagram** algorithms or other sequential set of tasks . In general the nodes (boxes) indicate operations to be done or decisions, the arrows indicated the sequencing of the operations. See Exercise 12, Fig.3.

It can be shown (C.Bohm and G.Giacopini 1966) that with two types of box, one representing assignation of values to a variable and other representing a decision, it is possible to build a graph to describe any algorithm. For programming commodity other boxes are introduced describing more complex procedures (multiple alternatives, iterative procedures, etc.)

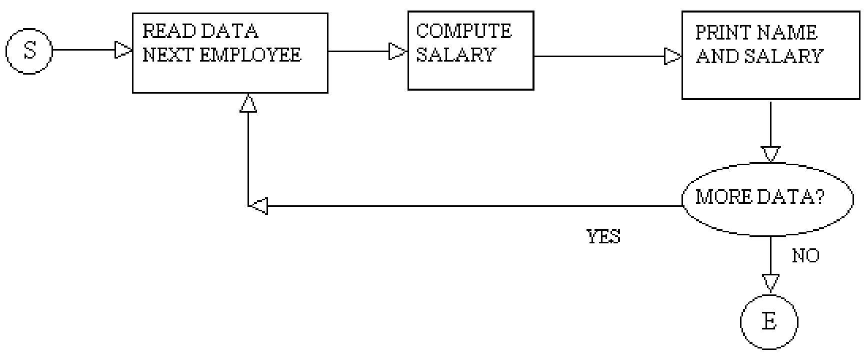


Figure 4-1 Payroll flow chart

Parallel procedure graphs (networks) are directed graphs that start in one node of which one or many arcs depart in the form of paths or trajectories through many nodes. From these nodes new trajectories may start that may interconnect each other, but finally all converge in a single end node. There are no closed cycles. These networks are used to represent a set of interrelated operations each of one taking a span of time, but they may overlap in time, as in the building of a house. Each arc represents an operation or task that ends in some node, in which other tasks may also finish. Tasks departing from one node only may start when all the tasks ending in the node are finished. This representation can be handled mathematically to estimate the total time of the whole work, the trajectory with the tasks whose delay or advance produce a delay or advance in the total time (critical path) and many other characteristics important for the scheduling and optimization of the work. See Exercise 13, Fig.4.

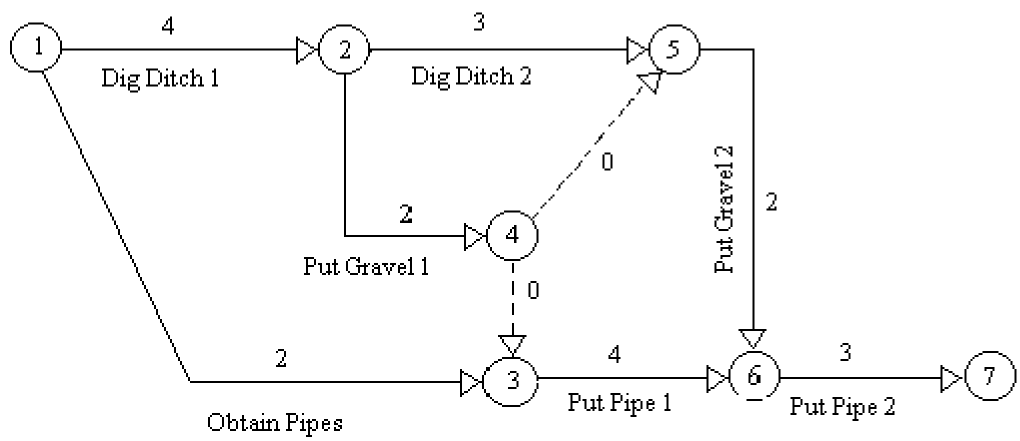


Figure 5-1 Critical Path Method. Installation of two underground pipes

Variables graphs. When the conceptualized system is described in term of variables it may be useful to represent their relationships using a digraph in which the nodes are variables and the arcs indicate their dependence. Each variable, in which node some arcs arrive, depends on the variables in which such arcs originate. See Exercise 14, Fig 5.

