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A HYBRID SYSTEM DYNAMICS-DISCRETE EVENT SIMULATION APPROACH TO SIMULATING THE MANUFACTURING ENTERPRISE

by

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A dissertation submitted in partial fulfillment of the requirements
for the degree of the Doctor of Philosophy
in the Department of Industrial Engineering and Management Systems
in the College of Engineering and Computer Science
at the University of Central Florida
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ABSTRACT

With the advances in the information and computing technologies, the ways the manufacturing enterprise systems are being managed are changing. More integration and adoption of the system perspective push further towards a more flattened enterprise. This, in addition to the varying levels of aggregation and details and the presence of the continuous and discrete types of behavior, created serious challenges for the use of the existing simulation tools for simulating the modern manufacturing enterprise system. The commonly used discrete event simulation (DES) techniques face difficulties in modeling such integrated systems due to increased model complexity, the lack of data at the aggregate management levels, and the unsuitability of DES to model the financial sectors of the enterprise. System dynamics (SD) has been effective in providing the needs of top management levels but unsuccessful in offering the needed granularity at the detailed operational levels of the manufacturing system. On the other hand the existing hybrid continuous-discrete tools are based on certain assumptions that do not fit the requirements of the common decision making situations in the business systems.

This research has identified a need for new simulation modeling approaches that responds to the changing business environments towards more integration and flattened enterprise systems. These tools should be able to develop comprehensive models that are inexpensive, scalable, and able to accommodate the continuous and discrete modes of behavior, the stochastic and deterministic natures of the various business units, and the detail complexity and dynamic complexity perspectives in decision making.

The research proposes and develops a framework to combine and synchronize the SD and DES simulation paradigms to simulate the manufacturing enterprise system. The new approach can respond to the identified requirements in simulating the modern manufacturing enterprise systems. It is directed toward building comprehensive simulation models that can accommodate all management levels while explicitly recognizing the differences between them in terms of scope and frequency of decision making as well as the levels of details preferred and used at each level. This SDDES framework maintains the integrity of the two simulation paradigms and can use existing/legacy simulation models without requiring learning new simulation or computer programming skills.

The new framework uses a modular structure by which the SD and DES models are treated as members of a comprehensive simulation. A new synchronization mechanism that that maintains the integrity of the two simulation paradigms and is not event-driven is utilized to coordinate the interactions between the simulation modules. It avoids having one simulation paradigm dominating the other. For communication and model management purposes the SDDES formalism provides a generic format to describe, specify, and document the simulation modules and the information sharing processes. The SDDES controller which is the communication manager, implements the synchronization mechanism and manages the simulation run ensuring correct exchange of data in terms of timeliness and format, between the modules. It also offers the user interface through which users interact with the simulation modules.

In loving memory of my Mother

ACKNOWLEDGMENTS

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I appreciate all encouragement and help from all faculty and staff of the Industrial Engineering and Management Systems Department at the University of Central Florida. And my sincere thanks and gratitude to Sandra Archer, Director of the Office of University Analysis and Planning Support for her understanding, support, and help and to the good friend Mohammad Fayez, Ph.D. for his encouragement.

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CHAPTER 1: INTRODUCTION

Businesses are facing unprecedented levels and types of competition at a worldwide scale. And this environment is continuously evolving. The flat world is pushing higher the levels of complexity in managing the already complex enterprise systems. The even-more complex system is the manufacturing enterprise where manufacturing and non-manufacturing functions coexist. The manufacturing enterprise system is invariably complex dynamic system and this complexity keeps increasing with the increasing levels of integration and the adoptions of the system perspectives and those sophisticated information technologies of today. Managers running such integrated enterprises in such business environments need new dynamic, comprehensive policy design and testing tools that are effectively and efficiently holistic, yet simple, scalable, and upgradable as the enterprise evolves.

Dynamism is critical in effectively managing complex systems. Still, managers fail to account for control actions which have been initiated by them or by others and not yet have their effects observable because of the misperception of feedback information and time delays involved in causing the dynamic behaviors of the systems (Lertpatarapong, 2002; Sterman, 2000; 1989). The success of an organization can only be achieved with managing manufacturing and other functions in a logical association with one another. Policies of empowering and enabling individuals often prove to be counterproductive unless managers account for the interconnections and long term impacts of their local decisions (Wu, 2002, Senge and Sterman, 1994).

A comprehensive simulation tool that captures the dynamics of the enterprise system and recognizes the role of feedback information in particular, and in the same time is scalable and can keep being simple as the enterprise evolves should be of a significant value. In the context of the manufacturing enterprise, it has moved from being an economy of scale to an economy of scope and is becoming a global economy of mass customization (Vernadat, 2002). And although there could be different ways to describe the goal of a manufacturing enterprise, the core of these is to create money and increase the wealth of the shareholders. All activities within the enterprise must be streamlined in that direction. Managers need to overcome the traditional organizational barriers and run their facilities in a more flexible, integrated and dynamic manner.

But trade-offs among various business units' objectives exist. The fact is that the manufacturing enterprises consist of manufacturing and non-manufacturing functions. For instance, the contradictory relationship and the, seemingly, conflict of interests between accountants and manufacturing analysts have been indicated (Viswanadham, 2000; Reid & Koljonen, 1999; Sterman et al., 1997; Wu, 1992; Baudin, 1990). Accountants want to limit spending while manufacturing analysts want more to spend. Many published reports have clearly indicated the need to combine the aggregate and operational levels of management in simulating the system. Reported cases showed that using the most advanced equipment and producing the same product quality as competitors do not offer a competitive advantage (Wu, 1992) unless marketing, customer relations, financial aspects and other professional supporting functions are coordinated. Implementing a total quality management (TQM) program can dramatically improve the operational level performance but could lead to a significant decline in financial performance (Sterman et al., 1997) unless coordination with an overall simulation model of the organization is achieved.

It becomes impractical to achieve the organization goals unless processes and activities within the organization are synchronized, coordinated, and integrated. The evolution of the information systems from materials requirements planning (MRP) via manufacturing resource planning (MRP II) through computer-integrated manufacturing (CIM) and enterprise resource planning (ERP) systems reflects this fact.

With the adoption of integration and system approaches in managing the manufacturing system and the pressure imposed by the increased competition and rapidly changing business environment, the need has arisen for new simulation modeling tools.

Simulation modeling has been successful and effective in simulating the manufacturing system. It is traditionally carried out using discrete event simulation (DES). But DES has limited the scope of simulation to detailed analysis techniques and at the operational levels (Huang *et al.*, 2003; Smith, 2003; Lee *et al.,* 2002a; Baines and Harrison, 1999). As systems get bigger and more integrated, DES faces serious challenges. In the one hand the detailed approach of DES is not appropriate for the strategic aggregate levels of decision making. Besides, the data needed for such data-driven simulation approach is not normally available at these levels. On the other hand the complexity of the DES simulation model increases exponentially with the size of system being modeled. When the focus is the entire manufacturing enterprise system, developing DES models can be impractical.

