Chapter 2

TECHNOLOGICAL SYSTEMS

MAJOR CHAPTER OUTCOMES

- You will be able to define and differentiate between a 'System', a 'Technological System', and a 'Complex System'
- You will be able to model structure of a system with a system diagram
- You will be able to distinguish between simple and complex systems
- You will be able to identify subsystems, components, parts and internal or external interface that exist in a complex system
- You will be able to model complex systems using subsystems, components and parts etc.
- You will be able to identify and explain, in general, the steps used in system development process
- You will be able to solve simple problems with tools used in management such as WBS or CPM etc.
- You will be able to identify various tools used in decision making process during the system development process

The world is made up of objects, living or non living; big or small. These things *interact* with each other and with the surrounding environment, working towards achieving c*ommon goals*. Their existence, in most of the cases, depends upon their *interaction*.

Figure 2-1: Co-existence of things in this world depends upon each other to survive

Imagine ourselves; we need air & water to live, materials to build shelter and to protect ourselves. Drinking water is available to us through rivers etc. To fill up rivers, sunlight is needed, so that clouds are made and there is rain. This hydrologic or water cycle is shown in figure 2-2.

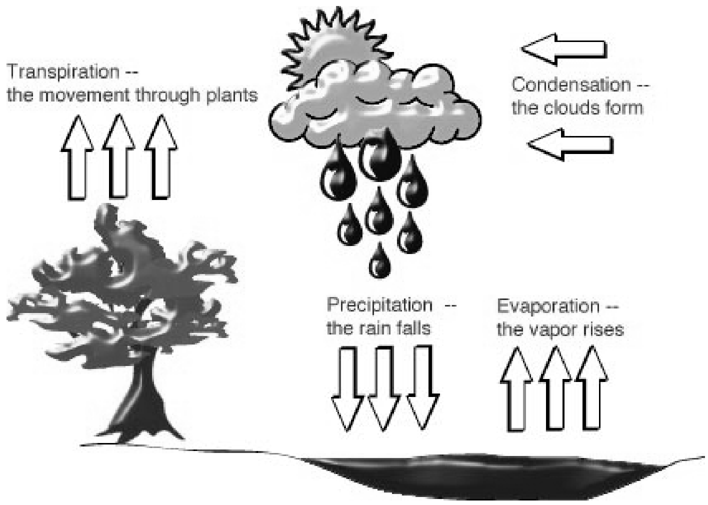


Figure 2-2: Hydrologic cycle

Let us think of a city. One of the fundamental aspirations of a city is to provide a restful place where all necessities of life are made available at a single place. A city, (Figure 2-3), is made up of people, buildings, roads, water distribution system, electricity distribution system, gas supply system, telephone network, healthcare system, municipality and so on. All of these can be considered as building blocks of a city and are equally required for its sustained functioning and existence.

These building bocks interact with each other. Electricity is needed for lighting, appliances etc. provided by electricity distribution system. Cooking and heating needs gas supply system to provide gas. Even some of the electrical power plants need gas to run; while gas supply systems need electricity to run pumps for its network.

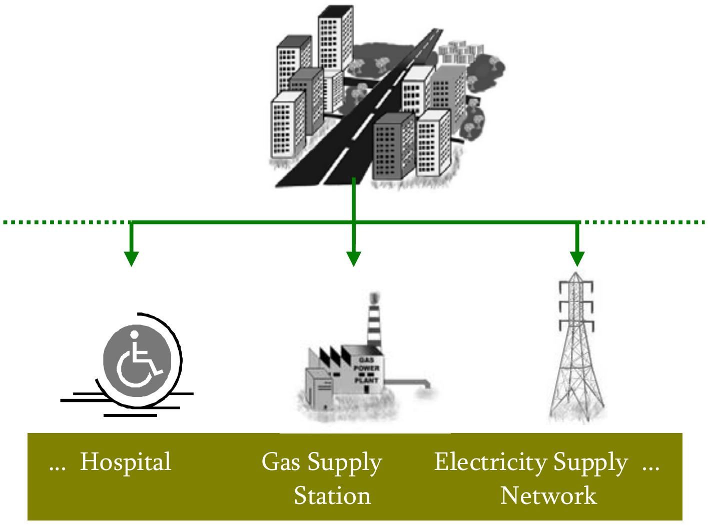


Figure 2-3: Building blocks of a city

Whether we look at entities in nature such as 'a hydrologic cycle' or something that we have built like a city, there exists a similar makeup or structure that exists within them. We will try to set apart and recognize this common structure or makeup in this chapter. This common structure is what we call a **system**.

'SYSTEM' DEFINED

The word system has a very broad meaning. It has been defined in many different ways. The most frequently used descriptions of a system are:

A set of interrelated components *working together* to accomplish common aims & objectives

A system is an entity that maintains its existence through the mutual interaction of its parts.

Multiplicity of interacting parts that collectively work towards a common goal.

A collection of entities or parts that are *linked and interrelated* such as hydrologic cycle, cities, and transportation modes.

Collection of workers, management, machines, processes, etc. that *work together*, e.g., to provide some major infrastructure's services (e.g., water distribution system, buildings, electrical system).

The main factor that comes to light repeatedly in all of these definitions is the *mutual interaction* or *working togetherness* that is taking place between the elements of a system. This mutual interaction over a period of time is what that is maintaining a system. If these interactions seize to exist over a period of time, the system will break apart and loose its life.

This mutual interaction gives rise to a very important characteristic of a system known as **emergence** or **synergy** — the properties that a system demonstrates can be entirely different from the properties of the constituent elements. For example, Sodium Chloride or table salt, a harmless salt used daily in our food, is made up of highly reactive *metal* called sodium and a poisonous *gas* called chlorine. The properties that table salt has vanishes if the two elements are separated form each other.

Classifying System

Systems may be classified into a number of ways. Following discussion is on classifying and comparing various types of systems.

Natural vs. Artificial or Man-Made Systems: **Natural systems** are those systems that exist as a result of natural processes. For example, 'the weather' which is driven by various factors present in nature. **Artificial** or **Man-Made systems** are systems developed by people. Examples can be cities, factories, transportation systems, computers, internet etc.

Static vs. Dynamic Systems: A **static system** has a structure but there is no change or activity over a period of time for example a building or a bridge. On the other hand, **dynamic systems** show varying behavior regularly over time. A city, a manufacturing or chemical plant, an automobile, weather, human bodies are examples of a dynamic system.

These systems vary in their complexity. For example an atom, a molecule, a cell, an organ, a person, a community, a state, a nation, the world, the solar system, the universe, is one such example demonstrating increasing level of complexity. Let us examine some of the systems around us and try to understand the significance of the mutual interaction that exists within those systems.

Examples of a system

Atom is an example of a natural system. An atom is made up of electrons, protons & neutrons, shown in figure 2-4. If we separate these particles, the system known as "atom" will collapse.