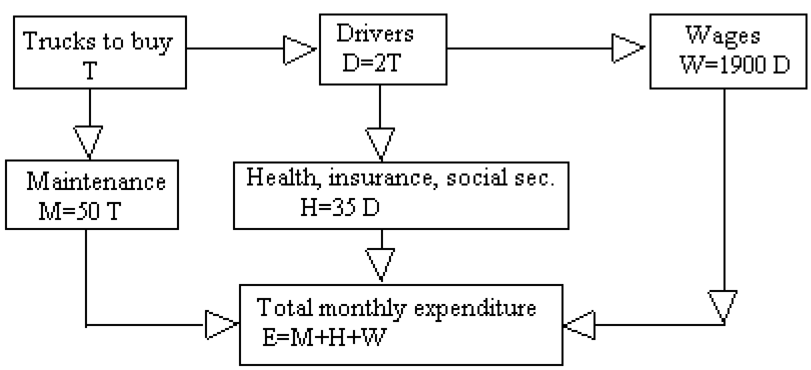


Figure 6-1 Impact of buying T trucks

Dynamic systems graphs. They are variable graphs used to represent systems whose mathematical expression includes **relations between variables and its rates of changes**, i.e. ordinary differential equations. Symbols are provided by variables that describe accumulated values for some variables (**levels**), rates of change (**flows**) of the variables and their relations. Each language for **continuous simulation** has its particular type of representation. See Exercise 15, Fig.6.

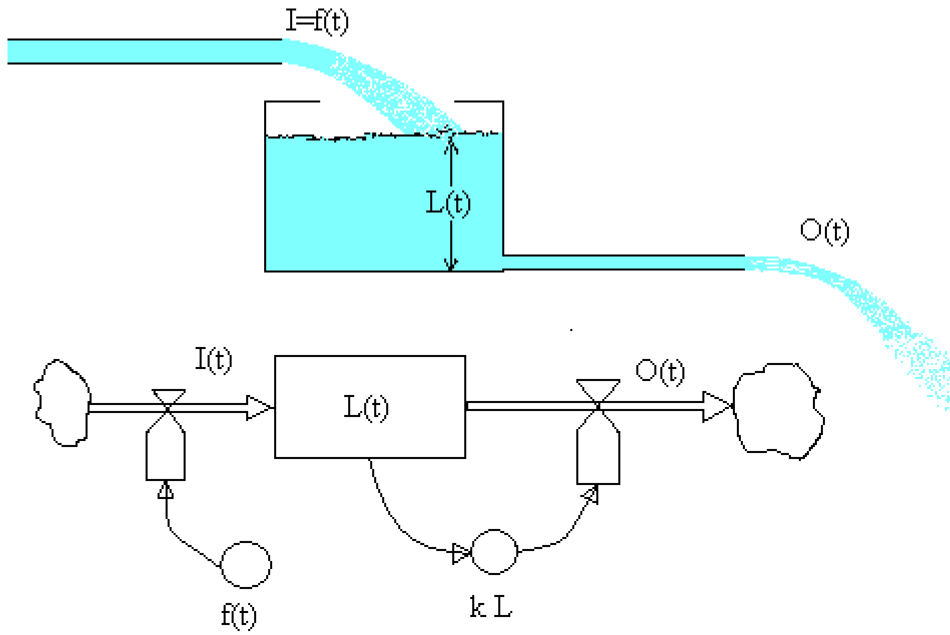


Figure 7-1 Tank with input and output. Schema and System Dynamics graph

Life cycles graphs. These graphs are used to represent the movement of entities through a set of subsystems. In each subsystem the entities and the subsystems interact and some of its properties change. The system may be a department store and the entities may be clients that flow through the different departments and sections, or the system may be an assembly line through which parts flow while they are assembled. Each language for **discrete event simulation** has its particular type of representation. See Exercise 16, Fig. 7.

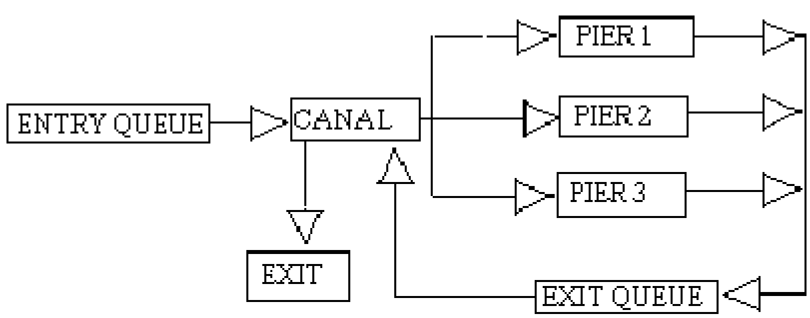


Figure 8-1 Port with three piers. Life cycle diagram.