The stability of the enterprise system implies the robustness of the system to sources of variations (equipment failure, performance variation, product changes, sales variations, competitors' actions, market changes, etc.). Detailed approaches like DES at the operational levels do not address the problem of stability as well (Rabelo et al., 2005). The complex, nonlinear cause-and-effect relationships with the impact of the feedback loops and time delays cause the system to respond to variations in input data with a tendency to amplify them and with fluctuations. Such fluctuations must be recognized and dealt with through the underlying causes, not the apparent consequences. The interest in the study of the stability of the system has started with the application of the control theory concepts to industrial systems by Forrester in the mid 1950s (Edghill and Towill, 1989). The study of stability and reactions to exogenous inputs must be done before any detailed analyses, and should be done over a long range. Meanwhile, the assumptions of statistical distributions in the DES cannot be considered fixed over long periods of time.

Meanwhile, simulations based on system dynamics (SD) methodology (Forrester, 1965) have showed very good results when used for the simulation of various social and economical systems. By definition SD is a system thinking approach that follows an integrative perspective in modeling systems while recognizing the information feedback characteristics so as to show how organizational structure (in policies), and time delays (in decisions and actions) interact to influence the behavior of the system (Forrester, 1965).

SD is appropriate as a system thinking approach, for modeling large systems and the higher levels of decision making where aggregation is preferred. An SD model is an intuitive dynamic picture of the perceived cause-and-effect relationships among the real system components. It focuses on system structure and the policy decisions that are embodied in the feedback loops, not on individual localized decisions or hypothesized data. Much less data is required for SD than for DES. The complexity of the model increases linearly so that complex system can be modeled with relatively simple models.

SD offers a theory of behavior of systems and it emphasizes the understanding of how behavior results from corporate structure and policies. It targets top management levels and is intrinsically appropriate for the design of management policies. Some of its application areas are corporate planning and policy design, supply chain management, public management and policy, biological and medical modeling, energy and environment, theory development in natural and social sciences, complex nonlinear dynamics and others.

We propose to combine the SD and DES in a hybrid discrete-continuous approach (we will call it SDDES) to simulate the manufacturing enterprise. This simulation methodology is expected to offer a simple, comprehensive, scalable, non-expensive dynamic policy design tool that fits the different scopes and planning frequencies of management levels. It combines the effectiveness of DES at the operational and detailed levels with the simplicity and overall system thinking approach of SD at the aggregate levels of management. The SDDES enterprise simulation model is proposed to consist of a comprehensive SD model for the enterprise system and connected to it is a number of DES models for selected operational and tactical functions as dictated by the analysis needs.

Because of the differences in structure, view of the world, state updating method, and time advance mechanisms, of the SD and DES simulations, the combination of them will follow a distributed-simulation-like arrangement that will be implemented in a modular format. There are no special requirements that SD or DES simulations have to meet to be utilized in SDDES. This implies the need for a methodology to synchronize these simulations. A synchronization algorithm is proposed for that purpose along with the *communication controller* whose function is managing the interacting simulations and implementing the synchronization algorithm.

1.1 The Purpose of This Research

This research recognizes the difficulties and challenges facing the use of DES techniques in simulating the integrated manufacturing enterprise, and the potentials and opportunities that SD offers as a continuous, system thinking approach to develop comprehensive simulation models of large scale complex systems. This research also investigates the adequacy of the existing hybrid and distributed simulation approaches in satisfying the needs of simulating the integrated manufacturing enterprise system. The research proposes and develops a hybrid continuous-discrete simulation methodology that combines SD and DES to simulate the manufacturing enterprise. The new methodology is directed towards building simulation models that are sophisticated yet simple and inexpensive and can encompass the aggregate and operational decision making levels in the enterprise to support management in developing their policies and testing them comprehensively.

1.2 Research Premises and Directions

This research follows and investigates the following research directions:

1. Managers of the integrated manufacturing systems need new simulation tools that can accommodate the differences between management levels in a holistic, enterprise-wide level.
2. Simulation models of modern manufacturing systems should incorporate in the same simulation, the operational and the aggregate management levels in a dynamic feedback-based structure
3. Current discrete and continuous simulation approaches fall short in meeting the challenges created by integration in manufacturing enterprises
4. The simulation of the integrated manufacturing enterprise should be approached using new hybrid continuous-discrete methodologies
5. The existing frameworks to implement hybrid simulation are inadequate for meeting the needs of managing an integrated manufacturing enterprise
6. SD and DES can complement each other for simulating the large, dynamic, integrated manufacturing enterprise system

1.3 Contributions

The contributions of this research include the following:

1. A new hybrid system dynamics-discrete event simulation approach that has the potential to overcome the difficulties facing existing simulation techniques for the simulation of the manufacturing enterprise system. The new approach allows using existing/legacy simulation models and does not require learning new simulation skills.

2. A new synchronization mechanism to coordinate the interactions between the continuous system dynamic models and the discrete event simulation models.
3. A functional design of the SDDES controller that is the core of the SDDES simulation approach. It implements the synchronization mechanism and manages the interactions between the SD and DES models.
4. An approach to extend the applicability of SD to the manufacturing applications and overcome its limitations in modeling detailed situation.
5. An approach to enhance the usability of DES in modeling large complex systems and overcoming the challenges it is currently facing

1.4 Chapter Outline

The remaining of this dissertation is organized as follows. Chapter 2 presents a review of the literature related to the research objectives. And as the proposed SDDES uses a distributed simulation-like structure, Chapter 3 studies the existing synchronization methodologies for the distributed simulation arrangements. Chapter 4 describes the research methodology. Chapter 5 describes the design of the SDDES simulation framework: the modular structure, the SDDES module formalism, the synchronization mechanism, and the communication controller. Chapter 6 presents the results of the experimental analysis of the proposed methodology. Chapter 7 summarizes the conclusions of the work and suggest directions for further research.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews and discusses the concepts related to this research, starting with an introduction to the manufacturing enterprise as viewed in this work. A brief review of the enterprise resource planning systems as they are often used to refer to the enterprise system itself will be made. Then a review of the enterprise modeling and simulation approaches will be presented with more details about the discrete and continuous simulation. The application of the different paradigms of simulation to the manufacturing system domain will then be discussed leading to defining the perceived gap in simulating the modern manufacturing system with the existing simulation modeling techniques.

2.1 The Manufacturing Enterprise System

The decision making processes in business systems are classified into strategic, tactical, and operational levels. Examples of activities performed and decisions made at each management level are shown in Table 2-1. The strategic level activities include establishing the philosophy and goals of the enterprise, formulating the management policies, allocating resources, and determining new products and investments. The tactical level activities are based on the strategic decisions and include establishing the functional control objectives, planning and selecting courses of action, acquiring and allocating resources to divisions and departments, preparing detailed work programs, and determining improvement plans. The operational level activities are the execution of the tactical decisions. They include measuring performance and preparing performance reports, in particular, about the exceptional or unusual performances. A comparison with respect to the nature of systems and information and types of problems and decisions is presented in Table 2-2 (Anthony and Jovindarajan, 1998; Hitomi, 1996).

