Chapter 1

Supply Chain Management Simulation: An Overview

1.1. Supply chain management

In this book we are concerned with the simulation of supply chain management (SCM). We focus on simulation approaches which are used to study SCM practices [VOL 05].

The existence of several interpretations of SCM is a source of confusion both for those studying the concept and those implementing it. In fact, this term can express two concepts, depending on how it is used: supply chain orientation (SCO) is defined ([MEN 01]) as "the recognition by an organization of the systemic, strategic implications of the tactical activities involved in managing the various flows in a supply chain". SCM is the "implementation of this orientation in the different member companies of the supply chain".

1.1.1. *Supply chain viewpoints*

As already mentioned, the main topic of this book is related to the use of simulations for supply chain management and control. However, in order to understand what simulations can be useful for this objective, it is important to highlight the different issues of SCM, and to understand what a supply chain is or how many types of SC can be considered. Thus, two viewpoints can be considered:

Chapter written by Caroline THIERRY, Gérard BEL and André THOMAS.

– the system under study is the SC of a given business, and we can consider:

- the internal SC of a business which focuses on functional activities and processes and on material and information flows within the business. In this case SCM may be viewed as the integration of previously separate operations within a business,

- the external SC of the business which includes the business, suppliers to the company and the suppliers' suppliers, customers of the company and the customers' customers (SCOR). In this case SCM mainly focuses on integration and cooperation between the enterprise and the other actors of the supply chain;

– the supply chain under study is a network of businesses (without focusing on one particular business of the supply chain): a supply chain is a "network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate consumer" ([CHR 92]). In this viewpoint, the focus is on the virtual and global nature of business relationships between companies. In this case, supply chain management mainly focuses on cooperation between the supply chain actors.

1.1.2. *Supply chain management*

1.1.2.1. *Supply chain processes: the integrated supply chain point of view*

To describe supply chains from a process point of view, we refer to the supply chain operations reference (SCOR) model. SCOR is a cross-industry standard for supply chain management and has been developed and endorsed by the supply-chain council (SCC). SCOR focuses on a given company and is based on five distinct management processes: plan, source, make, deliver and return.

SCOR Process	Definitions
Plan	Processes that balance aggregate demand and supply to develop a course of action which best meets sourcing, production and delivery requirements
Source	Processes that procure goods and services to meet planned or actual demand
Make	Processes that transform product to a finished state to meet planned or actual demand
Deliver	Processes that provide finished goods and services to meet planned or actual demand, typically including order management, transportation management, and distribution management
Return	Processes associated with returning or receiving returned products for any reason. These processes extend into post-delivery customer support

Figure 1.1. *The SCOR processes ([SCO 05])*

SCM addresses different types of problems according to the decision horizon concerned. Long range (strategic) decisions are concerned with the supply chain configuration: number and location of suppliers, production facilities, distribution centers, warehouses and customers, etc. Medium and short range (tactical and operational) decisions are concerned with material management decisions: inventory management, planning processes, forecasting processes, etc.

On the other hand, information management is also a key parameter of supply chain management: integrating systems and processes using the supply chain to share valuable information, including demand notices, forecasts, inventory and transportation, etc.

Figure 1.2 which is adapted from the SSCP-Matrix [STA 00] summarizes the different supply chain decision processes.

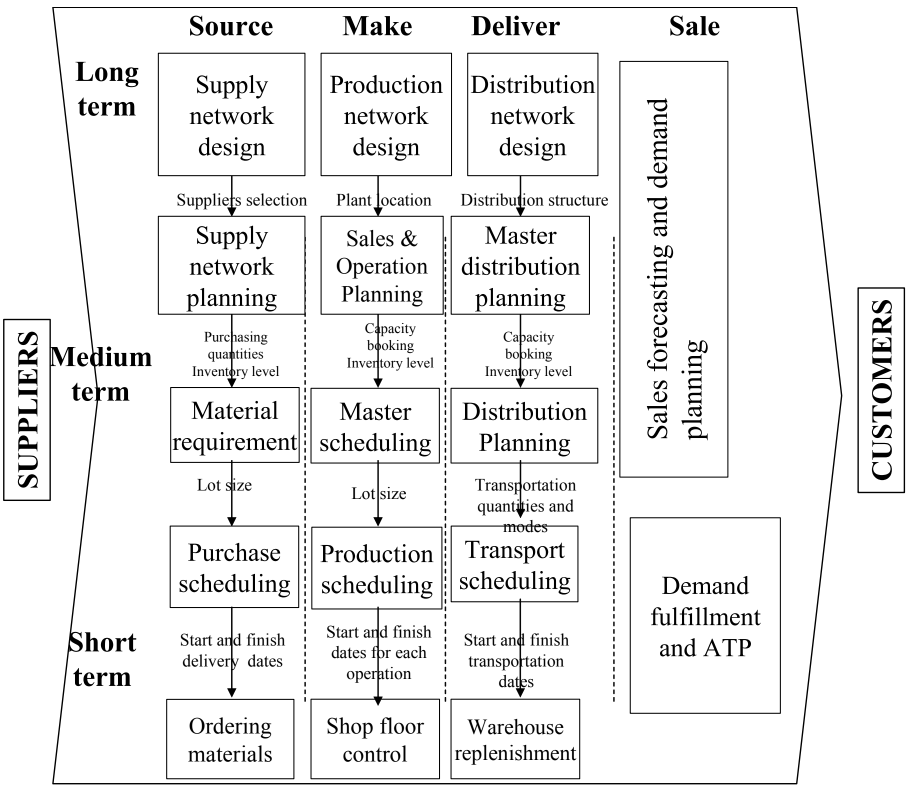


Figure 1.2. *Different supply chain decision processes (1 organizational unit)*

SCM deals with the integration of organizational units. Thus the different supply chain processes will be more or less distributed according to the level of integration of the different processes.

1.1.2.2. *Dynamic behavior of supply chain management system*

There is a process which organizes the decisions at different levels in the supply chain management system. This system (virtual world) is connected to the production system (real world) in order to compose a “closed loop” dynamic system.

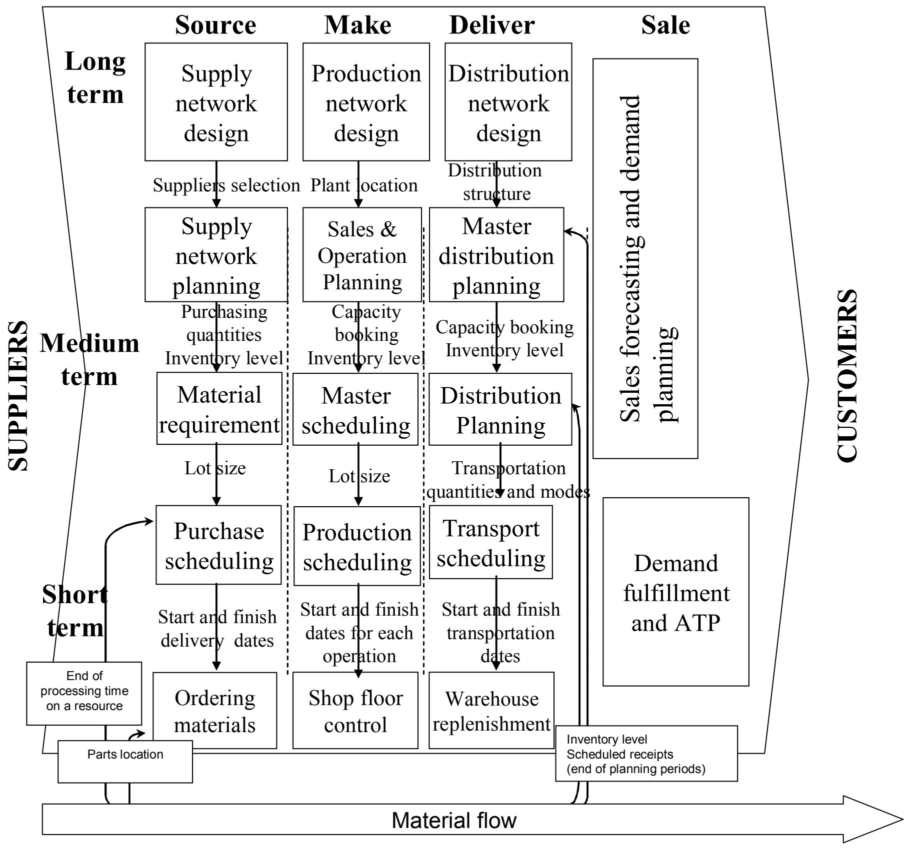


Figure 1.3. *Dynamic behavior of SCM system*

1.1.2.3. *Supply chain processes: the collaborative supply chain point of view*

Let us now consider (Figure 1.4) at least two independent organizational units (legal entities).