Fish bone graph. In these graphs, a long arrow represents the main objective or process. Other arrows that fall upon the main arrow represent the factors or causes that influence that objective. Factors influencing each factor may also be added. The representation is used when a single result has multiple, rather independent causes, as frequently happens in social processes. See Exercise 17, Fig.8. The diagram may also be useful to represent the development of a system produced by the contribution of many factors like a branch of science, cultural resources, external influences, etc.

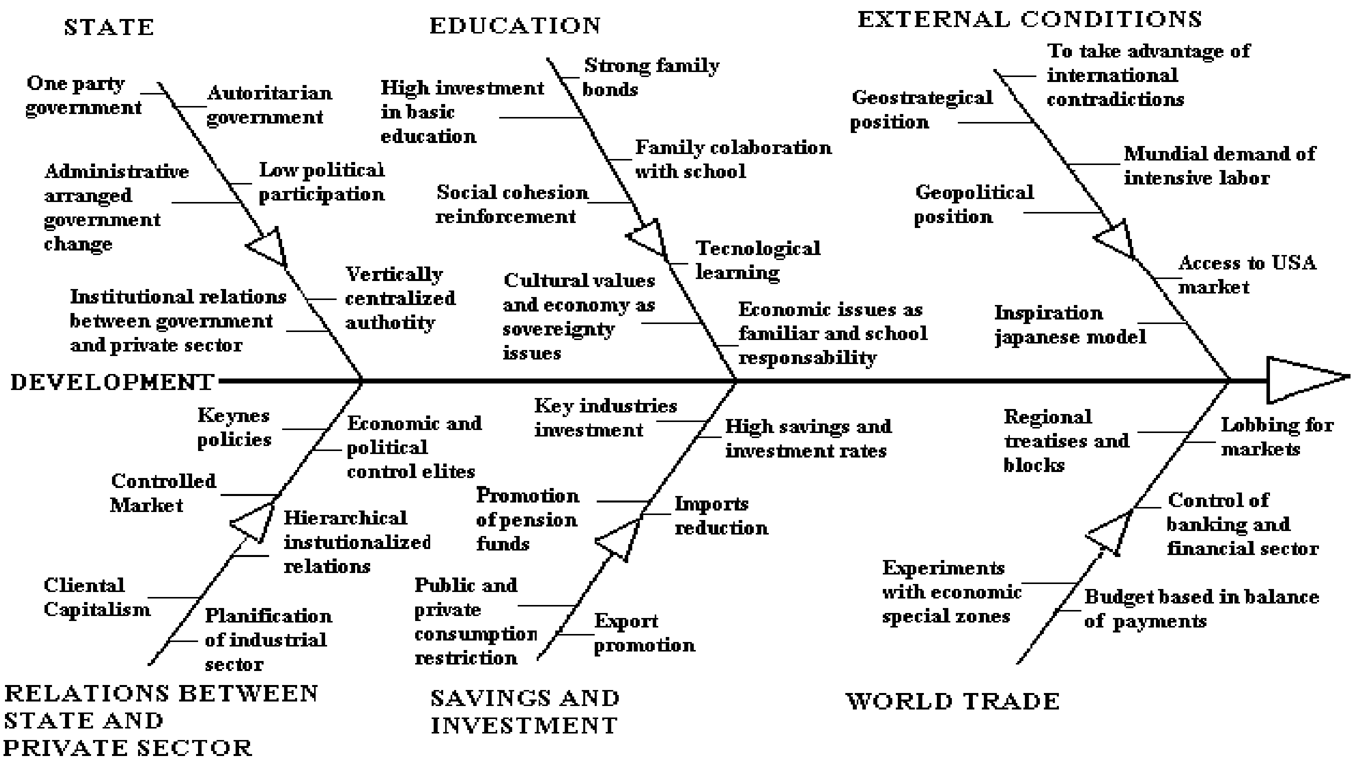


Figure 9-1 Developing plan for underdeveloped South Asiatic country

4. Matrices. Matrices are rectangular arrays of values. A value is determined indicating the number of the row and the number of the column in which the value is. So an array may be considered as a function of two integer variables. Matrices are used in system analysis to represent the binary relation between the elements of a finite set (numerated as the rows) and the elements of another (or the same) finite set (numerated as columns). A matrix is expressed by a name and the names of the two related sets, in subscript form or in functional form. For instance the elements of the matrix A that relate the elements of the sets I and J are represented by a_{ij} or a[i,j] where i ε I and j ε J. The value in the i row and j column represents the value of the relation of the i-th element of the first set with the j-th element of the second set. In particular a digraph of n nodes can be represented by a n×n matrix. If the i-th node has an arc towards the j-th node the [i,j] value of the matrix is 1, otherwise it is 0. The matrix representation of the graphic of a system has two advantages: firstly **it forces one to consider all the relationships between the elements** of the system, by exploring all rows and columns. See Exercise 18 Fig.9. Secondly, **it may be managed by algorithms** to find interesting properties of the graphic (number of connections of each node, existence of a path between two given nodes). If a flow of entities among some paths is specified, many important properties of the traffic can be found. The matrix may be transformed, changing the order of rows and column and this may be used to **decompose the system into loosely related subsystems**. See Exercise 19 Fig.10 .

In a graphic or matrix of a system it is important to discover **closed loops**, since they may correspond to causal chains that may produce stability or instability in the system. It may be also interesting to detect origins or **sources** (nodes without input) and ends or **sinks** (nodes without outputs) and the number of relationships of each node. In complex systems algorithms may be use to detect these characteristics. Arrays with more than two subscripts may be used to represent relations of many sets. (See Exercise 20).

1.3 A classification of problems

There are many types of problems and it is impossible a classification that claims to be exhaustive. An interesting one is based in which of the three main components (Input, System, Output) are known.