Table 2.1 Example of contents of activities at the management levels

Strategic Level	Tactical Level	Operational Level
Choosing company objectives	Formulating budgets	
Planning the organization	Planning staff level	Controlling hiring
Setting personnel policies	Formulating personnel practices	Implementing policies
Setting financial policies	Working capital planning	Controlling credit extensions
Setting marketing policies	Formulating advertising programs	Placement of advertising
Setting research policies	Controlling research organization	
Choosing new product lines	Choosing product improvements	
Acquiring a new division	Deciding on plant rearrangements	Scheduling production
Deciding on non routine capital expenditures	Deciding on routine capital expenditures	
Acquiring unrelated business	New product or product brand line	Order entry
Adding product line	Expanding a plant	Production scheduling
Adding direct-mail selling	Advertising budget	Booking TV commercials
Changing debt/equity ratio	Issuing new dept	Cash management
Inventory speculation policy	Deciding inventory levels	Reordering an item
	Formulating decision rules for operational control	Controlling inventory
	Measuring, appraising, and improving management performance	Measuring, appraising, and improving workers' efficiency

The classification of an activity or a decision as strategic, tactical, or operational should not ignore the overlaps between the strategic and tactical and between the tactical and operational. Such overlaps should occur in coordinated integrative way. Dealing with a function as strategic, tactical or operational should be based on the scope of the impact of the decisions made in that function.

Table 2.2 Charactristics of the three management levels

	Strategic	**Tactical**	**Operational**
	Nature of systems and information		
Structure	Essentially unsystematic	Both formal and informal	Primarily systematic
Nature of information	Mostly external Future oriented Expected results	Financial core External and internal Planned and actual	Much non monetary Internal Actual
Accuracy	Rough	Fairly accurate	Accurate
Timeliness	Speed usually not crucial	Speed more important than accuracy	Real time
Stored data	Relatively unimportant	Important	Important
	Nature of problems and decisions		
Focus	One aspect at a time	Whole organization	Each task distinct
Nature of problem	Difficult to identify Unstructured Many alternatives Causal relationships	Precedents exist Much repetition Limited alternatives Some parts programmed	Prescribed rules Mathematical models Specific
Criteria	Social and economical	Efficiency and effectiveness	Efficiency
Constraints	None	Generally stated in strategy	Tightly constrained
Planning horizons	As far as can be seen	Months to year	Immediate future
Decision process	Some formal analysis Mostly judgments Many iterations Irregular	Much formal analysis Deadlines Few iterations Rhythmic	Repetitive
End product	Often one decision Goals, policies, strategies	Comprehensive plan for whole entity	Specific actions
Evaluation	Subjective and difficult Long interval	Less difficult Few times a year	Usually clear cut Immediate
Planning vs. control	Planning dominant	Planning and control	Control dominant
Source disciplines	Economics	Economics Social psychology System theory	Management science Operations research Physical science

Four main functions (Hitomi, 1996) are normally performed in the manufacturing enterprise; namely production, marketing, finance, and personnel. Products are designed and engineered, materials and resources are acquired, designed products are manufactured and marketed, and revenues are then collected and managed. All four functions are performed at all management levels with varying significances (see Figure 2-1).

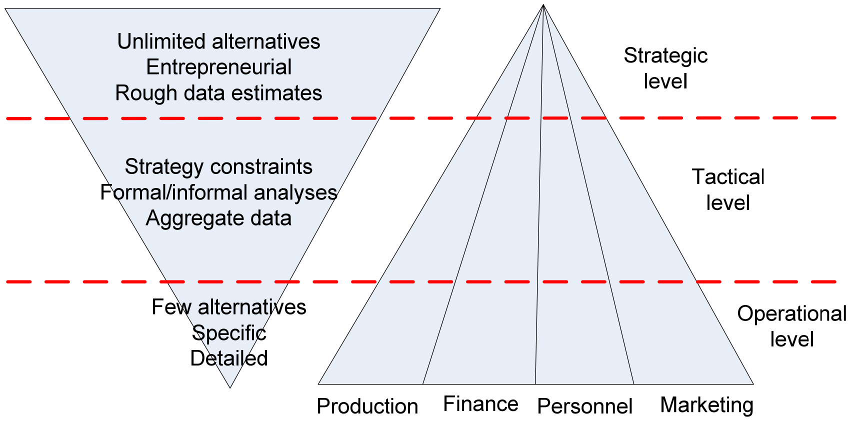


Figure 2.1 Functional structure levels in the manufacturing enterprise

The classification into different management levels, and the differences between functions and tasks performed at each level imply that these differences must be considered in analyzing the performance of the enterprise. Data in the operational control is in real time and relates to individual events, whereas data at the aggregate management levels is either prospective or retrospective and summarizes many separate events over relatively long intervals of time. Operational control uses exact data whereas higher management levels can use approximations.

It was noted (Anthony, 1998) that a system that can display to the management the current status of every individual activity could be developed but it should not be, because aggregate levels only need to know that the process is, or is not proceeding as planned; without too much details. Researchers have recognized these differences in the needed levels of details in data at the different management levels (Lee *et al.*, 2002b; Zulch *et al.*, 2002; Shapiro, 2001; Baines and Harrison, 1999). This becomes more important in the large-sized, integrated enterprise systems of today.

In our view, it is not only the differences in the levels of details in data that should be recognized. The frequency of needing data, revisions, and making decisions should also be considered. A view of the interactions between the management levels should consider an aggregation/disaggregation (data and time wise) function as depicted by Figure 2-2, where a triangle below line represents aggregation and a triangle above line represents disaggregation.