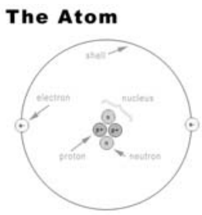


Figure 2-4: A Helium Atom

Water is another example of a natural system. Water is made up of hydrogen and oxygen. If there is no interaction between the two, we have two separate *gases* with different properties (e.g., both are gaseous at room temperature. Hydrogen is a combustible gas while oxygen is required in combustion). If hydrogen and oxygen interact, they will form water with a new set of properties (e.g., the state of water is liquid at room temperature and it is used to extinguish fire) that were not present in hydrogen or oxygen.

Technological systems, as mentioned earlier, are man made systems. For example, an airplane and a car are technological systems for traveling from one place to another. A telephone is a technological system that let us communicate to people far from us. Our main focus, in this book, is on these technological or what is also called engineered systems. A technological system can be a **simple system** e.g., water well with a rope and bucket to lift water, or it can be extremely huge and complex such as a dam, a skyscraper or a space satellite etc. In spite of the extent of size or complexity, all technological systems are similar in one way i.e., each has similar underlying structure.

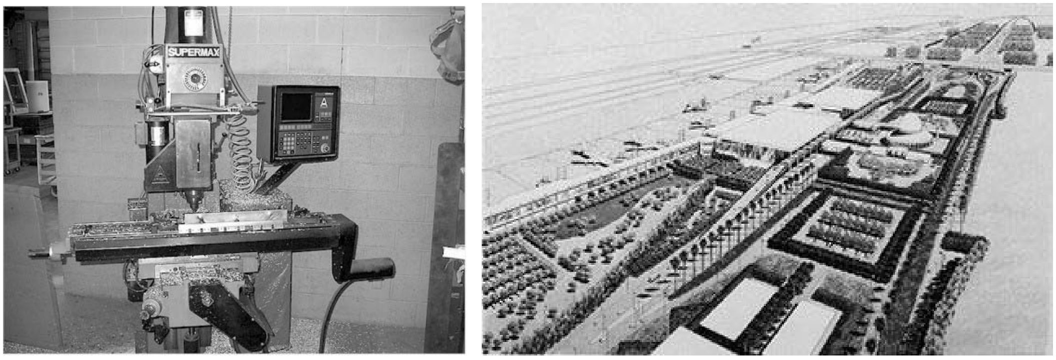


Figure 2-4: Man made technological systems
a) A CNC drilling machine in the left picture
b) Dammam airport in the right picture

Structure of a System

The basic elements, which make up this structure, are few. Let us now try to learn about these elements or components and there interactions with each other.

All systems have three basic components. These are **input**, **process** and **output**. This is shown in figure 2-5. The figure shown is also known as **basic system diagram** which is one of the ways to *model* or represent any system. In this system, a process takes *inputs* which may consist of *resources* to fulfill the task; *instructions* such as commands, *desired output*, etc., does some function or *process* on these inputs to yield *some output*.

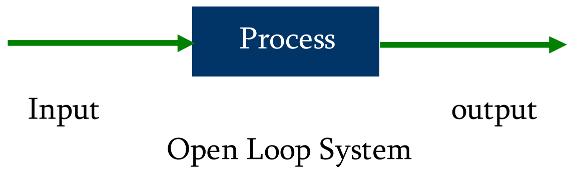
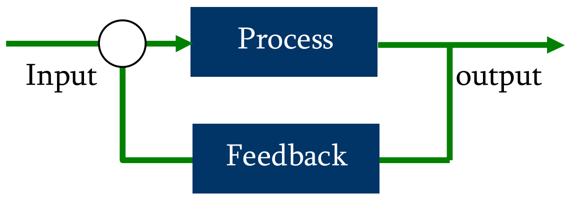


Figure 2-5: Basic System Diagram of an open loop system

The model of a system shown in the figure 2-5 is known as **open loop system**. An open loop system is defined as a system that has no means for comparing the *actual output* with *desired output* so that some corrective actions can to taken by the system. Control of open loop systems often requires human intervention. Example of an open loop system can be car speed controlled manually by observing the speed through speedometer and adjusting the amount of fuel being fed into the internal combustion engine by changing the pressure on the accelerator of the car. A cellular phone is another example of an open loop system. In this case, a loop begins with an incoming call or when a person dials a number, connects to the telephone network, and continues to transmit signals until a human turnoff the connection. As can be seen, the system cannot control itself. It does not have any means within to judge whether the output is the same as the desired output or not, consequently it cannot do anything to correct itself.

As opposed to an open loop system a **closed loop system**, as can be seen in figure 2-6, uses one more component know as a **feedback** to measure the output and circle it back to the input so that after comparing it with the desired output, rectifying instructions or commands can be given, if required, as new inputs to the system. In fact, in the example of an automobile speed given above the fourth feedback component is added, by the human intervention, to make the system work under controlled conditions. A very good example of closed loop system is of human body that keeps the temperature of a body at 98.6° F. The body reads its temperature through natural *sensors*, gives its feedback to the brain, which in turn acts accordingly by starting sweating or shivering, to increase or decrease the temperature, as required by the body.



Closed loop Systems

Figure 2-6: Basic System Diagram of a closed loop system

A system may have more than one input and more than one output as shown in figure 2-7. For example a coal power generation plants *primary* output is electricity. But besides electricity it is also outputting other things such as smoke, noise etc. Another output of the plant is heat generated, sinking into the atmosphere or thrown out with heated water, which is not utilized in electrical power generation. The main input for the power plant are coal, water, and other resources etc. required to run the plant.

Figure 2-7: Multi-input & Multi-Output System

COMPLEX SYSTEMS

When we talk about technological systems we often come across with systems that are *complex* in nature. The term **complex systems** refer to as systems in which the elements are *varied* and have *complex or convoluted* relationships with other elements of the system. The systems which are not complex in nature generally involve fewer engineering disciplines e.g., a washing machine is an electro-mechanical system. Now let us examine an example of a complex system i.e., a space satellite. To develop and operate a space satellite a vast spectrum of technological knowledge ranging from mechanical to electronics, computers to astrophysics, controls to signal processing is required. Examples of some complex technological systems, signifying the three basic components, are illustrated in table 2.1 below.

System	Inputs	Process	Outputs
Weather Satellite	Images, Signals	Data Storage, Processing & Transmission	Processed Images
Airlines Ticketing System	Travel Requests	Data Management	Reservation & Air Tickets
Oil Refinery	Crude Oil, Catalysts, Energy	Cracking, Separating & Blending	Petrol, Diesel & Lubricants etc.

Nuclear Power Plant	Fuel (uranium), heavy water	Fission Reaction, Power Generation	Electric AC Power
Road Cargo System	Cargo Request	Map Tracing, Communication	Routing Information, Cargo Delivery

Table 2.1: Examples of Complex System

The materializations of most recent technological systems are strongly driven from advances in technologies and are increasingly falling under the category of complex systems.

If we look at above examples of complex systems and try to model it using basic system diagram, it is clearly explicable that the representation is indeed deficient of any meaningful understanding of such a system. Even a system that can be categorized as a simple system, it is mostly insufficient to model it using simply the basic system diagram shown earlier. To accommodate this shortcoming of the basic system diagram, let us look at a more elaborate way to model such complex systems.