I and O known, to find S. When S exists, this is the classic problem of **experimental sciences** or **reverse engineering**. Applying known inputs to a system and observing the outputs, to determine the structure of the system. As it was seen (1.2.1) the solution is not well determined as the O depends not only of O and S but also on the state of S. The solution is not always unique, since different structures may produce the same O for the same I. If S does not exist, this is the problem of **system design**: to build a structure to obtain something given the actual resources or to design a procedure to transform a given situation in a desired one.

I and S known, to find O. Is the problem of the **deduction** or **direct calculus**. For example, given a circuit S and the voltages applied I, to find the resulting electric currents O. There are many solution methods depending of the particular system. In linear systems the solution is unique.

S and O known, to find I. If S exists this is the problem of **induction** or **inverse calculation** in sciences. For example: knowing the organism S and the symptoms O to determine the illness I. The solution is generally difficult and seldom unique.

O known, to find S and I. If O exists this is the problem of **observational science**. The geologist observes the relief O of a given area , from this he or she must imagine the original structure S and the perturbations I that produce the actual structure. If O does not exists this is the problem to **design a productive system and the necessary resources** to obtain some product or situation.

I known, to find S and O. It is, for example, the problem of using some available resource I, the obtained product O and the system S to produce the transformation must be find. The solution is usually not unique.

S known, to find I and O. It is, for example to invent a new use for a known structure.

EXERCISES

1. An arbitrary part of an organism (like a part of a living being, a city, a river, a branch of a tree, etc.) is usually a bad delimitation of a system. Why?

2. A monopolistic enterprise may fix the expected sales and the prices of its output. However, because the market does not fix price, the customers adjust their purchases to their income. So the sales depend on the prices. What must be included in the system?

3. An animal consumes oxygen and produces carbon dioxide. These inputs and outputs may be considered each one as dependent only of the activity of the animal.

What happens if the animal is enclosed in a small closed place. What must be included in the system?

4. A dam receives water from two inputs: a river and a channel originated upstream in the same river. This last contribution depends on of the first one. What must be included in the system?

5. An industrial plant emit two pollutants in a river. They react producing a gaseous contaminant. What process must be included in the system to estimate the pollution?

6. Enumerate the undesirable outputs of a carbon quarry.

7. An electric circuit consists in a battery of $E=10V$ connected to a resistor of 10 **Ω**. In parallel with the resistor there is another resistor in series with a switch. The system has two states according to the state of the switch ON or OFF. Find the output (total current I) in each state.

8. Represent in a Cartesian graph, for the exercise 7, the relation between E (as independent variable) and I, showing that it is not a function.