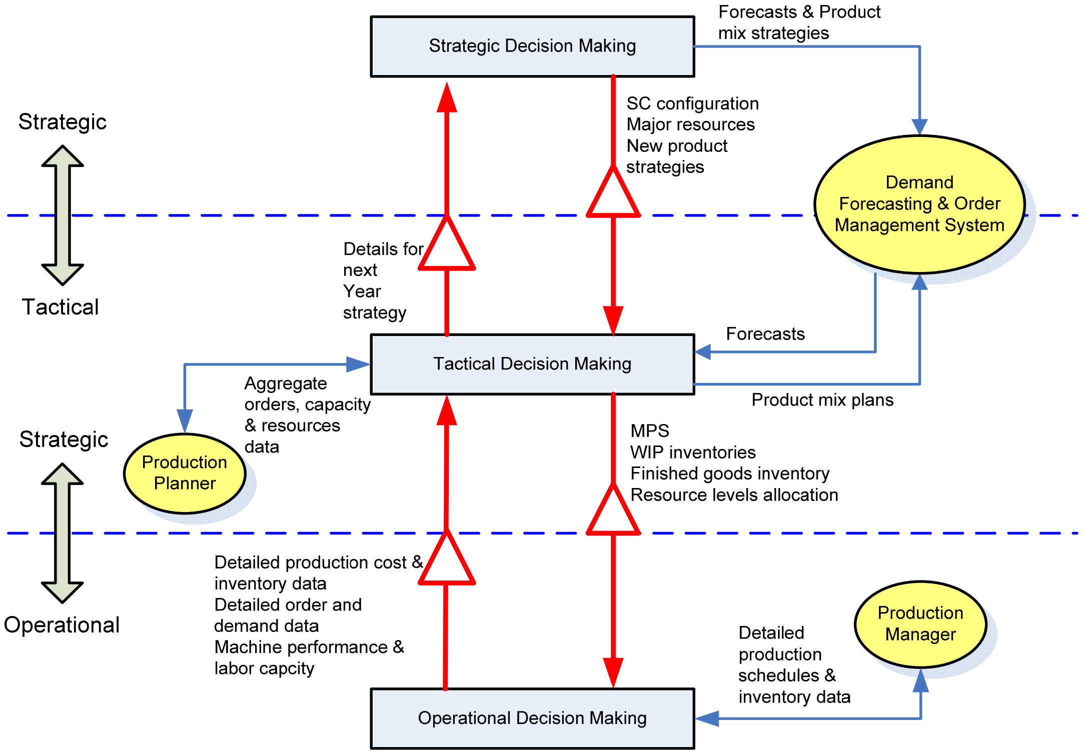

Strategic Decision Making
Forecasts & Product mix strategies
SC configuration
Major resources
New product strategies
Strategic
Tactical
Demand Forecasting & Order Management System
Details for next Year strategy
Forecasts
Tactical Decision Making
Aggregate orders, capacity & resources data
Product mix plans
Strategic
Production Planner
MPS
WIP inventories
Finished goods inventory
Resource levels allocation
Operational
Detailed production cost & inventory data
Detailed order and demand data
Machine performance & labor capcity
Production Manager
Detailed production schedules & inventory data
Operational Decision Making

Figure 2.2 Interactions among the three management levels

The distinction and the need to recognize the differences between the management levels becomes even more significant in the manufacturing enterprise due to the unique characteristic of the manufacturing enterprise which is the presence of the manufacturing functions and activities along with the non-manufacturing functions and activities. There are two directions of integration (Vernadat, 2002, Kosturiaks and Gregor, 1999) in the enterprise system: horizontal and vertical (Figure 2-3). Horizontal integration concerns the technological flow of materials from through the enterprise and is usually realized at a given organizational level (e.g. plant, cell, station). The vertical integration concerns integration across the management levels, that is the decision-making processes integration.

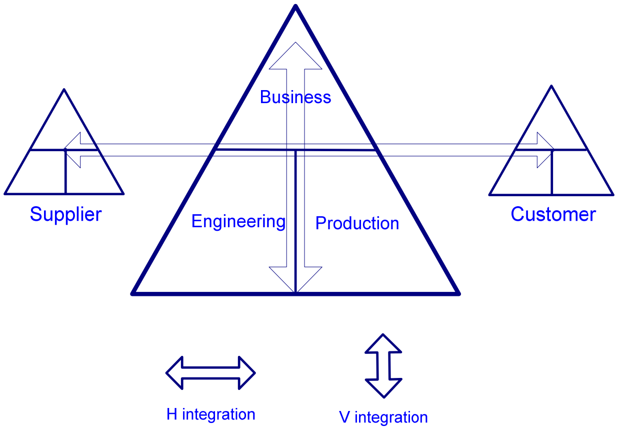


Figure 2.3 Horizontal and vertical directions of integration

The current research deals with the vertical integration of the manufacturing enterprise system. The manufacturing enterprise is defined as the vertically integrated firm encompassing the manufacturing and the non manufacturing functions.

2.2 The Enterprise Resource Planning System

It is fairly common to refer to the enterprise resource planning (ERP) system as the enterprise system. An ERP system is a database management system that acts to centralize the enterprise transactional data and distribute it to users. ERP is the third generation of data management systems. The first generation; the materials requirements planning (MRP) was developed in the 1970s in production scheduling contexts, to optimize materials inventories. The manufacturing resource planning system (MRP II), about a decade later extended MRP to become more comprehensive. It is a computer-based planning and scheduling and data management system designed for support the management's control over the manufacturing activities (Moustakis, 2000). First ERP systems were developed in the 1990s to run MRP II in a more integrated structure across all business units of the enterprise.

ERP is meant to ensure that every transaction in every activity within the enterprise is recorded. The risk associated with implementing ERP is huge (Botta-Genoulaz et al., 2005, Davenport, 2000). Implementation success rates in western companies, including big corporations, are around 33% according to Botta-Genoulaz *et al.* (2005) who also stated that:

> "… it is not enough to acquire the most advanced information systems to achieve better performance and integration. It is how usable these systems are … ERP systems should be extended by decision-making tools. This is one significant factor toward realizing the promise of ERP … But there are yet more serious issues".

Among these issues, assuming a successful ERP implementation is the appropriation of the system by its user, which is often seriously difficult (Hermosillo Worley *et al.*, 2005). A common side effect is the use of the electronic spreadsheets despite the presence of an active ERP system. Further, it is necessary for implementing ERP that the enterprise conducts a business process reengineering and remodeling for ERP to take over the enterprise data and information. By this it imposes a hierarchy on the company that reduces the flexibility and may create a rigid system, which can make future evolutions of the enterprise hard (Dillard and Yuthas, 2006).

The development of MRP, MRP II, and ERP indicates the increasing size of the of the enterprise system and the increasing levels of integration and needs for better management of the system. Modeling approaches can be advantageous over such transactional data management systems in establishing better coordination and understanding of the behavior and performance of the enterprise. Modeling can add the ability to perform what-if analysis and capture the inherent dynamics of the system to create future projections of behavior.

2.3 Enterprise Modeling and Integration

The current work is motivated by the integration in business systems. Enterprise integration concepts emerged, like other paradigms, as a result of the advances in information technologies and the changes in the business environment. Enterprise modeling (EM) is a prerequisite for enterprise integration (EI). A model is a description of a system or a situation that can be used to understand its behavior. EM is a representation of the structure, activities, processes, information flows, resources, people, behavior, goals, and constraints of a business. It can be both descriptive and definitional (Vernadat, 2002; Barton *et al.*, 2001; Fox and Gruninger, 1998). The role of an enterprise model is to develop enterprise design, analysis, and operational perspective. EI on the other hand implies breaking down the organizational barriers between the system units to improve synergy so that business goals are achieved in a more productive and efficient way.

The enterprise modeling and integration (EMI) techniques are particularly concerned with the creation of models to support the design of integrated systems. The capabilities of these are unlikely to match the requirements at the operational decision making in manufacturing systems (Barton *et al.*, 2001). The existing approaches for EM tend to offer fundamentally static models while providing little support for modeling the dynamics of the systems. Further, the enabling technologies to reuse and re-integrate EM models as the enterprise system evolves are lacking (Chatha and Weston, 2005). Meanwhile the manufacturing systems and other business systems, once designed and started, are inherently dynamic complex systems that evolve and change their behaviors over time.

2.4 Simulation Modeling

Systems can be modeled by physical or logical models. Logical models are also called mathematical models and they are either analytical or simulation models. The analytical models are many types including linear and integer programming, network models, and other operations research tools. The use of such models requires many assumptions and simplifications, which cannot always be practical. Relaxing these assumptions would make models very complex and unwieldy for analysis.

Simulation is a form of modeling that is used to dynamically analyze and evaluate the performance of systems as it changes over time to make future inferences. Technically, simulation is the process of designing and creating a computerized model of a real or proposed system for the purpose of conducting numerical experiments, for better understanding of its behavior for a given set of conditions. Simulation is more flexible than the mathematical analytical models and does not generally require those assumptions made with the analytical models. Virtually, any system can be simulated at any level of details.