Modeling a complex system

In order to begin modeling a complex system, the first thing we need to understand is what is known as *scope* of a system. The idea of scope defines the boundaries of a system. It is used to identify and encompass all the elements and their relationships necessary to form a system. Identification of the boundary of a system is vital so as to make it precisely clear what is inside and what is outside the system. Elements outside of the system boundary that are interacting with the system form what we call a **system environment**. Typical system environment is made up of system operators, operational maintenance and support systems, shipping and handling environment etc. The concept is illustrated in figure 2-8 below

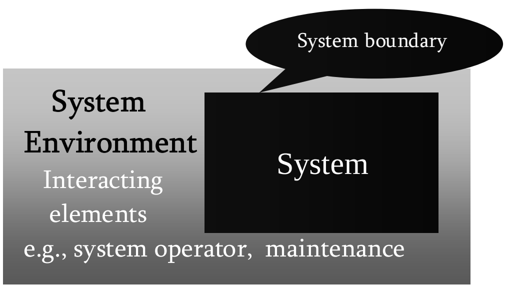


Figure 2-8: System Boundary and System Environment

As an example consider an intercity passenger transportation company as shown in figure 2-9 below. The system has various elements such as buses, ticketing system, bus terminal management system etc. The system interacts with its environment which is made up of road network, operators (bus drivers etc.), and traffic police and so on.

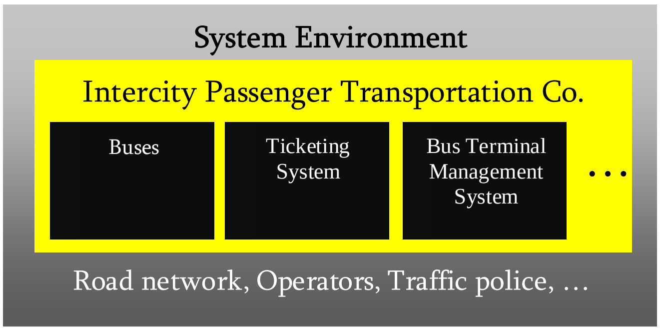


Figure 2-9: Intercity Transportation System

As seen in the example given above we can, not only define various systems and its environment by clearly identifying the system boundaries, but also can identify systems within a system based on the scope of our interest. For example, although buses terminal management system is an element of the bigger intercity passenger transportation system, here it is identified as a system by identifying its scope and consequently its boundary. Having understood this example, we have a new hierarchy or structure appearing for modeling such complex systems. Let us try to identify and illustrate the structure of modeling a complex system.

By character, complex systems can be made up of a number of major interacting elements, usually known as **subsystems** which themselves generally satisfies the definition of a *simple system* and are composed of further more simple working elements down to *primitive elements* such as gears, pulleys, buttons, resistors, and capacitors etc which are usually referred to as **parts**.

The architecture (see figure 2-10) shows the structure and terminologies used to model a complex system. As can be seen, the highest level is known as a *system* having the largest scope. This is followed by a number of subsystems with smaller scope. Collection of all these subsystems makes a system. Each subsystem is made up of **components**, each component has a simpler functionality as compared to a subsystems. These components are the first to provide a significant functionality. For this reason, the components are considered to be the basic system building blocks.

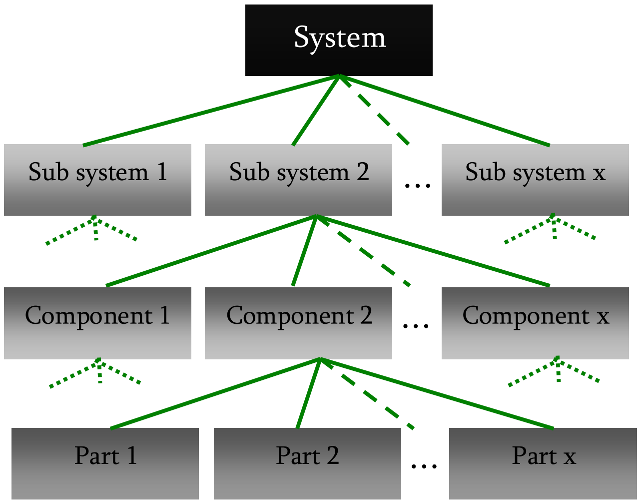


Figure 2-10: Architecture of a Complex System.

Let us divert our attention for a moment and define something that is necessary to describe a component. This is known as a **functional element**. As the main purpose of a system is to alter the three basic entities on which a system, generally, operates. These are **information, material & energy**, which provide us a good basis to classify principal functional elements. These are:

1. Signal (A system can generate, transmit, distribute and receive signals used in sensing and communication)
2. Data (A system can analyze, organize, interpret, or convert data into forms that a user desires)
3. Material (Provide structural support for a System. It can transform shape or composition of materials etc.)
4. Energy (Provide energy to a system).

Components are defined as physical embodiment of these functional elements which can be classified in six groups as shown in figure 2-11. These six categories are Electronic, Mechanical, and Electromechanical, Thermo-mechanical, Electro-optical and software.

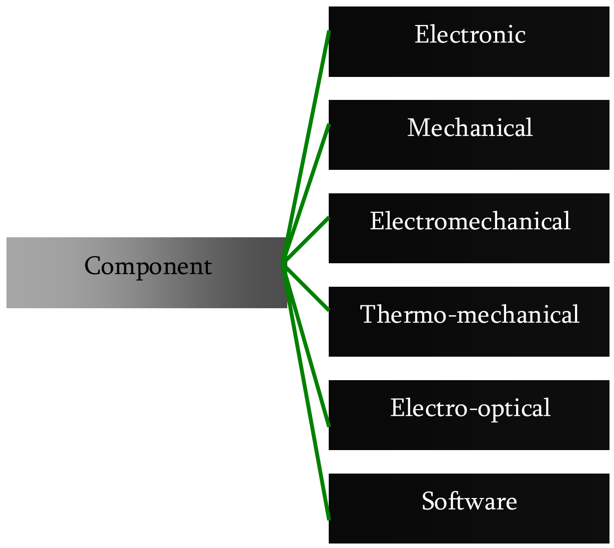


Figure 2-11: Classification of Component

Each of these six categories has further sub-classifications. These classifications with examples and their functions are presented in table 2.2. The table gives us a good idea about what unit to identifying as a component within a system.

Category	Component	Function
Electronic	Receiver Transmitter Data processor Signal processor Other devices	Receive signal Transmit signal
Mechanical	Structure Power transmitter device Other devices	Support material Transmit power and control motion
Electromechanical	Electric generator Transducer Other devices	Generate electricity Transduce signal
Thermo-mechanical	Heating unit Cooling unit Other devices	
Electro-optical	Electro-optical sensor Display device	Input signal Output signal/data

	Other devices
Software	Operating systems Application programs Other programs

Table 2.1: Detailed Classification of Components

Figure 2-12: Components of a system
a) A modem used in PCs
b) Speakers Used in Car Audio Systems
c) Fuel filter of an Engine
d) Truss: A structural Component of a Building or Bridge

The lowest or the most primal level in a system is known as parts (see figure 2-13). A part in itself does not have any functioning but are required to put together components. Examples of parts are Electronic: LED, resistors, transistors; Mechanical: gears, ropes, pulleys, seals; Electromechanical: wires, couplings, magnets; Thermo-mechanical: Coils, valves; Electro-optical: lenses, mirrors; Software: algorithms etc.