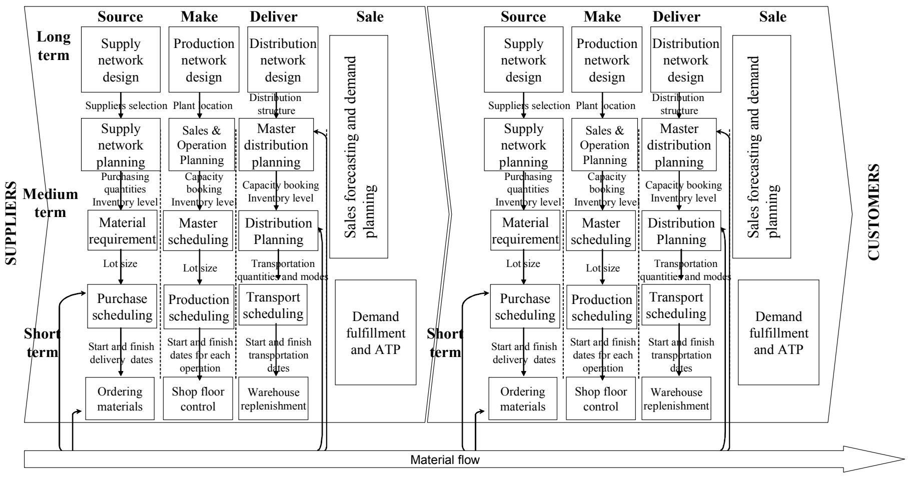


Figure 1.4. *Different supply chain decision processes (2 independent units)*

In this collaborative supply chain, as far as a supplier-buyer partnership is established, several problems arise:

– how can we exchange/share information?

– is it possible to perform mutual problem solving?

– how can we set up global supply chain indicators?

– etc.

Thus, the problem of the centralization or distribution of the information and decision processes within the supply chain becomes a main challenge for the supply chain managers.

1.2. Supply chain management simulation

1.2.1. *Why use simulation for SCM?*

As far as simulation is concerned the objective is to evaluate the supply chain performances. We distinguish three ways of carrying out SC performance measurement:

– analytical methods, such as queueing theory;

– Monte Carlo methods, such as simulation or emulation;

– physical experimentations, such as lab platforms or industrial pilot implementations.

In this SC context, analytical methods are impractical because the mathematical model corresponding to a realistic case is often too complex to be solved. Obviously, physical experimentations suffer from technical- and cost-related limitations. Simulation seems the only recourse to model and analyze performances for such large-scale cases. Simulation enables, on the one hand, the design of the supply chain and on the other hand, the evaluation of supply chain management prior to implementation of the system to perform what-if analysis leading to the "best" decision. This simulation includes supply chain flow simulation and decision process dynamics. In the field of SCM, simulation can be used to support supply chain design decisions or evaluation of supply chain policies. As far as supply chain design decisions are concerned, the following decisions can be considered:

– localization:
  - location of facilities,
  - supply and distribution channel configuration,
  - location of stocks;

– selection:
  - suppliers,
  - partner;

– size:
  - capacity booking,
  - stock level,
  - etc.

As far as the evaluation of supply chain control policies is concerned, the following decisions can be considered:

– control policies:
  - inventory management, control policies,
  - planning processes;

– collaboration policies:
  - cooperation/collaboration/coordination, etc.,
  - information sharing, etc.

1.2.2. *How can we use SCM simulation?*

To attempt to specify the different ways to use SCM simulation it is important to differentiate, on the one hand, the real system (the "real world") and on the other, its simulation model.

In fact, the simulation model must be built according to its usage and/or the SCM function that we want to model or to evaluate. Different classes of models can be highlighted to understand the variety of SC simulation models according to:

– the systemic decomposition of the SCM system:
  - decision system,
  - information system,
  - physical system;

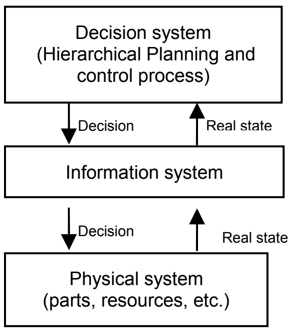


Figure 1.5. *Systemic decomposition of the SCM system*

– the level of distribution of the system:
  - simulation model for centralized SCM system evaluation. A centralized SCM system consists of a single information and decision system for the different entities of the supply chain under study;
  - simulation model for distributed SCM system evaluation. A distributed SCM system consists of a distribution of the decision system over different entities of the supply chain under study.

As a matter of fact, the execution of the simulation can be performed:

– in a centralized way on a single computer;

– in a decentralized way:
  - on multiprocessor computing platforms: parallel simulation,

- or on geographically distributed computers interconnected via a network, local or wide: distributed simulation.

Decentralization of the simulation is "the execution of a single main simulation model, made up by several sub-simulation models, which are executed, in a distributed manner, over multiple computing stations" [TER 04].

The need for a distributed execution of a simulation across multiple computers derives from several main reasons [TER 04]:

– to reduce execution simulation time;

– to reproduce a system geographic distribution;

– to integrate different simulation models that already exist and to integrate different simulation tools and languages;

– to increase tolerance to simulation failures;

– to test different control models independently;

– to progressively deploy a control system;

– to prepare protocol modifications at supply chain control.

Furthermore, it is important to stress that simulation mostly focuses on the dynamics of the supply chain processes concerning both physical and decision systems (i.e. production management systems, see section 1.3.1).

1.3. Supply chain management simulation types

This section is dedicated to the presentation of the different types of models and approaches mainly used for supply chain management simulation.

As seen before, an important part of the model is the decision system model (hierarchical planning and control processes). Thus, section 1.3.1. presents the main production management models which are used in SCM.

Then, the different types of well known simulation models will be quickly presented. For each of them we will highlight how the different production management models can be linked with the simulation model.

1.3.1. *Production management models focus*

The objective of this section is to focus on and present a very synthetic and simplified description of production management models in order to introduce, in a following section, how they can be integrated in a supply chain simulation model. Here we focus only on production processes. The approach could be extended to supply and distribution processes.

There are two main categories of production management models.

1.3.1.1. *Time bucket models*

In production planning and control, and mainly for the long and medium term, we are concerned with the determination of quantities to be produced per time period for a given horizon in order to satisfy demand or/and forecast. In order to perform these decision processes, time bucket models are needed. They are characterized by:

– decision variables: produced, stocked or transported quantities;

– data: resource capacities (in number of parts per period, for example);

– constraints: conservation of flow, cost of materials, limited capacities, demand satisfaction, etc.

EXAMPLE.– for a production line composed of two production resources (see Figure 1.6).

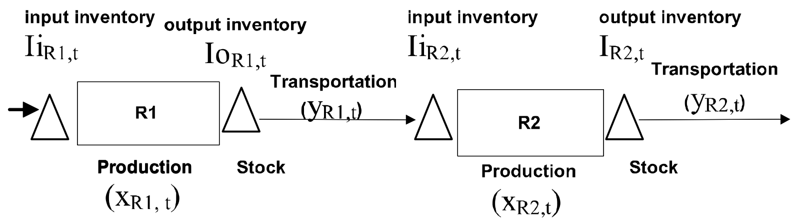


Figure 1.6. *Time bucket model (example)*

The demand is d_t and the production resource capacities are $C_{R1,t}$, $C_{R2,t}$. Each item is produced from one single component.

The planning model variables are:

– $x_{Ri,t}$ = quantity of items to be produced with resource Ri during time period t;

– $y_{Ri,t}$ = quantity of items to be transported from resource Ri during time period t;

– $Ii_{Ri,t}$ = input inventory level of resource Ri at the beginning of time period t;

– $Io_{Ri,t}$ = output inventory level of resource Ri at the beginning of time period t.