9. Consider a port, in which the following activities take place: charge and discharge of merchandises (essential activity) supply of fuel to ships, sanitary control, reparation and maintenance of ships, immigration control, custom activities, workers activities, storage of merchandises, reception and delivery of imports and exports, sedimentation control (dredging), port pilots and tug activities, passenger attention, smuggling, handling of dangerous materials, etc.. Ports require also a lot of supplies and produce some kind of pollution that must be controlled. Give arguments and examples to show that to improve the port operation it may be useless to improve the activities, even the essential ones. What is important? Why is the system approach necessary?

10. Which may be the difficulties of making a model of economic competition?

11. Complete the system graph representation of a port Fig. 7. Including some of the activities mentioned in 9.

12. Complete details in the flow diagram for a program for payroll Fig. 3.

13. Fig.4 describes the activities of the construction of a drainage. The time that each activity takes is indicated. From this the duration of the whole task can be estimated. The set of activities whose delay will delay the total time can also be determined (critical path). Make a similar diagram for the construction of a small deposit or other system that you are familiar with.

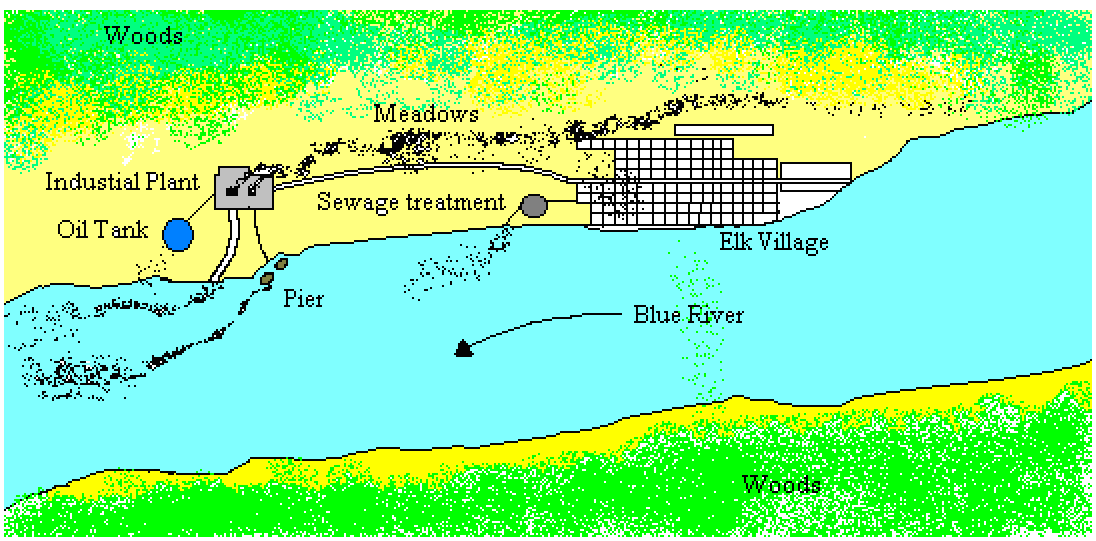
14. Fig. 5 describes the impact of the acquisition of T trucks; in a small enterprise. Add details.

15. Fig.6 describes the graphic representation of a system in System Dynamics graphics (Dynamo Language). The system is a water tank whose input (a flow) depends on time and whose output (a flow) is proportional to the level in the tank. Add to the graphic another tank, whose input is the output of the first one and it has constant output. In this last tank, when the level exceeds a certain value L_m a part of the excess goes back to the first tank.

16. Fig. 7 describes the life cycle of entities (ships) in the system (port) described in Exercise 11, with the icons of the GLIDER language. The figure corresponds to different sections of the program to simulate the system. Modify the diagram for a port with two canals, one entry and one exit canal.

17. Fig. 8 describes the factors brought on or considered to develop south Asiatic countries (see Cejas 2001). Make a similar diagram (fish bone diagram) for the development of another national economy or a complex institution.