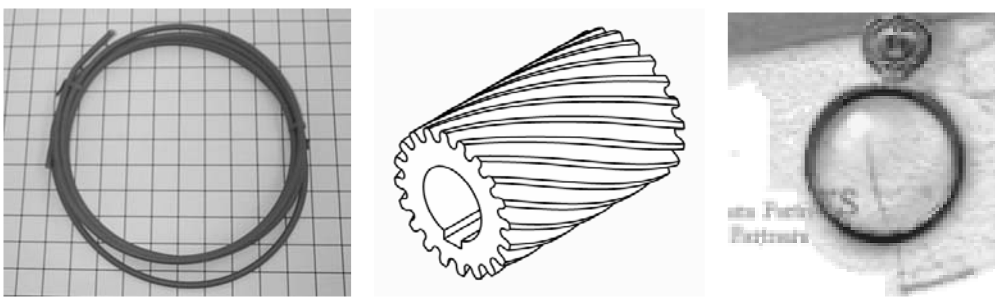


Figure 2-13: Part of a System
a) A copper wire
b) A helical gear
) An Optical Lens

Interfaces & Interactions

As seen earlier, a system has to interact with its environment including other systems. All of these **interactions** occur at various boundaries of the system. Such boundaries are known as **external interfaces**. The definition and control of these external interfaces are extremely important in the functional well being of any system. There are also interactions that occur at the boundaries between individual components of a system. These interfaces are known as **internal interfaces**. Interaction between two individual elements of the system is affected through the interface. Consider example of a car steering system. Interface between a car steering wheel and the driver's hands enable a driver to interact with the car by transmitting force that turns steering wheel and consequently the car. The example shows how functional interaction (guiding a car) is affected by physical interaction (turning wheel by force) using physical interface. There are three types of interface that may occur in a system. These are:

1. *Connectors*: connectors facilitate the transmission of physical interaction e.g., transmission of fluid through pipes or electricity through cables etc.
2. *Isolators*: Isolators impede or block physical interaction e.g., rubber cover over copper wire etc.
3. *Converters*: converters alter the form of the physical medium e.g., pump changes the force in a fluid etc.

More examples of interfaces along with type of physical medium is given in table 2.3

Type (medium)	Electrical (current)	Mechanical (Force)	Hydraulic (Fluid)	Human-Machine (information)
Connectors	Cable, switches	Cam shaft, connecting rod	Value, piping	Control display panel
Isolators	Insulator	Bearing, shock absorbers	Hydraulic Seal	Window shield
Converters	Transformer, Antenna	Crank shaft, Gear train	Pump, nozzle	Software

Table 2.3: Examples of Various types of Interfaces

The discussion so far highlights all important aspects to model an existing system. Modeling a system gives a far more insight into its functioning and eliminates misperceptions about how it interacts with the environment, its working and reason for sustainability, growth and existence.

SYSTEM DEVELOPMENT PROCESS

Developing a *new system* is a complex effort that requires several interrelated tasks. Such systems usually evolve over a longer time period, starting from, when the need is identified through the development stage to its final operational use and support efforts. This whole complex effort is referred to as **system development process** that can be summarized with an acronym known as **SIMILAR**.

1. *State the problem.* Stating the problem is the most essential task in system development. It entails recognizing customers, appreciating customer needs, establishing the need for change, delineating requirements and defining system functions.
2. *Investigate alternatives.* Alternatives are explored and evaluated based on criteria such as performance, cost and risk.
3. *Model the system.* Modeling the system sheds light on requirements, reveals bottlenecks and fragment activities, reduces cost and exposes replication of efforts.
4. *Integrate.* Integration means designing interfaces and bringing system elements together so that they work as a whole. This requires massive communication and coordination efforts.
5. *Launch the system.* Launching the system means operating the system and generating outputs -- letting the system do what it was intended to do.
6. *Assess performance.* Performance is assessed using output data -- measurement is the key. If output data cannot be measured properly, than system cannot be judged appropriately and consequently there will be no right curative actions.
7. *Re-evaluation.* Re-evaluation should be a recurrent and iterative process, available throughout all of the stages of SIMILAR in system development process. See figure 2-13.

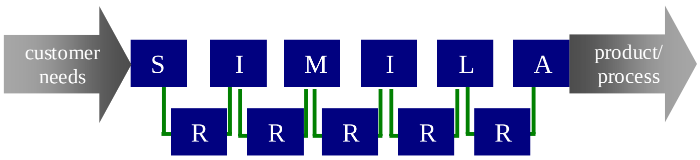


Figure 2-13: 'SIMILAR'. The system Development Process

System development process can be achieved through a mechanism called **system life cycle**. System life cycle is referred to as the stepwise realization of a new system from conceptualization through development and so on to, production, operation, and to final disposal. There are several system life cycle models presented in the various texts. We will look at the system life cycle models know as ISO/IEC 15288, National society of professional engineers (NSPE) model and the more elaborate systems engineering (SE) model. Table 2.4 demonstrates the ISO/IEC 15288, NSPE and the SE model.

As can bee seen, all of the phases shown in the three models are related. The most detailed and elaborate model is the SE model. We will describe this model in detail.

<table>
<tr><th colspan="9">ISO/IEC 15288 MODEL</th></tr>
<tr><td colspan="3">Concept</td><td colspan="3">Development</td><td>Production</td><td>Utilization</td><td>Support</td></tr>
<tr><th colspan="9">NSPE MODEL</th></tr>
<tr><td colspan="2">Conceptualization</td><td>Technical Feasibility</td><td colspan="2">Development</td><td>Production Preparation</td><td>Production</td><td colspan="2">Product Support</td></tr>
<tr><th colspan="9">SE MODEL</th></tr>
<tr><td colspan="3">Concept Development</td><td colspan="3">Engineering Development</td><td colspan="3">Post Development</td></tr>
<tr><td>Needs Analysis</td><td>Concept Exploration</td><td>Concept Definition</td><td>Advanced Development</td><td>Engineering Design</td><td>Integration & Evaluation</td><td>Production</td><td colspan="2">Operation & Support</td></tr>
</table>

Table 2.4: Various System Life Cycle Models

As in Table 2.4, SE model has three main stages i.e.,

1. Concept development stage
2. Engineering development stage
3. Post development stage

While the above mentioned three stages form the central subdivisions of SE system life cycle, each of these stages are further subdivided into stages that have objectives and activates of entirely varied nature. Now we will discuss each of the stages in detail.