The planning model constraints are:

– $Ii_{R1,t+1} = Ii_{R1,t} - x_{R1,t}$;

– $Io_{R1,t+1} = Io_{R1,t} + x_{R1,t} - y_{R1,t}$;

– $Ii_{R2,t+1} = Ii_{R2,t} - x_{R2,t} + y_{R1,t}$;

– $Io_{R2,t+1} = Io_{R2,t} + x_{R2,t} - y_{R2,t}$;

– $y_{R2,t} = d_t$;

– $x_{R1,t} \leq C_{R1,t}$;

– $x_{R2,t} \leq C_{R2,t}$;

– $Ii_{R1,t0} = \infty$;

– $Ii_{R,t} \geq O\ \forall R \in \{R1, R2\}, \forall t$;

– $Io_{R,t} \geq O\ \forall R \in \{R1, R2\}, \forall t$;

– $x_{R,t} \geq 0\ \forall R \in \{R1, R2\}, \forall t$;

– $y_{R,t} \geq 0\ \forall R \in \{R1, R2\}, \forall t$.

Associated with these models, the following methods are used to perform the plan: MRP-like methods, mathematical programming, constraint programming, metaheuristics.

1.3.1.2. *Starting time models*

In production planning and control, and mainly in the short-term, we are also concerned with the determination of the starting time of tasks on different resources. For that we use starting time models (sequence of timed events). These models are characterized by:

– decision variables: starting time of tasks (t_i);

– data: ready dates (r_i,) due dates (d_i);

– constraints: precedence, resource sharing, due dates.

Example:

– $t_i \geq r_i$;

– $t_i \geq t_j + p_j$ OR $t_j \geq t_i + p_i$;

– $t_i + p_i \leq di$.

Associated with these models, the following methods are used to perform the schedule: mathematical programming, constraint programming, metaheuristics, etc.

1.3.2. *Simulation types*

Due to the special characteristics of supply chains, building the supply chain simulation model is difficult. The two main difficulties are highlighted, and then the different types of models for SCM simulation are quickly presented.

1.3.2.1. *Size of the system*

One characteristic of supply chain simulation is the huge number of "objects" to be modeled. A supply chain is composed of a set of companies, a set of factories and warehouses, a set of production resources and stocks. Between all these production resources circulate a set of components, parts, assembled parts, sub-assemblies and final products. Thus, the number of "objects" of the model can be very large.

1.3.2.2. *Complexity of the production management system*

To simulate a system it is necessary to simulate the behavior of the "physical" system and the behavior of the "control" system. For a supply chain this implicates that it is necessary to model the behavior of the supply chain management system of each company and the relationship between these production management systems (cooperation).

As this SCM system is very complex, it can be difficult to model it in detail. However, it is absolutely necessary to model it, as it is this system which controls the product flow in the supply chain. Thus, according to the objective of the simulation study and the type of model chosen, various aggregated or simplified models of the production management system must be designed. The following sections present different examples of these models.

1.3.2.3. *Different types of models for SCM simulation*

1.3.2.3.1. Simulation model

A simulation model is composed of a set of "objects" and relationships between these objects; for example, in a supply chain the main objects are items (or sets of items) and resources (or sets of resources).

Each object is characterized by a set of "attributes". Some attributes have a fixed value (for example, name), while others have a value which varies over time (for example, position of an item in a factory).

The state of an object at a given time is the value of all its attributes. The state of a system at a given time is the set of the attributes of the objects included in the system.

The purpose of a simulation model is to represent the dynamic behavior of the system.

There are various modeling approaches according to how state variations are considered:

– states vary continuously: continuous approach;

– states vary at a specific time (event): discrete-event approach.

The following parts of this section will introduce Chapters 2 to 4 which will go into detail on the viewpoint and present related works (state of the art and recent works).

1.3.3. *SCM simulation using continuous simulation approach*

In this section we will introduce system dynamics, a continuous simulation approach where states vary continuously. Chapter 2 will go into detail and present recent works related to SCM simulation from this point of view.

1.3.3.1. *System dynamics*

This new paradigm was first proposed by Forester for studying "industrial dynamics".

Companies are seen as complex systems with [KLE 05]:

– different types of flows: manpower, technology, money and market flows;

– stocks or levels which are integrated into time according to the flow variations.

System dynamics are centered on the dynamics behavior. This is a flow model where it is not possible to differentiate between individual entities (such as transport resources).

Management control is performed by making variations on rates (production rates, sale rates, etc.). Control of rates can be viewed as a strong abstraction of common production management rules.

The model takes into account the "closed loop effect": the manager is supposed to compare the value of a performance indicator to a target value continuously. In case of deviation he implements corrective action.

Example:

– $I_{t2} = I_{t1} + p(xr_{t1,t2} - dr_{t1,t2})$;

– $xr_{t1,t2}$ = production rate between two dates t1 and t2;

– $dr_{t1,t2}$ = sale rate between two dates t1 and t2;

– p = time duration between t1 and t2.

1.3.3.2. *Production management models/simulation models*

The two models do not consider the same objects states:

– in system dynamics, objects are continuous flows. The behavior of these flows is represented by a differential equation (with derivative) which is integrated using a time sampling approach;

– in planning models, the objects are resources and their activities. It is considered that the attributes of these activities change only at a special periodic date. There is no notion of a derivative.

This type of model seems well adapted to supply chain simulation as it was designed by Forester for "industrial dynamics" studies which used the same concepts as those recently used in supply chain studies.

1.3.4. *SCM simulation using discrete-event approach*

In this section we will detail the discrete-event approach. We will distinguish between the time bucket-driven approach and event-driven approach. This differentiation is based on the time advance procedures which characterize these two approaches. Chapter 3 will go into detail and present recent works related to SCM simulation from this point of view.

For the "discrete-event approach" they are:

– different ways of "looking at the world": event, activity and process,

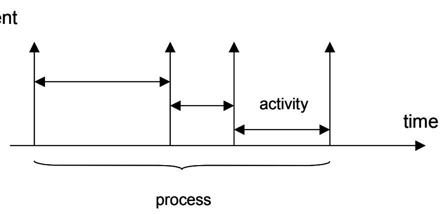


Figure 1.7. *Events, activities, processes*

– different procedures to make the time advance in the simulation:
- event-driven,

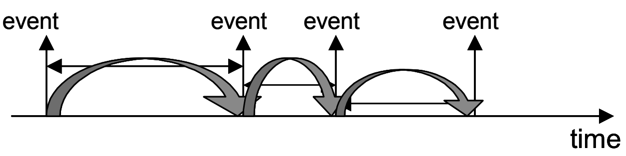


Figure 1.8. *Event-driven discrete-event simulation*

- time bucket-driven.

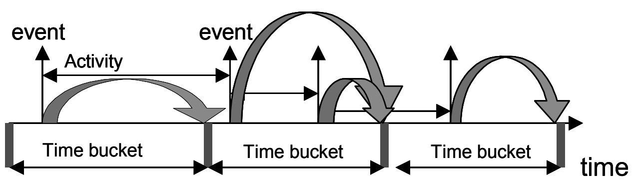


Figure 1.9. *Time bucket-driven discrete-event simulation*

The main practices for "mixing" various types of models and time advance procedures are listed below.

	continuous	activities	events	process
Time bucket driven	**X**	**X**	x	x
Event driven	Not possible with the approach	x	**X**	**X**

Figure 1.10. *Discrete-event simulation*

1.3.4.1. *Time bucket-driven approach*

Discrete-event simulation using the time bucket-driven approach is rarely used for job shop simulation but it fits well for simulation of supply chain management (see the specific characteristics of this simulation in sections 1.3.2.1 and 1.3.2.2).

1.3.4.1.1. Time bucket-driven discrete-event models

In such a model:

– time is divided into periods of a given length: time bucket;

– time is incremented step-by-step with a given time bucket. At the end of each step a new state is calculated using the model equations. Thus, in this approach it can be considered that events (corresponding to a change of state) occur at each beginning of a period;

– the lead time for an item on a production resource is considered small compared to the size of the time bucket;

– the main states are the states of resources (or set of resources) during a given period: they describe the activities in which resources are implicated in a given time period. They are characterized by the quantities of items processed in this activity in a given time period: for example, the number of items of a given type manufactured, stocked or transported by a given resource in a given period;

– the simulation has to determine all the states of all the resources at each period of a simulation run.