Simulation models can be deterministic or stochastic. Deterministic models describe the system's dynamic behavior assuming no random effects and give same output for the same input. Stochastic simulation models describe the dynamic behavior when there are random effects and they give only estimates of the true system response since outputs are random variables themselves. This necessitates the need for several runs of the models to estimate the system response with the minimum variance.

Simulation models can also be discrete or continuous depending on how the variables included in the model change over time. When the state of the system (represented by selected variables) changes discretely at specified points in simulated time then the simulation model is discrete and those points in time are the event times. When the change is continuous over simulated time and is cause by the progress of time then the model is continuous (Banks et al., 2005; Pritsker et al., 1997).

There are two ways of being discrete: the time-stepped and the event-stepped (Law and Kelton, 2000). Time-stepped models update the system state at each preset time step. Event-stepped (event-driven) models update the system state upon the occurrence of some events that affects the state. Event-driven (discrete event simulation; DES) is the common discrete simulation approach.

Figure 2-4 compares continuous and discrete system state updating. The state is updated only at times of the occurrence of the events (the start or the end of an activity). Between events the state is ignored or assumed unchanged. In continuous simulation the state variables are defined as functions of time and they change in value because of time passing. Simulation time in DES advances from an event time to an event time. In continuous simulation, time advances in fixed steps. The step size is selected to achieve the desirable accuracy.

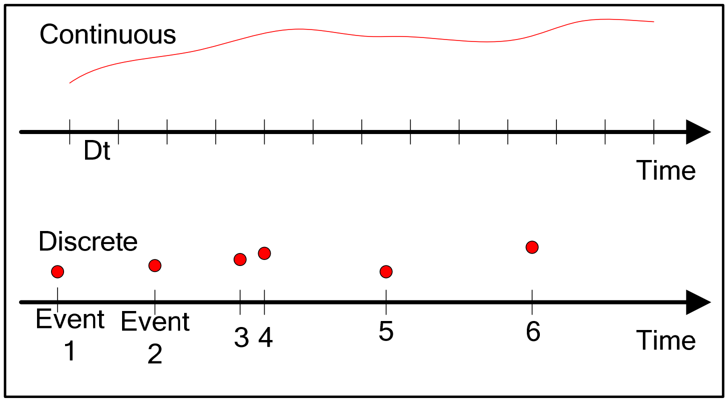


Figure 2.4 Updating state over simulated time in continuous and discrete simulation

Ignoring the system state between events in DES can lead to erroneous evaluation of the system performance. The validity of this assumption depends on the nature of the system being modeled and the desirable accuracy and resolution of the simulation model. For instance, assume a machining workstation that is modeled by a DES model. If the system state is measured by the number of parts at the workstation, then the state does not change except by the events of the arrival and departure of the parts. If the state variable of interest is the level of completeness of processing then it has to be observed continuously because as long as the workstation is running values of the level of completeness is changing. Observing the machine at the events of start or finish may not be enough to describe its behavior.

The point being made here is that there are parameters and situations in the same system that are better be simulated by DES and others that better be simulated by continuous simulation. In practice, DES is commonly used to approximate continuous parameters. If, for instance, a continuous variable is approximated by DES, due to the way the state is updated in DES overestimation or underestimation of the continuous parameter will be obtained. This is depicted in Figure 2-5. Further, there may not be events to be assumed in an efficient way to reduce the times between events in order to improve the approximation.

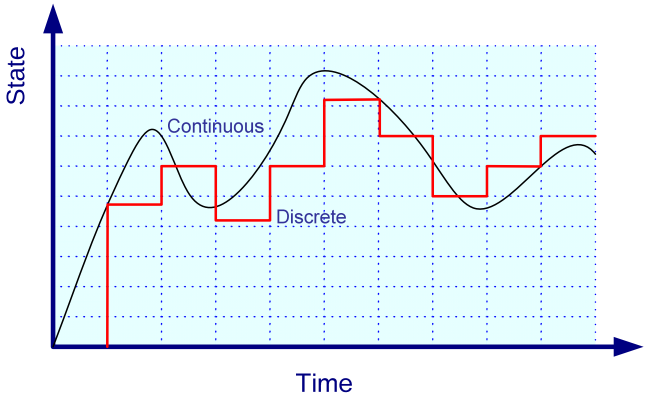


Figure 2.5 Discrete vs. continuous state estimates

2.4.1 Discrete event simulation

The entity-flow view is the common DES simulation approach. *Entities* flow through the system and compete for the *resources* and use these resources to do *activities* or have activities done onto them. If resources are busy, entities wait in *queues* until resources become available. Seizing a resource, releasing it, starting or ending an activity, and entering or exiting the system, etc. are all *events*. Events are timeless occurrences and only their occurrence can change the system state. The terms in italics above are the core elements of the DES model.

The simulation calendar is a list of events that are scheduled to occur during the simulation time. Upon the occurrence of an event the simulation engine schedules new events and/or reschedule others. For example, an entity seizes a resource. The simulation engine samples the time needed for the entity to end sizing the resource (seizure duration, e.g. processing time) and schedules the resource-release event and adds it to the calendar at a time equal to current time plus the resource seizure duration. Each entry in the calendar is made of the entity identifier, activity that the entity will interact with, and the event time. There are three ways to describe and define a DES model, as noted by Pritsker et al. (1997). These are by describing the changes in the state at each event time, describing the activities in which the entities engage, or describing the processes thorough which the entities flow. Consequently the DES model can be viewed in three ways:

1. The event view in which the modeler determines the events that change the state of the system and develops the logic of their occurrence. The model is the implementation of that logic.
2. The activity scanning view in which the modeler determines the activities that the entities engage and the conditions that cause the start or the end of the activities. This implies specifying the events in an indirect way. Events start and end the activities. Here the events are not explicitly scheduled. Instead they are linked to activities-related conditions that when true the events are scheduled and executed. The

conditions are scanned during the simulation time and all included activities must be scanned for their conditions at each time step.

3. The process interaction view which takes a relatively comprehensive approach to define the flow of entities through the system.

2.4.1.1 Output analysis in DES

DES is driven using data that are generated using appropriate probability distributions. Durations of activities, number of expected events, arrival rate, etc are all sampled using probability distributions that are chosen for fitting the real data in the real system at the best feasible level of accuracy. Consequently, model outputs are random variables and must be interpreted using statistical techniques.

The analysis of simulation output should consider whether the system is terminating or non-terminating. A terminating system has specific starting and ending conditions, which define the simulation run length. Run replications are necessary. Replications are repetitions of the model run using different sets of random numbers. This creates independent, identically distributed samples of data that can be analyzed statistically.

Analyzing the output of a DES model is summarized herein based on Law and Kelton (2000). Assume a terminating DES model that is run for n replications. Let X be the state variable of interest. For replication $j = 1,2,...,n$, the random variable X_j represents the state variable value for the replication. Unbiased point estimators for the mean and variance of the state variable are given by equations (1) and (2).

$$\overline{X}(n) = \sum_{i=1}^{n} \frac{X_i}{n} \qquad (1)$$

$$S^2(n) = \frac{\sum_{i=1}^{n} (X_i - \overline{X}(n))^2}{n-1} \qquad (2)$$

A $100(1-\alpha)\%$ confidence interval for the mean is calculated using equation (3), where $t_{n-1,1-(\alpha/2)}$ is the α-quartile of the t-distribution with $n-1$ degrees of freedom.

$$\overline{X}(n) \pm t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}} \qquad (3)$$

The correctness of the confidence interval given by (3) depends on the assumption that the X_j's are normal random variables. This assumption is rarely satisfied in practice and more stochastic investigations must be performed to assess the robustness of the confidence interval before making inferences on the performance of the system.