Concept development stage

Concept development stage is made up of three sub-stages. These are

1. Need analysis
2. Concept exploration

3. concept definition

In **need analysis**, need for a new system is defined and validated. 'Clear definition' and 'through validation' of the need is an important factor and is extremely important. Developing a complex system consumes a lot of effort and resources and if this first step is worked out incorrectly the whole exercise would lead to failure and disaster. In this stage questions like 'Is there a genuine need for a new system?' etc. are asked.

Concept exploration involves investigation of feasible ideas and concepts. In this sage functional performance requirements are laid out and goals are set. The question answered during this stage are e.g., 'What performance is required from the new system?', 'Are there any feasible methods to achieve such goals at affordable cost?' etc.

The third stage in conceptualization also known as **concept definition phase**. In this step, preferred concept is selected. Key characteristics such as capability of the systems, operational life and cost etc. are set and estimated. In order to do that a number of alternative systems are compared and their relative performance, costs, operational utility, risks are compared.

The above three phase provide a firm ground to move into the next bigger stage of engineering development. As the next stage requires a lot of investment, fitting efforts in the above stages reduces the risk of failure and consequently prevents the loss of investment.

Engineering development stage

The main objective of engineering development stage is to wangle the system to perform functionalities, specified in earlier stages, in an economical and maintainable form. Engineering development stage has three sub-stages. These are:

1. Advanced development
2. Engineering design
3. Integration and evaluation

In **Advanced development stage**, concept development phase is furthered and all possible unidentified unknowns are unearthed. One of the main objectives in this stage is to identify associated risks, reduce those identified risks through analysis, development, and testing.

Engineering design involves preliminary and final engineering design of the system. It also takes in building and testing phase of hardware and/or software components. Issues such as reliability, ability to produce and maintain are of paramount importance in this phase.

The final stage of engineering development is the **Integration and evaluation** phase. In this phase all system components are integrated into production prototype or model, which is evaluated or tested, and any deviations or inconsistencies are rectified.

Post development stage

Third and final stage is divided into two main phases:

1. Production
2. Operation and support

In **production** phase, system is made available to user with facilitation of initial operations to produce system outcome.

The final phase of the post development stage and system life cycle is **operation and support** which defines all the details required to supports system operation and its continuous maintenance. Most new system evolves from some older systems. During all of the above phases, their functional structure or components can be utilized to reduce time, effort and investment.

Testing Throughout System Development

Developing a system, in itself, is a closed loop process in which testing or evaluation or feedback of the efforts done so far is an inherent part of the whole development process. Thus continues monitoring is done during all phases of system development so that the error at any stage can be detected without delay and rectification can be done at the spot to avoid any loss of time, effort or investment.

MANAGING SYSTEM DEVELOPMENT

One can envisage easily the exceeding complexities that arise during the system development process. Proper management of this system development process, therefore, is the key to the success of the entire effort. In this section, we will look at some of the principles and central elements indispensable for managing such convoluted system development process.

Work Breakdown Structure (WBS)

A major strategy in successful planning is to break up the project into small manageable fractions that can be separately planned, estimated and controlled.

An essential element of the management of system development process is known as **work breakdown structure** or **(WBS)**. WBS is a graphical tool in which tasks are identified, assigned, scheduled etc. WBS always starts with the concept development stage. It has a hierarchical structure splitting all tasks into a tree like structure. The WBS acts as a skeleton or framework on which the whole project or system development process can be implemented. Generally WBS is a contractual requirement especially in large projects.

Typically the role of WBS is to:

- Split the major project deliverables into smaller component
- Offer a means for collecting and organizing actual costs
- Provide a mechanism for performance measurement and control

Figure 2-14 presents an example of high level WBS of a software development project

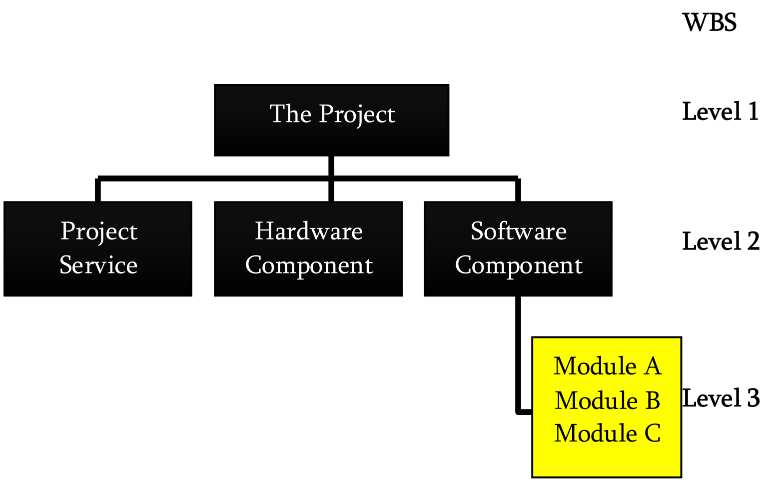


Figure 2-14: Work Breakdown Analysis Example

The box at the top level represents the system under development also known as level 1. Partition at level 2 is the major breakup of the project. Other lower levels are the further fragmentation of individual steps with increasing details and are numbered as 3, 4, and 5 and so on.

Cost Control and Estimation

Based on WBS, cost of individual tasks can be estimated, which in turn lead to the overall cost estimation of a project. Project cost control measures can then be applied by comparing the actual reported cost of a task with the cost estimated earlier. The actual cost of task may, invariably stray with estimated cost, but only those which deviate to a very large degree are identified, evaluated and cost control measures are applied.

Critical Path Method (CPM)

Critical path method is an essential project management tool that estimates not only the scale but also the duration of each major task or activity that undertakes during a project. A particular path is identified which is taking the longest time to complete its constituent steps during the course of the project. This path is known as the 'critical path'. This longest path also defines the total span or duration of a project.

With CPM it can be figured out that 1) how long it will take to complete a project 2) activates which are assumed to be *critical*, meaning that they have to be completed on time otherwise the whole project will be delayed. Hence all activates on critical path are assumed to be critical and focus on these activities are kept very tight in order to keep the actual time to be as close to the estimated time as possible. The resulting CPM *network* is an immediate application of WBS.

CPM analysis starts when you have a table showing each activity in your project. For each activity, you need to know which other activities must be done before it starts, and how long the activity takes. This table can be generated from WBS exercise as discussed in earlier section.

Here is an example: Set of activities along with the required predecessors and time required as show in table 2.5 below. Each activity has been labeled by a letter. Description of the activity is also shown in the same table. For example first activity is 'A', which is 'product design'. Since it is the first activity, therefore 'none' is mention in the 'predecessor activity' column. Duration for 'A' activity is 5 months.

Activity	Description	Required Predecessor	Duration
A	Product design	None	6
B	Market research	None	2
C	Production analysis	A	3
D	Product model	A	4
E	Sales brochure	A	3
F	Cost analysis	C	4
G	Product testing	D	5
H	Sales training	B, E	3
I	Pricing	H	2
J	Project report	F, G, I	1

Table: 2.5: Set of Activities to be performed

First step, after creating the above table of activities, is to create what is called a network diagram. In order to create or understand a network diagram, few symbols or network elements are needed to be understood (See figure 2-15). In this figure a circle is known as a node. A node indicates start or ending of an activity. It also represents project landmarks. Each node has a number for identification. The other element is an arrow which represents an activity along with the time that an activity takes. No activity, can start from a node, until all activities, entering the node, are finished. This network diagram is also known are AOA diagram or 'Activity-On-Arc' diagram.