This type of model is also called a “spreadsheet simulation” [KLE 05]. We do not use this designation because a spreadsheet is a tool which it is possible to use with all the modeling approaches.

1.3.4.1.2. Simulation models

It must be noted that the planning models presented in section 1.3.1 are also time bucket models which are well known and used in the production management domain. We will see hereafter that they are very similar to time bucket-driven discrete-event simulation models but that they are used in a different way in simulation.

In order to illustrate this, we consider a very simple example of a production line composed of two production resources with no specific production management. Shop floor control is a first-in first-out strategy; k is the number of parts from M1 to be used to produce one part on M2.

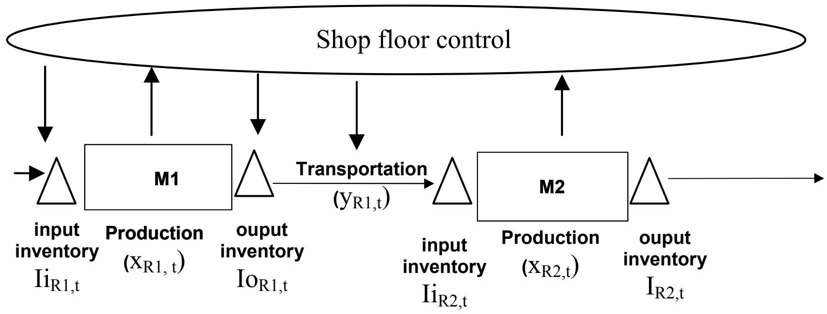


Figure 1.11. *Production management models/simulation models (example)*

The simulation model uses the following state variables:

– $Ii_{Ri,t}$ is the input inventory level of resource Ri at the beginning of time period t;

– $Io_{Ri,t}$ is the output inventory level of resource Ri at the beginning of time period t;

– $x_{Ri,t}$ is the quantity of parts produced by resource Ri during the time bucket t (available at the end of t);

– $y_{Ri,t}$ is the quantity of parts transported from Ri during time bucket t (available at the end of t).

The model of the dynamic behavior of the system is the following:

– $Ii_{R1,t+1} = Ii_{R1,t} - x_{R1,t}$;

– $Io_{R1,t+1} = Io_{R1,t} + x_{R1,t} - y_{R1,t}$;

– $Ii_{R2,t+1} = Ii_{R2,t} - x_{R2,t} + y_{R1,t}$;

– $Io_{R2,t+1} = I_{oR2,t} + x_{R2,t} - y_{R2,t}$;

– $x_{R1,t} \leq C_{R1,t}$;

–$x_{R2,t} \leq C_{R2,t}$.

It can be noted immediately that this model is very similar to the production management model presented in section 1.3.1.1.

In order to illustrate this, let us consider a simulation with this model corresponding to the following hypothesis: resource R1 sends parts to resource R2 according to a production and transportation plan determined outside of the system. Thus, $Ii_{R1,t0}$, $Ii_{R2,t0}$, $x_{R1,t}$, $x_{R2,t}$, $y_{R1,t}$, $y_{R2,t}$ are known at the beginning of the simulation.

In this case, the true state variables of the model are $Ii_{R1,t}$, $Ii_{R2,t}$, $Io_{R1,t}$ and $Io_{R2,t}$.

The simulation must determine the variation over time of these variables taking into account the values of the exogenous variables ($x_{R1,t}$, $x_{R2,t}$, $y_{R1,t}$, $y_{R2,t}$). Thus, simulation allows the evaluation of the proposed production and transportation plan. It is also possible to introduce hazard into the behavior of the model.

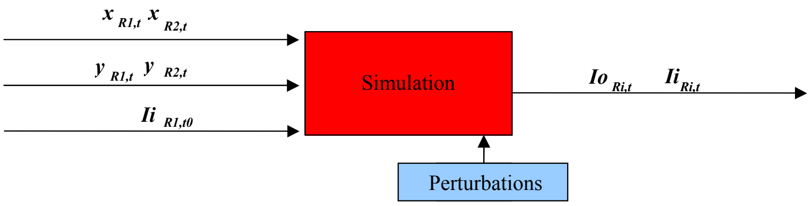


Figure 1.12. *Simulation process*

This shows that the same model can be used in a:

– simulation decision process: taking into account $x_{R1,t}$ $x_{M2,t}$, $y_{R1,t}$ and $y_{R2,t}$. The problem is to determine $Ii_{R1,t}$, $Ii_{R2,t}$, $Io_{R1,t}$ and $Io_{R2,t}$;

– production planning decision process: in a centralized planning (APS or SCM like) the problem is to determine $x_{Ri,t}$ and $y_{Ri,t}$ which satisfy the constraints of the planning model (stock capacity, supplier demand).

NOTE.– it is possible to use a "what if" approach with the planning model testing different demands or different production management policies. In this "what if" approach, the problem is solved several times, each time with this different data. Then it is possible to see the influence of these data on the generated plan. This approach is not considered in this book; we refer to simulation only when the dynamics of the system are considered.

1.3.4.1.3. Production management models/simulation models

Now the question is: how can the different production management models be linked to a discrete-event simulation model with the time bucket approach?

The time bucket production planning model can be easily linked to the global simulation model as the modeling approach is the same. In this case the two models will be joined up: the simulation model focuses on the circulation of the flow of parts, the planning model determines the quantities to be produced. Chapter 3 provides a study of both discrete-event and time bucket simulation used for supply chain management and proposes case studies to illustrate the pivotal role that simulation can play as a technique to aid decisions.

If we now consider the other category of production management models that we call in section 1.3.1.2 “starting time models” (scheduling, etc.) we can state that:

– “time bucket-driven discrete-event simulation models” do not use the same “object states” as “starting time production management models” (which use the “start time of an activity”);

– between two periods the bucket-driven activity simulation model does not represent the state of the system. Thus, the start time of an activity is not known and cannot be used as data in a “starting time” scheduling model. The only way to obtain a good approximation of this date is to use a very small time period. However, this is often not possible because this will contradict the fundamental hypothesis for this kind of model: the production duration for an item on a production resource is much less than the time bucket of the model.

1.3.4.2. *Event-driven approach*

In this section the main characteristics of the discrete-event models for an SCM simulation using an event-driven approach are presented. Remember that this approach is intensively used for job shop simulation. Thus, it can be considered as convenient to use this type of model for supply chain simulation.

However, using the specific characteristics of supply chain management simulation (see sections 1.3.2.1 and 1.3.2.2) can lead to some difficulties for this type of simulation. The main difficulty comes from the size of the model induced by this context. It can be inefficient to model the circulation of each individual part in each production resource of the different companies of the supply chain: the number of events can become prohibitive and considerably slow down the simulation which can become unworkable. This is why it is often necessary to use model reduction techniques introduced here in section 1.5.2. We recall hereafter the main characteristics of this approach.

1.3.4.2.1. Event-driven approach for discrete-event simulation

In an event-driven discrete-event model:

– the main states are the states of items (or set of items);

– the simulation must determine the dates of all the events (state variation) which occur during a simulation run;

– each state is characterized by the resource used by a given item at a given time and correlatively the “occupation state” of the resources; for example, the position of a given item (“on a given production resource”, “in a given stock”, or “being transported by a given cart”);

– each state variation is represented by a “state variation logic”;

– time advance event to event. A “simulation engine” using a “timetable” determines the date of the “next event” (for example, the delivery date of a job).

1.3.4.2.2. Production management models/simulation models

Consider again the question of how the different planning models can be connected in an event-driven discrete-event simulation.

The time bucket planning models cannot be directly connected to an event-driven discrete-event simulation because the modeling approach is not the same. We will see in Chapter 3 how different adaptations can be produced in order to allow connections.

The “starting time models” presented in section 1.3.1.2 (scheduling level) can be directly connected to an event-driven discrete-event simulation because they use the same modeling approach.