A non-terminating system on the other hand has no defined end conditions. A manufacturing system can be modeled as a non-terminating system where, although there may be shifts and workers may arrive and leave at specified times, the system itself is running continuously and each day is a continuation of the previous day. To analyze a non-terminating system a very long simulation run is made of the steady state performance is analyzed. The single long run is divided into sequences of observations that are approximately independent of each other. The batches of observations are used as if they are replications of a terminating system. The batch size is a function in the correlation structure of the system response. Batch size should be at least 10 times as large as the largest lag for which the correlation between observations remains significant. However, correlation will still be there. Observations at the end of a batch are correlated to observations at the beginning of the following batch. But if the batch length is large enough compared to the time extent of the correlation between individual observations then the approximation is acceptable. Pegden *et al.* (1990) recommended between 10 and 20 batches.

The elimination of the initial bias from the output is the hardest problem in analyzing the non-terminating simulations. Let X be the steady state random variable for a state variable in the simulation model and n data points $X_1, X_2, ..., X_n$ are collected for estimating its mean. Assume I as the initial system state (initial condition). As $n \to \infty$, $\Pr(X_n \leq x / I) \to \Pr(X \leq x)$. The steady-state mean of X is given by equation (4).

$$\mu = \lim_{n \to \infty} E\left(X_n \mid I\right) \qquad (4)$$

This makes estimating the mean hard as a finite n cannot be sufficient unless I is eliminated. A common way to do so is the graphical way of Welch (1983) which uses k independent runs each producing n observations, then an across-runs averages are computed by formula (5) (Alexopoulos and Kim, 2002):

$$\overline{X}_j = \frac{1}{k} \sum_{i=1}^{k} X_{ij} \qquad j = 1, ..., n \qquad (5)$$

Moving averages are then plotted for a given time window w against j. If a smooth plot results then observations up to j are truncated. If not smooth another time window is used. The choice of the time window can be a difficult problem. In addition, the truncated observations waste the computing resources before they are excluded.

DES has been an effective approach to simulate complex system and manufacturing systems in particular (at the manufacturing functions side as shown later in this chapter). It can describe the most complex systems, at any level of details. It allows analysts to track the status of individual entities and resources and to estimate numerous performance measures. However, it suffers major drawbacks. Analysts can only establish estimates of and correlations among variables and performance measures using statistics. Understanding the differences between correlation and causality is not always easy, especially when modeling the contemporary large sized integrated manufacturing systems. As was briefly shown the statistical analysis of the simulation output, being terminating or non-terminating can be a tedious task that becomes harder as the system becomes bigger and complex. Further, at the strategic levels, these outputs are hard to comprehend.

DES models allow analysts to evaluate the system performance for specific values of decision variables or control policies. They do not allow for determining the stability of the system in any region or neighborhood of those values or policies. This is critically important in complex systems where performance may be driven by hidden causal relationships that could be highly non-linear. In such systems, small deviations from the optimal decision point can cause disproportionately large changes in the system performance.

In addition to that, DES is too demanding for data. The task of input data preparation can be very difficult and tedious. Building and validating models is a very time and resources consuming. And the complexity of the model increases exponentially as the size of the system being modeled increases.

In a manufacturing enterprise, detailed data at the operational level are normally available at detailed levels. At aggregate management levels, data is not normally available in the level of details needed by DES (Zulch et al. 2002; Anthony and Govindarajan 1998). The qualitative and continuous nature of aggregate management levels parameters, also, creates challenges to the use of DES at these levels (Zulch et al. 2002; Baines and Harrison 1999). These drawbacks with DES become more critical when attempting to simulate the integrated manufacturing system. A review of reported cases is presented in a later section.

2.4.2 Continuous simulation

In continuous simulations the state variables change continuously over time. Such models often require the construction of influence diagrams (cause-and-effect diagrams) that show the relationships and interactions among the set of system variables. Associated with the influence diagrams is a set of mathematical equations that describe the rate of change of the state variables with respect to time. This set of equation is solved to estimate the system state. Compared to DES this is an important advantage since DES has no standardized way for describing the systems (Wu, 1992). Continuous simulations are generally more intuitive, simpler to build, and they need much less data and data preparation than DES. The state of the system in continuous models is known for any point in time not only at certain points in time.

A continuous system can be represented by the vector of its state variables; $\mathbf{X} \in \Re$ (Formula 6) where the set of n state variables; $X_i, i = 1,2,...,n$ changes in values continuously with time t:

$$\mathbf{X} = \begin{bmatrix} X_1 & X_2 & \cdots & X_n \end{bmatrix}^T \tag{6}$$

In practice, the state equation is not known. Instead the rates of change of the state variables over time are defined (Pritsker et al., 1997). Consequently, derivatives (the rate of change equations) are used in continuous simulation models. Only first order differential equations are used. If higher order equations are involved, they can be converted into first order sets. Differential equations are called ordinary if all of its derivatives relate to the same variable; typically time in simulation applications (Wu, 1992; Pegden et al., 1990).

Conceptually, a continuous simulation model is used to find solutions to complex differential equations using numerical techniques and given a set of initial conditions. Analytical solutions of these differential equations are practically impossible. Randomness may or may not be introduced but most often, continuous simulations are deterministic.

2.4.2.1 System Dynamics simulation

System dynamics (SD) (Forrester, 1965) is a well-elaborated methodology for continuous simulation. It is useful in capturing the dynamics of complex real world systems where delays and feedback loops are in effect. The fundamental concept is the recognition of the complex, nonlinear feedback processes inherent in the structure of the system. Economic and industrial activities are closed loop, information feedback systems, and models of such systems should preserve the closed loop structure. SD is the application of feedback concepts to social systems for analyzing and designing robust policies rather than making optimal decisions based on assumed forecasts. SD is a system thinking approach that takes an integrative perspective in modeling systems. Forester saw it as an approach to solving important problems at the top management levels (Sterman, 2000; Lyneis, 1980; Forrester, 1975; 1965).

SD uses causal and feedback loop structure and a few diagramming tools to describe the relationships among the factors that affect the performance of a dynamic system. The main diagramming tools are the stocks (also called levels) that are usually used to represent the system state variables, and the flows (also called rates) that represent the factors or the actions (the policies of the management) that influence the stocks. Stocks are modeled mathematically as the time integration of the sum of the flows connected to them. Flows can be modeled by any relevant form of mathematical relationships. Computer simulation is then used to solve these equations such that deterministic simulation experiments are conducted.

Feedback loops can be negative or positive based on the direction of influence that parameters have on each other. A negative loop is a series of causal relationships that tend to force behavior towards a certain goal value. A positive loop is self-reinforcing; it amplifies disturbances in the system to create even higher variations in behavior. Figure 2-6 shows a negative and a positive causal relationships and a positive feedback loop.