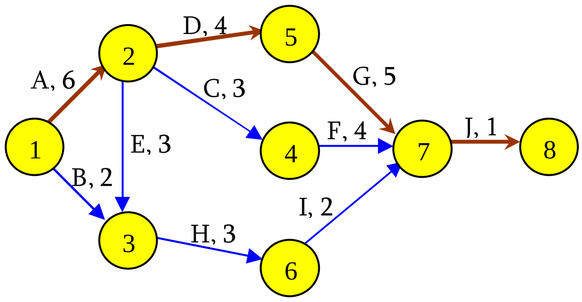


Figure 2-15: Critical Path Analysis

Few important rules to draw above diagram are:

1. Number of starting node is always 1.
2. All activities with no predecessor come off of node 1.
3. All activities with no successor points to the last node, which has the highest number.
4. There could be only one starting and one ending node.
5. No activity from a node can start until all entering activities are finished.

Identifying and evaluating time taken by all the possible paths we have following results: (Considering only put to node 7)

	Path	Time	Status
1	A→D→G	6+5+5 = 16	Critical
2	A→C→F	6+3+4 = 13	
3	A→E→H→I	6+3+3+2 = 14	
4	B*→H→I	3*+3+2 = 8	

Table 2.6: Critical Path Analysis

As can be seen from the table 2.6, path A→D→G is taking the longest time hence considered as 'critical path' for the project. So if any of these activities is delayed, even by a small period of time, the whole project will be delayed. An important point to note during calculation keeping rule 5 in our minds, is that in path number 4 although activity B needs 2 unit of time to finish but in time estimation 3 unit of time is used because activity A is also entering node 3 which is taking 3 units of time.

After identification of critical path focus on this path is kept to make sure that all activities are completed without any interruptions or delays.

DECISION MAKING TOOLS

In all of the preceding sections, it is obvious that a lot of decision making is involved throughout the system management and development processes. Most of these include uncertainties, incomplete requirements, complex technical factors, labor & human resource issues and other managerial issues to solve. In this section, we will look at some of the tools that are extremely useful and effective in such difficult decisions. The tools are mainly classified into three categories. These are:

1. Modeling
2. Simulation
3. Trade off Analysis.

Modeling

Modeling is a tremendously helpful tool in the decision making process. In modeling, instead of creating the actual system, a model is used instead. Here a model is defined as the simplified representation of the actual system. Modeling is especially useful in cases where actual system is either very expensive or time consuming to build or hazardous or unsafe. Example of such a system is building an airplane etc. The cost of failure or the cost of testing the actual systems in such cases is enormous. Modeling in such cases not only reduces the risks of failure but it also cost at which it is done.

Following are some modeling techniques commonly used in system management and development processes.

Scaled Models and Prototypes

Scaled models are small scale version of the actual system. They are used where physical appearance of the system is needed to be visualized and tested such as a building or a car. Prototypes on the other hand are full scale version of the system which generally contains all of the properties of the operational system.

Figure 2-16: A Wind Tunnel Experiment
Courtesy Aerospaceweb.org

Another of the vastly used application is in aerospace or automobile industry where scaled models are tested in what is called 'Wind Tunnels' (see figure 2-16) where various properties such as air resistance, or amount of lift generated on the winds etc. are tested.

Mathematical models

Mathematical model represents system functionality using mathematical equations. They help us understand complex systems. For example: the following mathematical model represents a piston and cylinder example (see figure 2-17) where air is filled in a cylinder.

$$Pressure_1 \times Volume_1 = Pressure_2 \times Volume_2$$

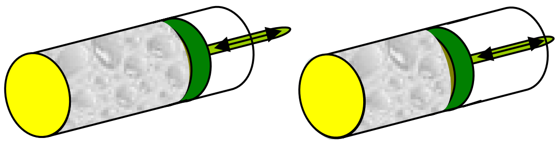


Figure 2-17: Pressure Vessels

Piston can move to and fro as indicated by the arrow directions. As the piston moves in or out, the pressure of the gas filled inside will increase or decrease along with the volume changing in the opposite direction i.e., decrease or increase respectively. Now in order to determine the pressure at any given volume, if the piston position changes, the mathematical model can be used to determine the new pressure. For example: if initially the pressure and volume are: $Pressure_1 = 10\ N/m^2$ and $volume_1 = 10\ m^2$ and we have a changed volume of $volume_2 = 5\ m^2$ as the piston pushes inside the cylinder, we can calculate the new pressure using the mathematical model as follows:

$$Pressure_2 = (Pressure_1 \times Volume_1) / Volume_2 = (10 \times 10) /5 = 20\ N/m^2$$

Mathematical models are perhaps one of the most widely used modeling methods in technology.

Schematic Models

Architectural Drawings and Walkthroughs:

This modeling technique is extremely popular in construction. The owner of the project would like to visualize its structure, such as a building or bridge, before it is made. Architectural drawings are the answer to this problem. An example of an architectural drawing is shown in figure 2-18. With the advancements in computers and graphics technology, a new technique called walkthrough is becoming extremely popular in visualizing such models in a 3D animated form.

Figure 2-18: A 3D schematic of a Residential Area

Architectural Drawings and Walkthroughs, generally, keep the fine detail of the physical appearance. Even the environmental details such as lighting etc. are kept so that proper visualization can be done by the viewer.

System Block Diagram (SBD)

One of the simplest tools that are used in modeling a system is the **system block diagram** representing the relationships between elements of a system using a hierarchal tree structure. This structure is used earlier which is show again in figure 2-19 below.

The terminology used in this system block diagram is already explained in this chapter, earlier. System block diagram is the first

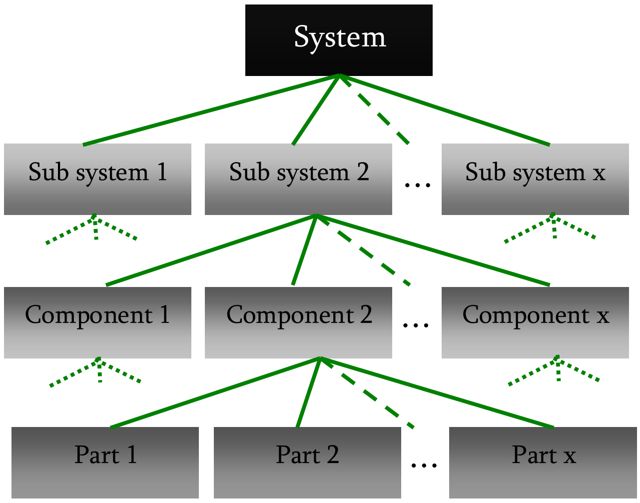


Figure 2-19: System Block Diagram

Functional Flow Block Diagram (FFBD) & Functional Flow Process Diagrams (FFPD)

System block diagram, as discussed previously, deals with the static and physical relationship that exists in a system. It does not illustrate the more significant characteristics of a system such as the behavioral response that happens with the changes in the system environment. This behavioral response depends on the function that a system can performs to such environmental inputs and constrictions. To model this functional behavior **FFBD** or **functional flow block diagram** is used. FFBD elaborates functional flow in a system.