In summary for this event-driven approach:

– simulation models and planning models do not use the same “object states”;

– simulation models and scheduling or shop floor control models use the same “object states”.

1.3.5. *Simulation of supply chain management using games*

In this section we will introduce business games, then Chapter 4 will go into more detail and present recent works related to SCM simulation from this point of view.

1.3.5.1. *Games and simulation*

Different games can be used to perform simulation. Games make it possible to simulate real conditions offline, and explore new ideas or strategies in a safe, interactive and also fun environment. Basically, the complexity of their model allows us to split games into two classes:

– board games have a model simple enough to be played with tokens or pieces that are placed on, removed from or moved across a “board” (a premarked surface, usually specific to that game);

– sophisticated games have a more realistic model which may need, for example, to be run on computerized devices.

1.3.5.2. *Production management models/simulation models*

In this type of simulation model (board games), the simulation of time can be performed using either a clock which synchronizes the players, or the time of the simulation is the real time (each player evolves independently). [KLE 05] distinguishes:

– strategic games: in these games every player represents a company competing or collaborating through other companies by interacting with the simulation model during several rounds. The well-known Beer Game belongs to this category;

– operational games: in these games every player represents an actor (for example, a worker in a workshop) interacting with the simulation model either during several rounds or in real time. Examples include games for training in production scheduling.

1.4. Decision systems and simulation models (systems)

The preceding sections have presented the main concepts which are used in supply chain management simulation and introduce the first part of the book (Chapters 2 to 4).

The second part of the book is dedicated to the problem of distribution of the supply chain management simulation. This concept of simulation distribution is extremely important in the case of supply chain simulation because of the naturally distributed aspect of the supply chain itself. This section introduces this part of the book (Chapters 5 to 10).

1.4.1. *Models and system distribution*

There is a consensus on the architecture of simulation environments putting the emphasis on modularity between the control system *CS* and the shop-floor system *SF*.

This separation principle enables us to introduce the concept of emulation. Emulation is not new: it is used in automation to test computer-aided manufacturing software, for example [COR 89].

Fusaoka proposed a theoretical formulation and an experimental run consisting of verifying the assertion $SF \wedge CS \supset G$ [FUS 83], where G is the required performance level of the shop floor. The real shop-floor system (SFr) may be replaced by a model (SFm), that we call an *emulated* shop floor. Likewise, a model of the control system (CSm) can be used instead of the real one (CSr). Therefore, four experimental situations can be defined, using either models or real systems [PFE 03]:

1. (SFr, CSr): experimentation consists of deployment of the real control system at the shop floor. This is the more traditional case;

2. (SFr, CSm): a control system model is applied for the real shop floor. This configuration could be used to test a new control system;

3. (SFm, CSr): the real control system is used with a shop floor model (emulation with the real control system);

4. (SFm, CSm): both shop floor and control system are modeled.

Let us first focus on a single company of the supply chain or on a centralized SCM system. The real system is made up of the physical system, the information system and the control (or decision) system (cases 1 and 4 in Figure 1.13). These three systems make up the SCM system. Basically, building a simulation model leads to the design of a virtual model representation of these (or at least one of these) three preceding systems implemented on a computer S1, as seen in section 1.3.

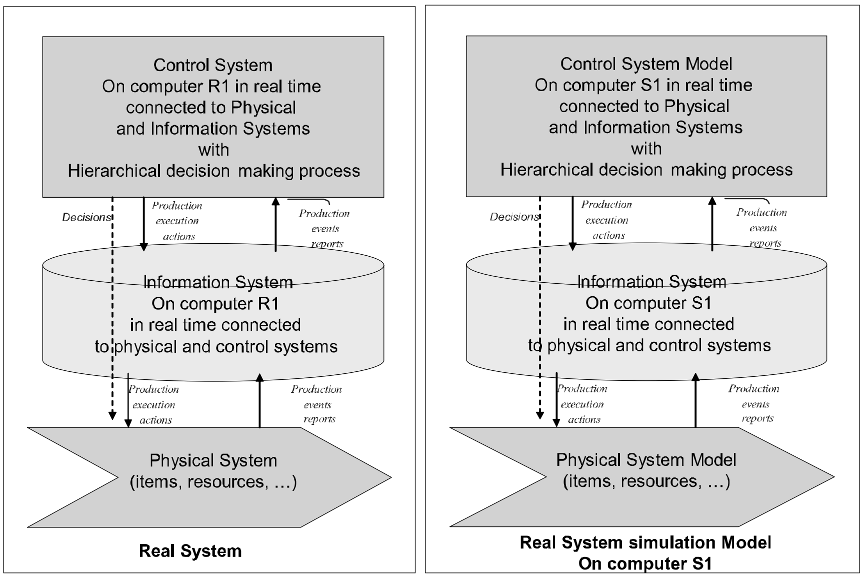


Figure 1.13. *Real-time simulation model*

Let us now consider different cases where this model can be distributed.

If we want to evaluate the effect of different control rules, on a specific physical system, it could be interesting for example to build an emulation system corresponding to this physical system. This emulation model is controlled by the real decision system (case 3 in Figure 1.14) connected to the actual information system. Actually, emulation aims to mimic the behavior of the physical system only. It can be seen as a virtual shop floor which can be connected to an external control system. Like simulation, emulation can be used to model complex cases, but emulation removes the additional task of modeling decision processes (this task is often one of most difficult as stated by [VAN 06] and presented here in section 1.3.2.2).

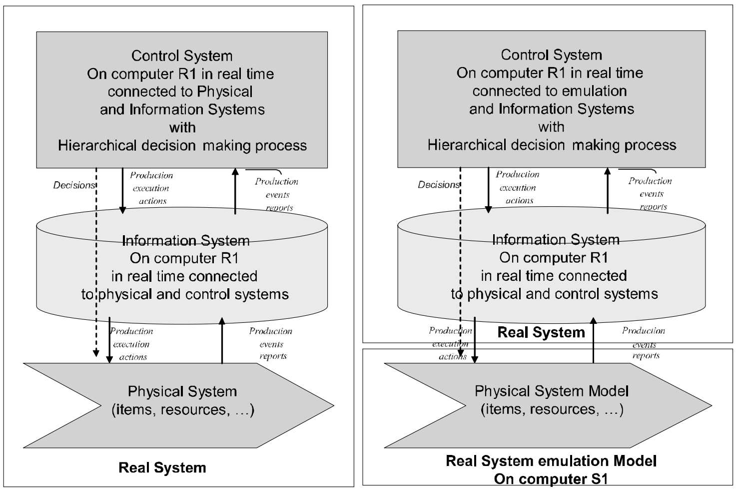


Figure 1.14. *Emulation system connected to real control system*

Using emulation provides modularity between test cases and control systems to be tested. This modularity is useful to try a control system in various situations, or to try various control systems on the same test case. It can also be useful to validate the real control system before actually deploying it.

Obviously, the same concept can be used for a supply chain system (Figures 1.15 and 1.16). However, as with supply chains of networks of companies that are often independent (i.e. section 1.1.1), simulation models can be built in a centralized way (Figure 1.15) or in a distributed way (Figure 1.16). In a distributed context, different simulation models can be implemented on different computers, each one representing company behavior.