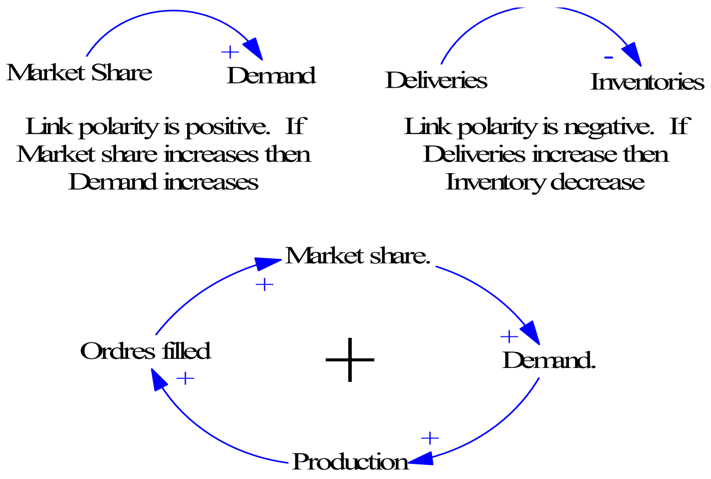

Market Share
+
Demand
Link polarity is positive. If Market share increases then Demand increases
Deliveries
-
Inventories
Link polarity is negative. If Deliveries increase then Inventory decrease
Market share.
+
+
Ordres filled
+
+
Demand.
+
Production

Figure 2.6 Negative and positive causal relationships and feedback loop in SD

The overlapping feedback loops that make up the model structure are mapped into stocks and flow rates. Stocks are mapped into time integrations. They accumulate the results of taken actions in the system. They create system continuity between points in time and they are changed only by flows. The flows depend only on present values of the stocks and other constant input values. They are mapped into simple algebraic formulas.

Stocks and flows are represented by rectangles and valves respectively. In Figure 2-7, Inventory and Goods on Orders are two stocks. Each stock can have one or more flows flowing into or out of it to increase or decrease its value. The arrows represent causal relationships. For instance Order Rate is a flow that is a function in Desired Order Rate, Adjustment time, Desired inventory level, and Inventory. Parameters other than stocks or flows are the auxiliary variables. The formulas for flows can be long and complex. To simplify them, they are broken down into pieces each represented by an auxiliary variable. Then the flow's formula is made up of these variables. The negative sign beneath Goods on Order indicates a negative feedback loop that starts with Order Rate, passes through Goods on Order, Arrival Rate, and Inventory, and ends at Order Rate.

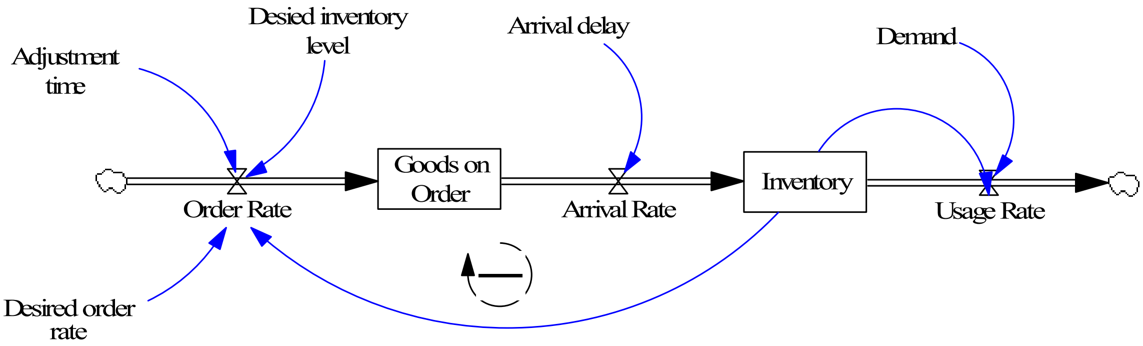


Figure 2.7 Levels and rates symbols as used in SD models

The SD model in its final form is the set of stocks that are interconnected by the set of flow rates, in an alternating fashion, as symbolized in Figure 2-8, in which stocks are rectangles and flows are valves. The arrows denote the relationships between them. The dashed arrows denote sharing data.

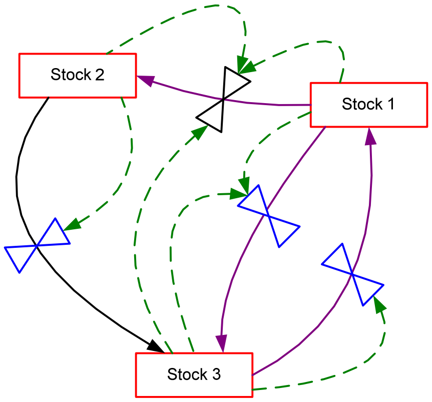


Figure 2.8 Generic structure of the SD model (Forrester, 1965)

The structure of Figure 2-8 implies that the stocks are influenced only through the flows while the flows are dependent on the stocks; that is dependent on the state of the system. For instance, in a manufacturing system, stocks can be the levels of the accounts payable or receivable, or the levels of inventories. The flows are the policies of managing inventory, production rate that uses the inventory, the policy of collecting or paying the accounts. Only through the policies the stock level can be changed. And for the management to decide the appropriate policies it has to monitor the stocks. The presence of feedback loops can be observed since stocks determine flows and flows influence stocks. A SD model in fact is a collection of overlapping feedback loops the capture the mutual interactions among all system components. Building a model starts with the identification of the related parameters to the objective of analysis then defining the causal relationships among them in a feedback structure. The stocks and flows are then defined out of these parameters and the model is finally mapped into the mathematical formulation.

When mapped into mathematical formulas, this structure should be able to describe any cause and effect relationship in the system while being mathematically simple. And as indicated by Forrester (1965, 1975) it should handle continuous interactions such that any discontinuities introduced by solution-time intervals (because of using numerical methods) do not affect the results. It should however be able to generate discontinuous changes in decisions when these are needed (which makes it the proper choice of a continuous approach for SDDES, where it interacts with independent DES models)

Solving a SD model starts with initializing the values of the stocks; that is the initial state of the system must be known. Given the state of the system, the management determines its policy to run and influence the system evolution and performance over time. Having determined the policy and set the system parameters by the management considering the starting system state, the new values of the stocks (new system state) can be calculated by adding the impacts of the policy (flow rates) on the starting state values. Flow rates (management actions) work to increase or decrease the values of the stocks. New system state then allows the management to review and modify, if needed, the policies undertaken. This loop continues until the end of the planning horizon. The rule is that stocks (system state) can only be influenced through the flow rates. This is realistic. For instance, the management cannot increase its product inventory except by increasing the production rate.

The continuous advance of time is broken into very infinitesimal time intervals of magnitude Δt. Numerical techniques are used. Figure 2-9 shows the calculations sequence in SD (Forrester, 1965). If current time is t_2 then the state (stocks) should be known at t_1. The system advances from t_1 to t_2 to reach system state at t_2. The state at t_2 is the result of the state at t_1 plus the effect of the flow rates during Δt from t_1 to t_2. At t_2, the stocks are calculated and using them the flow rates for Δt from t_2 to t_3 are calculated. And once they are calculated then the system state at t_3 can be determined. This calculations sequence reduces the dependence of the state on the old states. Only the state before Δt is used.