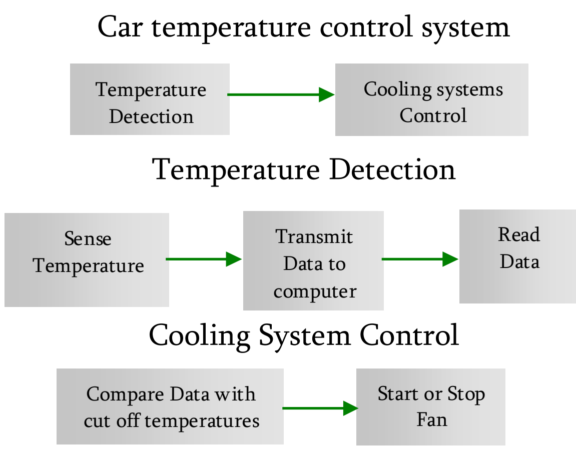


Figure 2-20: Functional Flow Block Diagram

Figure 2-20 shows example of functional flow block diagram for a car temperature control system. The system has two main functions: 1) Temperature detection and 2) Cooling Control. Each function is further explicated by FFBD discretely. FFBD is used to model functional behavior of a system or a system product. If the same diagram is used to model process it is called **Functional Flow Process Diagrams or FFPDs**. System life cycle model, as discussed earlier, is an example of FFPD.

Simulation

In spite of improved visualization given by FFBD and FFPD, most complex process requires some tools that would enable the developer to envisage the dynamic behavior of the system as they run. Simulation is a tool used most extensively for this purpose. It is the technique of representing the real system's dynamic behavior with the help of a computer program. A simulation imitates the internal processes and not merely the results of the system being simulated. For example, a system developer, designing a bank counter system can design the flow of customers using system FFBDs and FFPDs. However, he will still be unsure as to how it will behave in practice. Simulation will help him create the situation that can occur in the bank counter system with the help a computer simulation. Consequently, he will be able to predict better about the behavior of his system.

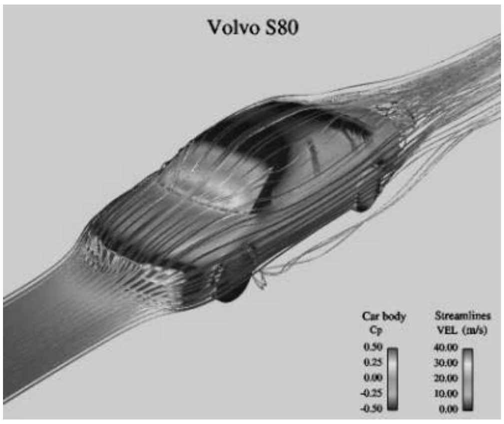


Figure 2-21: A Computation Fluid Dynamics Simulation of a Volvo S80
Courtesy Royal Institute of Technology Stockholm

Trade off Analysis

Trade off analysis is an approach used to analyze and evaluate various alternatives based on a set of criteria. Though informally, normally this is what we do, when we make decisions. We tend to compare the alternatives based on various criteria and select the one best suit the *overall* situation. It might not be fulfilling some of the criteria ideally, but the key word in our minds when we are making a decision is '*best overall fit*'.

A formal method of this trade off analysis will help us go through the same process more efficiently. Here are the steps that can be followed to do a formal trade off analysis.

1. Define objective of your trade off analysis. This step is carried out with *requirements analysis* i.e., identifying what is required from the solution. These requirements are best reflected in what is defined as MOIs or 'Measures of effecitveness'. MOIs are, generally, quantitative measures of the system requirements. For example one requirements of a bank customer counter system is that is must be designed to meet high customer satisfaction levels. Now for this requirement, one KPI could be customers catered per hour or CCPH by the system. Since CCPH is a number so we can score different systems based on how high CCPH this system is spawning.

2. Identifying the alternatives: To create a list of alternative, all possible courses of action, required to solve a problem, are needed to be identified. Any alternative that fails to comply with the minimum level of any fundamental requirement is rejected.

3. Comparing the alternatives: To decide, which of the alternative holds the most merit, all solutions are c\to be compared with respect to the MOIs. The relative merit of an alternative is judged by the cumulative score of all the MOIs. An important issue, regarding the MOIs is that each KPI may hold different magnitude of significance. To accommodate the scoring is done on weight bases. For example weight of one MOI may be twice that another i.e., first MOI is twice as important, in view of the developer, as the second one. Generally weights are decided during meetings by all system stakeholders.

Example of this trade off analysis is shown in the table xx below. In this example, the problem was to buy a fleet of trucks for a goods transportation company. A brand was to be selected. There are three MOI on which the decision has to be made. These are 1) Average maintenance cost per year, 2) Carriage volume 3) Engine horse power. The four contenders were 1) ABC motor company 2) MARS Motors 3) MAX Trucks 4) XYZ automobiles. The result is shown in table 2.7. The score is on the scale of 1-5

MOI (weight)	ABC Motor Co.		MARS Motors		MAX Trucks		XYZ Auto.	
	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Avg. Maintenance cost/year (100)	4	400	3	300	5	500	2	200
Carriage volume (80)	3	240	4	320	4	320	5	400
Engine horse power (70)	4	280	2	140	3	210	3	210
Total		920		760		1030		810
Cost		5000		5200		5400		5000
Weighted sum/cost		0.184		0.146		0.191		0.162

Table 2.7: Trade off Analysis

MAX Truck's weighted score is the highest amongst all which is 1030. However keeping cost and performance together in mind the ABC Motor company is also a close contender. MAX Truck company's trucks were selected. If we evaluate the MOIs individually MAX Truck is not number one either in carriage volume or engine horse power but the over it the best fit for the goods transportation company.

In using this tool of trade off analysis it is important to note that this is a worthwhile tool in decision making but rather than a fail-safe prescription for success. It simply organizes and formalizes our informal evaluating process during decision making. Its results totally depend upon quality and sufficiency of the inputs given to it.

Chapter Summary

In this chapter, we talked about a mechanism that is inbuilt, not only in nature, but in what we are producing by mimicking the nature called 'system'. We conversed about the terminologies and modeling techniques of a system. A detailed discussion was also presented on a methodology that can be used in successful development and implementation of a system. Finally, Some decision making tool were introduced that are required during this development and implementation phase.

CASE STUDIES

1. CPM application in tier I suppliers of the three big Auto Giants – General Motors, Ford Motor Company & Chrysler.

In any manufacturing company, to manufacture a products lots of finished parts and materials are ordered from other companies. For example, an auto-manufacturer dose not produces paints. It merely orders it from a paint company, or car tires are ordered by tire manufacturers. Similarly tire manufactures does not produce rubber in there plant, rather they buy it from rubber manufacturers and the chain goes down to companies that handles raw material in crudest form. In case of auto-manufacturing, the companies that supplies goods and materials to auto-manufacturer directly, they are called tier I suppliers, while the companies that are suppliers for tier I are called tier II companies and so on.