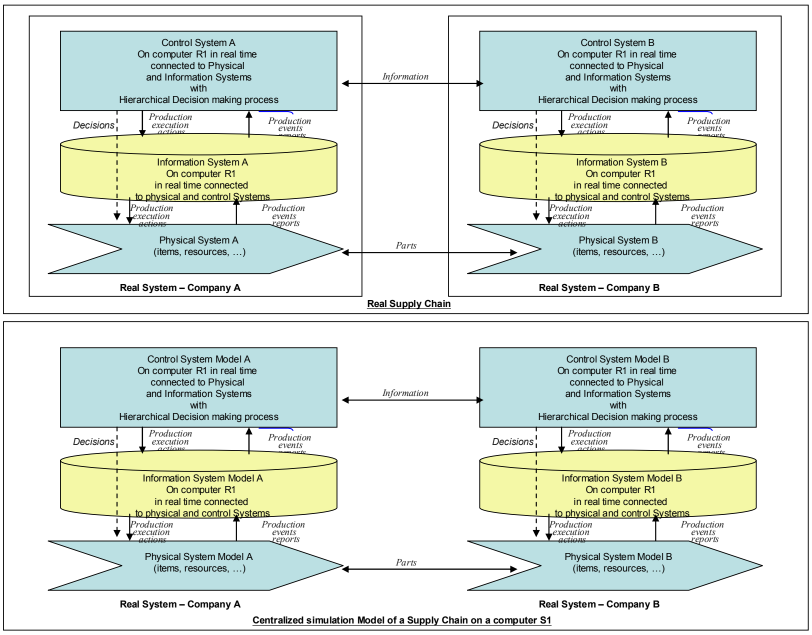


Figure 1.15. *Centralized supply chain simulation model*

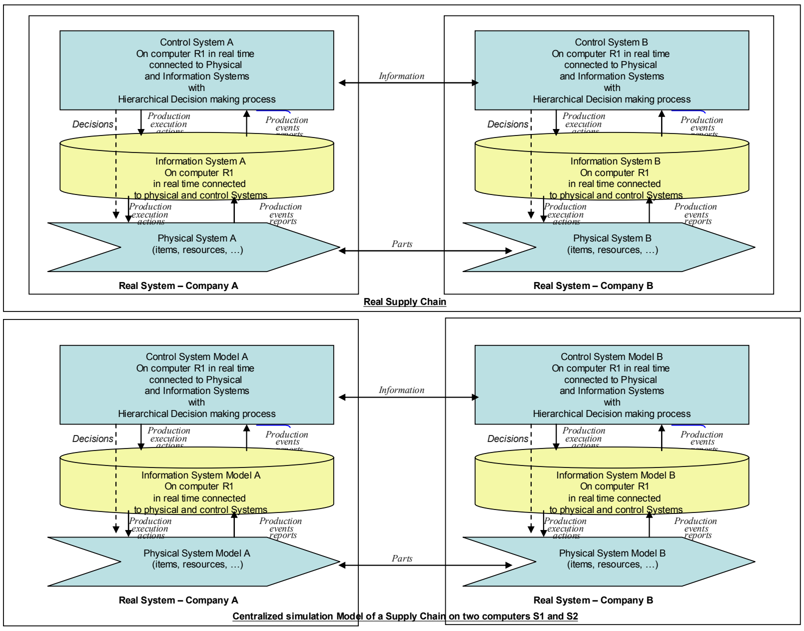


Figure 1.16. *Distributed simulation models of a supply chain*

As underlined in the preceding sections, SC management systems are traditionally organized in a hierarchical way. Different decision functions exist: planning, master scheduling, detail scheduling and control according to the traditional MRP² system described by [VOL 05]. This type of architecture exists in each company belonging to the SC. In an internal SC, the same ERP software could be used, but in an external SC, often different information and decision system ERP must be connected, leading to interoperability problems and/or synchronization problems.

The following parts of this section will introduce Chapters 5 to 10. These different chapters will describe simulation problems relating to centralized architectures, simulation synchronization problems and distributed simulation architectures respectively.

1.4.2. *Centralized simulation*

The decisions that are usually taken before planning the implementation of any supply chain can be classified into two categories: structural (for long-term objectives) and operational (for short-term goals). Simulation can be used as a tool for carrying out the decision-making process for both structural and operational decisions thanks to dynamic simulation of material flow and taking into account all random phenomena. The opposite of distributed simulation, in a centralized approach, one single simulation model reproduces all the supply chain structures (entities and links).

Chapter 5 is dedicated to this type of approach. It presents a brief literature review on supply chain centralized simulation and discusses two developed centralized simulation approaches. Effectively, for most simulation evaluation approaches, supply chain processes are modeled to perform "what-if" analysis. Firstly, a discrete-event simulation-based optimization is used to estimate the operational performances of the solutions suggested by the optimizer. The optimizer was developed based on the NSGA-II, which is considered to be one of the best multi-objective optimizations using a genetic algorithm [DEB 02].

Furthermore, Chapter 5 illustrates the applicability and efficiency of the two preceding approaches using three industrial applications. In the first one, a case study from the automotive industry will be presented. The objective is to improve the profitability and responsiveness of the company's supply chain by redesigning its production-distribution network. A centralized simulation-based optimization approach is used for the optimization of facility open/close decisions, production order assignment and inventory control policies. In the second case, the authors applied the centralized simulation-based multi-objective genetic algorithm approach to a real-life case study of a multi-national textile supply chain, which consists of several suppliers, a single distribution center and all customers seen as a whole. The modeling and simulation details are discussed and numerical results are presented and analyzed. In the third case, another automotive industry case, a generic model is proposed, which can be used by different automotive industries. The developed model is limited only to the interactions between the assembly line and its direct suppliers. Taking into account that the model is generic, it is able to help supply chain decision makers in their choices.

1.4.3. *Multi-agent system decision simulation*

New forms of organizations have emerged from the supply chain concept in which partners have to collaborate and have strong collaboration. Production businesses operate as nodes in a partner network and share activities to produce and deliver their goods. In such a context, the integration of planning of all the nodes is needed, i.e. partners have to be able to distribute and synchronize their activities.

To obtain the optimal performance level in such a dynamic environment, multi-agent systems (MAS) can be used. Effectively, MAS are composed (as a supply chain network is) of a group of agents that can take specific roles within the organizational structure. Different agents may represent different objects belonging to the studied network. This idea is not new; Parunak used agents for manufacturing control or collaborative design ([PAR 96] or [PAR 98]) but these approaches are particularly well adapted when studying SCM.

Chapters 6 and 7 are dedicated to MAS usage for SCM. Chapter 6 highlights the interest of using MAS for supply chain simulation and Chapter 7 considers MAS decision system simulation for a business network.

Just as in a supply chain in which distributed activities and decisions are carried out in order to obtain a global optimal performance, MAS simulation leads to a distributed system, within which there is generally no centralized control, to have a global point of view; where agents act in an autonomous way and do not locally have global knowledge, but obtain a global optimum. Effectively, several analogies between supply chains and MAS can be highlighted:

– the multiplicity of acting entities;

– the entities' properties, abilities or decision-making capabilities, etc.;

– information sharing and task distribution, etc.

A review of research works on agent-based supply chain modeling and simulation is also carried out in Chapter 6. On the other hand, Chapter 7 presents specific contributions in agent-based supply chain modeling and simulation for decision system development. The first part of this chapter will concern the supply chain control, and the second one, is related to the design of a decision system based on simulation.

1.4.4. *Simulation for product-driven systems*

As mentioned before, in the distributed supply chain and manufacturing control context, MAS are often used according to the fact that each company could act, in some circumstances, in an autonomous way. Consequently, it is possible to implement agents to describe their behavior. Thus, the SCM system could be composed by planning and scheduling agents and by agents representing physical elements as products, for example.

Moreover, it is also possible to build emulation models for distributed supply chains. This type of model can be produced in a centralized or distributed way (using several models and computers for physical, control and decision systems). This last possibility is interesting for all contexts where products and/or physical entities are able to take some autonomous decisions. The main idea is to focus the decision-making processes as near as possible to the shop-floor or physical system, where events (disturbing or not) actually occur. Current research focusing on autonomy includes, for example, holonic manufacturing systems (HMS), multi-agent-based control or more generally intelligent manufacturing. These take their roots both in fundamental research such as distributed artificial intelligence, artificial life or cooperative control, and also in practical experiences such as Kanban-controlled systems or powered operators.

Centralized control systems showed their limits to efficiently respond to frequent changes, which put researchers on the path of distributed manufacturing systems [DIL 91]. However, advances in this domain show limitations with system stability and global optimization.

The qualities and complementarities of both centralized and distributed approaches (hybrid architectures) make it possible to see considerable benefits of coupling them together, adding the global optimization abilities from centralized control systems to the reactivity and possible robustness of decentralized systems. Both hierarchical and heterarchical approaches share benefits and drawbacks. As a consequence the idea of coupling both systems has emerged, with the aim of ensuring global optima while keeping the heterarchical system reactivity. This concept would be realistic by using technologies such as RFID. This technology enabled us to postulate that embedding intelligence into the product could lead to some types of product-driven systems ([WON 02; MOR 03]).