18. Fig. 9 is a matrix describing ecological impact of an industrial plant near of a small town. The matrix consider the impacts and the receptors. Add other impacts and describe the impact type in each element of the matrix. Some impacts, that do not proceed from the industrial plant may be added to establish comparisons and detect interactions. The matrix may be generalized including interactions between impacts and processes generated for the impacts that, once established, maintain by themselves (regresive erosion is an example). These matrices called APR (Actions, Processes, Receptors) may be very useful in the analysis of ecological impacts. See C.Domingo 1997.



	lue River	/oods	Ieadows	lk Village	tmosphere
Smoke		X	X	X	X
Pier	X				
OilTank	X		X		
Sewage	X		X		X

Figure 10-1 Impact Matrix (Actions-Receivers). Contamination from Industrial Plant

19. Fig. 10 shows the partition of a graph in quasi-independent sub-graphs using matrices. Imagine a method to rearrange the matrix. It may be very complex. Design an algorithm to detect the important properties of the graphic mentioned in the text.

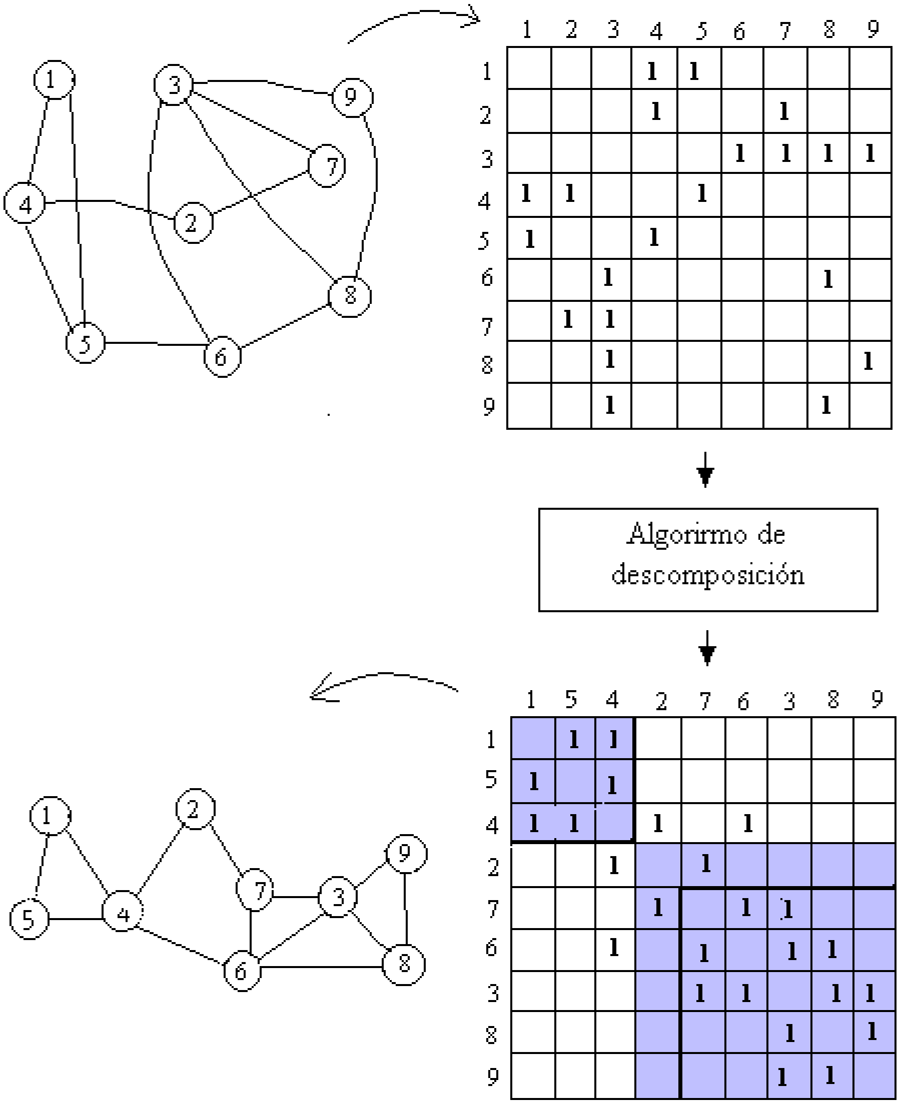


Figure 11-1 Decomposition of a graph using a matrix

20. In a sociopolitical model there are many actors (institutions and social groups) that have different attitudes, from strong support (+3) to strong opposition (-3) to a list of solutions about many issues. Design a three subscripts matrix to represent those opinions. How can it be used to give a measure of the agreement or disagreement of two actors?

21. Select a problem related to a complex system. It may be ecological, economical (regional, urban, national, international), industrial, social, biological or physical, and apply the system analysis to design a model.

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