In this case study tier I suppliers are forced by the three big auto giants to qualify for a quality system certification called QS – 9000, used to prevent defects, reduction in variation, elimination of waste and continues improvement of quality .

The CPM approach used by one of the auto part company, know as Metro City Auto Parts Co., to get itself registered for QS – 9000 is shown here. List of activities conducted the Metro are listed in the table xx below.

Activity	Description	Required Predecessor	Duration (weeks)
A	Appointment of QS-9000 task force	None	1
B	Preparation of a feasible plan	A	1
C	Delegation of authorities and responsibility	B	1
D	Searching for a QS-9000 registrar	C	1
E	Preparation of 3 levels of documentation	C	12
F	QS-9000 awareness training	C	6
G	Training of auditors & quality Personals	F	6

H	Preparing the plant to QS-9000 requirements	C	24
I	Conference with lead auditor	D	1
J	Examination of documents	E, I	3
K	Internal audit of plant sections	G, H, J	12
L	Corrective actions of plant sections	K	12
M	Audit plant with lead auditor	L	1
N	Audit conference and corrective action plan	M	2
O	Implementation of corrective action plan	N	12
P	Lead auditor re-audits corrective actions	O	2
Q	Lead auditor's recommendation	P	1

The network diagram was created. The diagram showed that the total registration process would take 69 weeks and the critical activates were, A, B, C, H, K, L, M, N, O, P and Q. The company found use to this method extremely successful in planning and identifying critical activates. The overall exercise was a success.

1. A core based system-to-silicon design methodology. Motorola, Motorola's new media division.

IC Designers face great challenges in designing and verifying the complex systems on silicon demanded by today's marketplace. IC integration levels have become more complex, time-to-market windows get shorter, and device sizes continue to get smaller. These causes have created the need for new design methodologies and new electronic design automation tools to cope with the problems of deep-submicron system design and verification.

Motorola have developed a, what they called, 'core based system IC design methodology' that helps them face these challenges. By rapidly taking a design from system level to physical implementation, this methodology allows designers to focus on system-level design trades and IC performance, while addressing deep submicron design issues. Here core mean reusable component or design. In order to develop this methodology Motorola has used the systems approach.

Motorola used this new design methodology in designing and verifying a complex, cell-based QAM demodulator/FEC decoder for digital cable TV set-top boxes and cable data modems.

Functional flow diagram of the old so called Motorola ACIS methodology is shown below in figure 2-22.

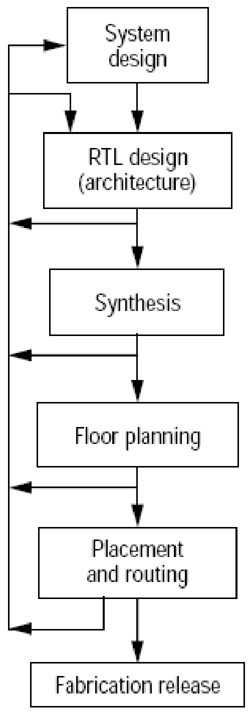


Figure 2-22: FFBD of old ACIS methodology

The use of FFBD to demonstrate new core based methodology is shown below in figure 2-23. Use of systems approach and tools such as FFBD help them reduce time by 10%-15%.

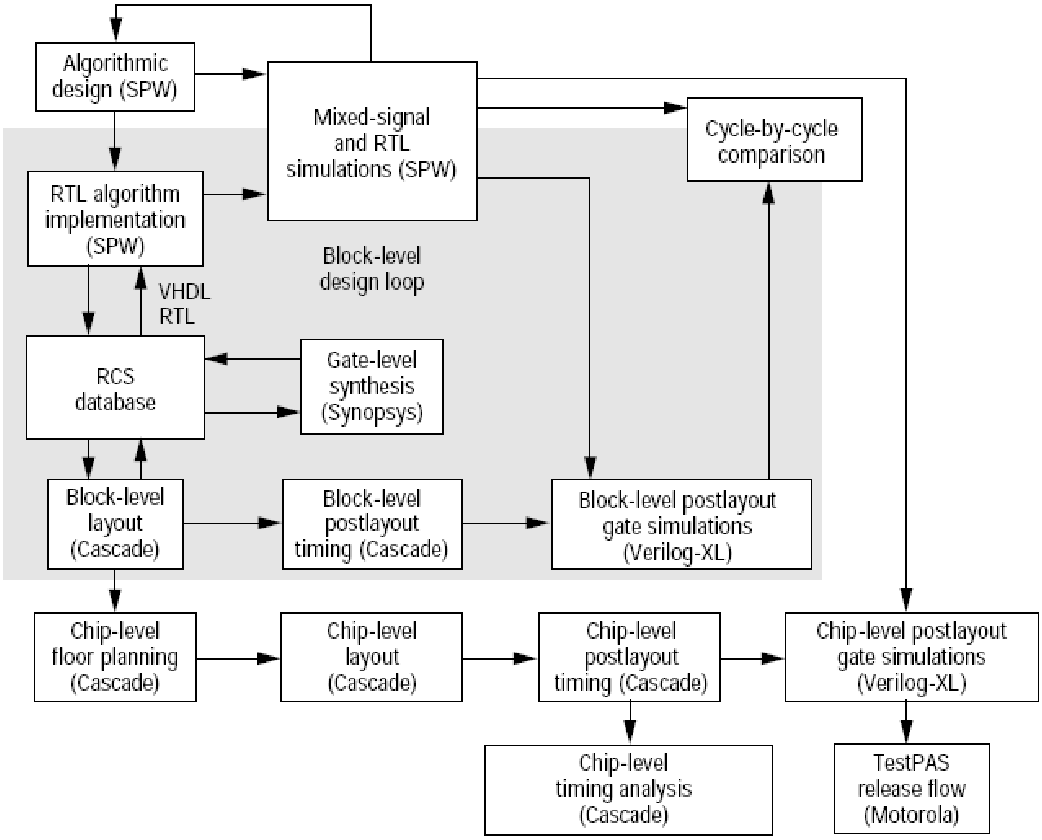


Figure 2-23: FFBD of new core based methodology

Challenge Tasks:

1. Develop the CPM network diagram as shown in case study number one and verify the results.

2. Describe system in your organization. Your organization may be made up of people, machines, computers etc. Use subsystem diagram to model your organization as a complex system.

3. Assume you are working in your city's municipality. There have been complaints about the performance of the public transportation system. You have been assigned by Mayor to asses the system. Your task is to:

   a) Model the public transportation system by identifying all the subsystems. Use system block diagram to model the system.

   b) Identify all inputs and outputs & desired output levels of the system and all the subsystems.

   c) Use Functional Flow Process Diagram (FFPD) to show the process of the subsystem that is most important in your view.

   d) Have a detailed discussion on how to improve the current system using developed model.

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