This concept needs to use simulation in a different way; in particular, the simulation tool must reproduce the "communicant product" behavior. Consequently, the simulation tool is built in two parts: the first is an "emulation model" where the entities represent items and do not have any attributes (no information or decisions are implemented in the model), and the second is a "control model" where the entities represent an information flow activated by events occurring in the emulation model.

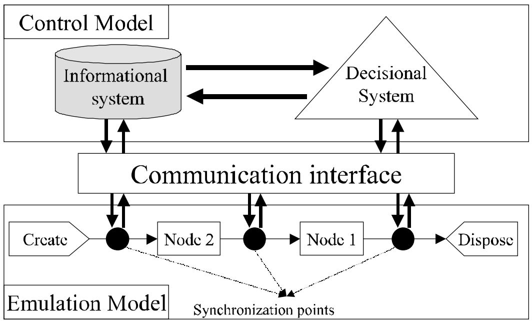


Figure 1.17. *Product-driven system simulation*

As shown previously, in order to assess the impact of synchronizing physical and informational flows we need to model them as distinct flows (Figure 1.17). In that way, it could be interesting to represent them in two distinct models that work simultaneously and have to be synchronized. Moreover, the interface standardization enables us to exchange different control models with the same physical emulation model. To represent the implementation of RFID technologies, with fixed readers, the notion of synchronization points is implemented in the model, which are points where the physical system emits events to update the information system. This event update could launch a decision process that will react by acting on the emulation model. Chapter 8 will be dedicated to this concept.

1.4.5. *Model synchronization = HLA distributed simulation approaches*

To face flexibility and reactivity SC problems, recent research consists of developing adapted simulation environments, allowing the analysis and the evaluation before considering an operational deployment. In a supply chain context, we can imagine that building a unique SC model could be a very difficult task, that could lead to simplifying, to strong hypotheses and finally to unrealistic results. Furthermore, running such a model could lead to data problems. As a result, there is a real need for distributed simulation (DS) in SCM, i.e. a unique control system could manage several physical system simulation models (Figure 1.18) or such an implementation needs a communication protocol allowing the exchange of information between the various components.

The appearance of distributed simulation specification standards allows us to facilitate the implementation of such simulations. A treatment in distributed simulation must be ensured to respect the existing causality relations. Moreover, it is important to take into account all events arising as time goes on, i.e., it is important to manage the time. In fact, the problems of message coordination between the partners of the supply chains and of synchronization of these partners must be managed. Chapter 9 will present various techniques of existing distributed modeling and simulation (DEVS (discrete-event system specification), SIMBA (simulation-based applications), HLA (high level architectures)) by exposing the characteristics.

To have an unambiguous description of the system and a definition of discrete-event simulation algorithms whose validity is founded and verifiable, DEVS and SIMBA formalisms can be useful to obtain a model formal specification. The American defense has developed the HLA (high level architecture) protocol in order to synchronize within a large simulation, simulators being carried out on different computers.

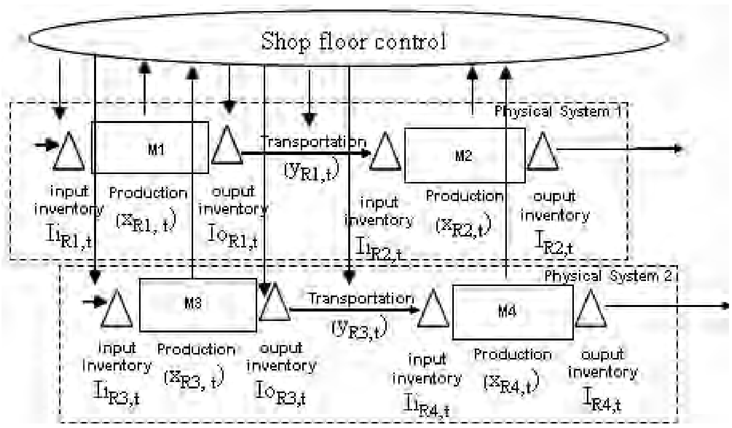


Figure 1.18. *Multi-line synchronization problems*

Chapter 9 relates to the study of the multi-line synchronization problems in internal logistics. Emulation and control models will be presented. This study is illustrated by an industrial case. This application takes into account two production sites containing several lines of assembly. HLA ensures interoperability between these various models.

1.5. Simulation software

To evaluate decision impact or to choose a management production or SC organizations, today it is natural to use simulation. Law and Kelton [LAW 91] summarize several reasons for the spectacular increase in the use of simulation in the field of manufacturing and SC systems. Consequently, today we can find a lot of relevant simulation software, increasingly used according to the complexity inherent in SC problems.

The main goal of Chapter 10 is to highlight simulation software functionalities. Firstly, a software typology will be proposed. This typology is established for discrete-event simulation, according to some literature criteria as event, activity or process approaches, etc. Secondly, supply chain test games will be presented. They are described by a knowledge model and particular formalism that will be explained. These test games are useful to choose or to analyze different simulation software. Finally, a special methodology will be proposed to help the modeler to specify his needs and choose his simulation tool.

1.6. Simulation methodology

1.6.1. *Evaluation of simulation models*

The simulation model quality evaluation is a hard problem. It is not possible to carry it out in a formal way (especially for discrete-event simulation). At least, we want to have a model behavior leading us to obtain simulation measure indicator values, as close as possible, as the same indicator measures on the real system. As we said previously, the model always contains approximations due to necessary simplifications. Thus, to evaluate this quality, we have to focus on the simulation system architecture, on the one hand, and on its proposed results (indicators), on the other.

Two criteria concern the study of reference architecture quality:

– the first concerns the architecture structural proprieties (nature of information, easiness of use and implementation, reusability, etc.);

– the other concerns the operational performances of the simulation model.

It is possible to study the structural aspects using a theoretical approach, without any application. However, on the other hand, operational performances must be evaluated by simulation runs.

1.6.2. *Reduction of simulation models*

In the simulation model, the number of "objects" of the model and the number of event occurrences can be very large. As a consequence, the simulation duration on a computer can be unacceptable for an operational use as stressed previously in section 1.3.4.2. Thus, it is necessary to reduce the model size of a supply chain.

To reduce the model of a supply chain, various approaches exist:

– abstraction, which is a "method for reducing the complexity of a simulation model while maintaining the validity of the simulation results with respect to the question that the simulation is being used to address" ([FRA 95] – Figure 1.19). Its objective is to reduce the calculus combinatory;

– aggregation, which is a "form of abstraction by which a set of data or variables with common characteristics can replaced by an aggregated piece of data or variable" [MER 87];

– number of events reduction which consists of replacing "part of a discrete-event model by a variable or formula" ([ZEI 76]).

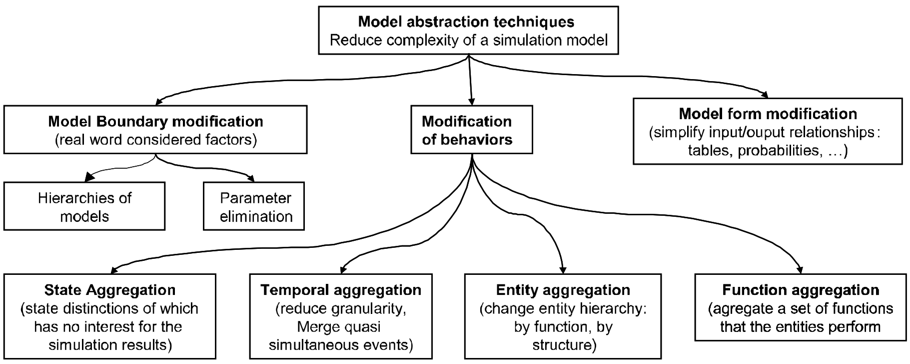


Figure 1.19. *A taxonomy of a model: abstraction techniques [FRA 95]*

1.6.2.1. *Reducing model literature review*

Even though most research concerning model reduction relates to manufacturing flows, it could be useful to analyze their results, especially concerning reduction problems, in order to highlight similarities between manufacturing process simulation models and SC simulation models.

Amongst various authors, Zeigler was the first to deal with the reduction simulation model problem [ZEI 76]. In his view, the complexity of a model relates to the number of elements, connections and model calculations. He distinguished four ways of simplifying a discrete simulation model by replacing part of the model by a random variable, coarsening the range of values taken by a variable and grouping parts of a model together.

Innis *et al.* [INN 99] first listed 17 simplification techniques for general modeling. Their approach was comprised of four steps: hypotheses (identifying the important parts of the system), formulation (specifying the model), coding (building the model) and experiments.

Brooks and Tobias [BRO 00] suggest a "simplification of models" approach for those cases where the indicators to be followed are the average throughput rates. They suggest an eight stage procedure. The reduced model can be very simple and then an analytical solution becomes feasible and the dynamic simulation redundant. Their work is valid in cases where the required results are averages and where the aim is to measure throughput.

Hung and Leachman [HUN 99] propose a technique for model reduction applied to large wafer fabrication facilities. They use "total cycle time" and "equipment utilization" as decision-making indicators to do away with the work center (WC). In their case, these WC have a low utilization rate and a fixed service level (they use standard deviation of the batch waiting time as a decision-making criterion).

Tseng [TSE 99] compares the regression techniques applied to an "aggregate model" (macro) by using the "flow time" indicator. In fact, he suggests reducing the model by mixing "macro" and "micro" approaches so as to minimize errors in the case of complex models. Here again, for the "macro" view, he only deals with the estimation of flow time as a whole. For the "micro" approach, he constructs an individual regression model for each stage of the operation to estimate its individual flow time. The cumulative order of flow time estimates is then the sum of the individual operation flow time estimates. He then tries to mix the macro and micro approaches.

1.6.2.2. *The reducing model problem*

Within the framework of control decision-making scenario evaluation, such model reductions could be useful. Moreover, concerning SC planning, the more interesting decision-making level is the master planning. At this level of planning, load/capacity equilibrium is obtained via the "management of critical capacity" function or rough-cut capacity planning. Consequently, it could be interesting to put forward a reduced model (Figure 1.20 explains its principle) in which we find the bottlenecks and the "blocks" which are "aggregates" of the work centers required by released manufacturing orders (MO) [THO 05].

The WC remaining in the model are either conjectural and structural bottlenecks or WCs which are vital to the synchronization of the MO. All other WCs are "aggregated blocks" upstream or downstream of the bottlenecks.

By "conjunctural bottleneck" we mean a WC which, for the MPS and predictive scheduling in question, is saturated, i.e. it uses all available capacity. By "structural bottleneck" we mean a WC which (in the past) has often been in such a condition. Effectively, for one specific portfolio (one specific MPS) there is only one bottleneck – the most loaded WC – but this WC can be a different WC from the traditional bottlenecks.

We call a "synchronization work center" one or several resources enabling the planning of MO with bottlenecks and those without to be synchronized. To minimize the number of these "synchronization work centers", we need to find WC having the most in common amongst all this MO portfolio not using bottlenecks and which figure in the routing of at least one MO using them.

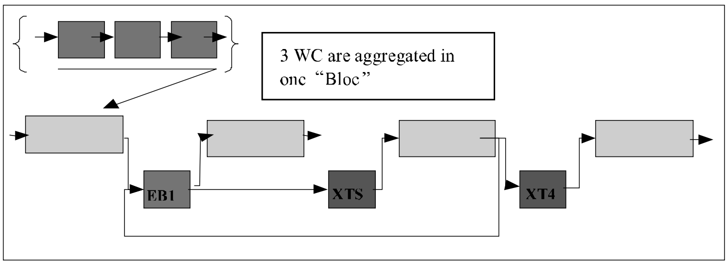


Figure 1.20. *Reduced model – principle*

A reduction algorithm highlights these so-called "synchronization" WC. In fact, the MO using structural or conjunctural bottlenecks may be synchronized and scheduled in comparison with one another thanks to the scheduling of these bottlenecks. However, for certain MO that do not use them, the synchronization WC will need to be used.

1.6.2.3. *Another state reduction using the bottleneck notion*

In this section we show examples of model reduction using the bottleneck notion.

With this modeling approach, the "physical part" of the factory is modeled as a network of interconnected flow shops with the following hypothesis:

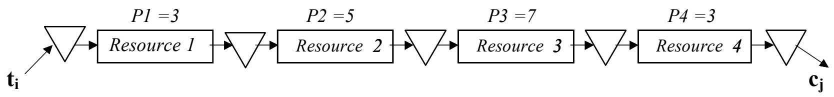
– in each flow shop, items cannot overtake each others;

– in a given flow shop, there can be an identical machine in parallel;

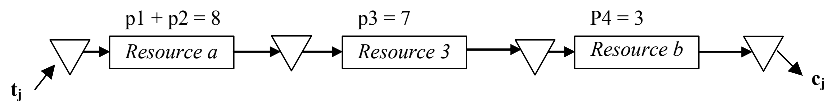
– an item is launched in a given flow shop only when all its components are available (assembly);

– these hypotheses are consistent with the tendency to use the “product line” organization of a business:

- detailed model,



- reduced model (state reduction using the bottleneck notion),



- industrial application: this reduction method has been applied (i.e. [TEL 03]) to a factory included in an aeronautic supply chain. The model of the factory is shown on the right side of the following figure. The reduced model using this type of method is presented on the left side of the figure. There is a strong reduction of the number of resources nevertheless modeled in a validation phase; the results of the simulation with the reduced model have been compared successfully with the real case.

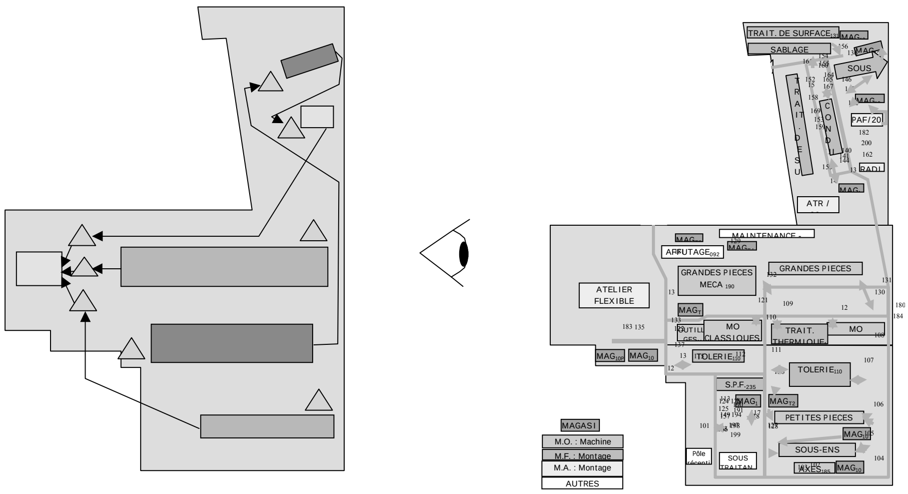


Figure 1.21. *Model reduction – a case study*

1.7. Conclusion

In this introductory chapter we have presented the main concepts which are used in supply chain management simulation. The specificities of this type of simulation and the modeling problem difficulties in this context have been highlighted. Different types of approaches and models have been presented to solve this problem. Finally, the links between the distribution level of both the system and the model have been characterized.

The remainder of the book includes three mains parts.

The first part takes the viewpoint of the simulation model types:

– continuous simulation (Chapter 2);

– discrete-event system – event-driven or time bucket-driven (Chapter 3);

– simulation games (Chapter 4).

The second part takes the viewpoint of the distribution level of the system and the model:

– centralized approaches (Chapter 5);

– interest of agents for supply chain simulation (Chapter 6);

– decisional system simulation of a business network with MAS (Chapter 7);

– simulation for product-driven systems (Chapter 8);

– HLA distributed simulation approaches for supply chain (Chapter 9).

The third and final part is dedicated to the simulation products (Chapter 10).

Even if we are convinced of the importance of the simulation methodology, no part of this book is explicitly dedicated to this aspect. However, the simulation methodologies (reduction simulation models, simulation model validation and simulation analysis) will be mentioned throughout the different chapters:

– a presentation of such simulation concepts and techniques highlighted in Chapter 1;

– applications of these concepts and techniques in case studies that illustrate the pivotal role of simulation in the decision-making process.

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