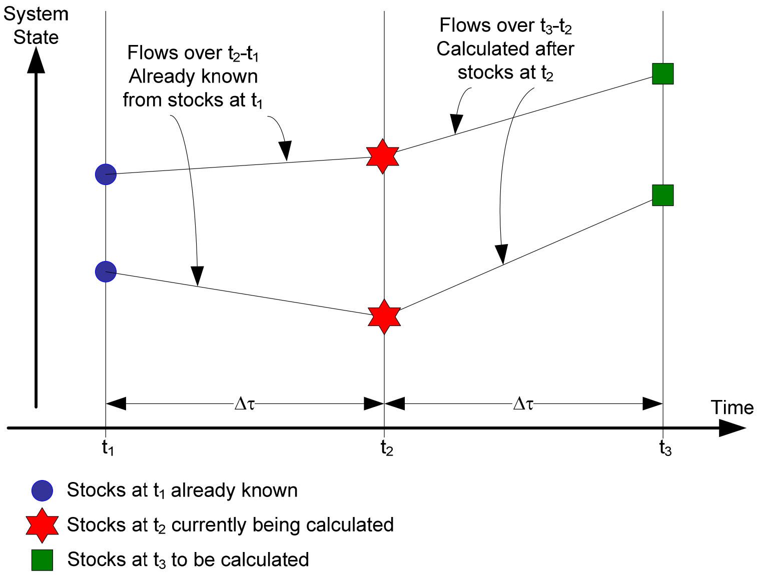

System State
Flows over t2-t1 Already known from stocks at t1
Flows over t3-t2 Calculated after stocks at t2
Δτ
Δτ
Time
t1
t2
t3
● Stocks at t1 already known
✶ Stocks at t2 currently being calculated
🟩 Stocks at t3 to be calculated

Figure 2.9 Computing sequence of SD

2.4.2.2 Generic mathematical formulas for the stocks and flows

Referring to Figures 2-9 and 2-10 and using $Stock$ to represent the system state and assuming two rates are affecting it: an $Inflow$ that increases its value and an $Outflow$ that decreases its value, the value of $Stock$ at any time t_i is given by equation (7):

$$Stock_{t_i} = Stock_{t_i - 1} + \Delta t(Inflow - Outflow)_{(t_i - t_{i-1})} \qquad (7)$$

As a numerical calculations approach, equation (7) is generalized to determine the value of the stock at any point in time $t$starting from time 0. The formula becomes the time integration of the net change made by the flow rates, as given by equation (8) where $Stock_0$ is the initial value of $Stock$. This is equivalent to the SD model structure shown in Figure 2-10 (without the Delay variable or the curved arrows).

$$Stock_t = Stock_0 + \int_0^t (Inflow - OutFlow)dt \qquad (8)$$

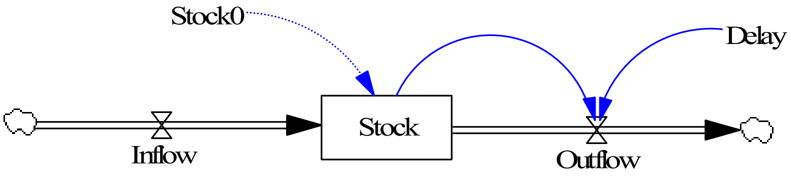


Figure 2.10 Stock and flow represented in SD models

On the other hand flows can take many mathematical forms. Still they are functions in the stocks. Flows are calculated for every time interval Δt. The value of the flow rate is the slope of the curve that represents the behavior of the stock over Δt. Flows are functions in the values of the stocks they are related to at the beginning of the interval. If a stock is to contain entities of any type (units of products, people, cash, water, etc.) then flows are then measured in terms of entities per unit time. From Figure 2-10, the $Outflow$ is defined by equation (9). The $Inflow$ can be a function of other stocks in the models, not necessarily the one shown in the figure.

$$Outflow_{(t_i - t_{i-1})} = \frac{Stock_{t_{i-1}}}{Delay} \qquad (9)$$

The parameter $Delay$ in equation (8) is a time period defined in the context of the system being modeled. It is the average time needed for the entire population of $Stock$ to flow to the next part of the system at the $Outflow$ rate. $Outflow$ rate is the rate at which the population of the $Stock$ leaves, so the rate is the size of the population divided by the time needed for the population to leave completely.

The formulas for flows are usually broken down into smaller components should they be complicated. In this case auxiliary variables are added to the SD model and each of them is calculated based on management policies as functions in the system state. Then auxiliary variables are algebraically summed to make up the definition of the flow. This maintains the fact that flows are functions in the stocks. Using auxiliaries simplifies model development and allows modelers to record information about detailed issues in the system structure. Consequently, auxiliaries and flows are functions in stocks and other auxiliaries. Equation (10) is generic for flows and for auxiliaries, where *f* and *g* are arbitrary functions.

$$\begin{aligned} Flows &= f(Stocks, Auxiliaries) \\ Auxiliaries &= g(Stocks, Auxiliaries) \end{aligned} \tag{10}$$

Delays are critical in SD models. The presence of time delays creates the dynamics in the system. Sterman (2000) emphasized that the inability of managers to recognize the impact of delays in the feedback system contributes to all problems faced by them. A stock is not normally consumed up or filled instantaneously. It takes time to build up inventory, for instance, and to deplete it. A management policy to order raw material at a certain rate will take time before making observable effect on the inventory level (until materials arrives from the supplier). This delay between actions and their impacts is the source of dynamics in the system and must be recognized in the model, which is the case in SD.

Equation (9) is a simple situation where it takes the time period *Delay* to consume the level of *Stock*. This is called first order delay function and it results in a simple exponential behavior of *Stock* over time. If the flow is a function in two cascaded stocks then a second order delay is present in the system. A stock-flow structure that creates 3rd order delays can be as shown in Figure 2-11. This is common in modeling manufacturing processes. Equation (9) applies here such that the outflow of the first level is the inflow to the next, and so on. Degrees higher than three can be defined similarly.

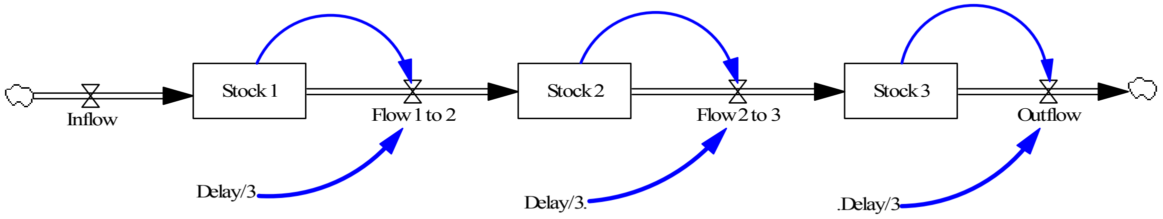


Figure 2.11 Third order delay structure in SD

The behaviors due to the 1st, 2nd, and 3rd order delays are shown in Figure 2-12 assuming a step increase in the input to the system. According to the real behavior of the system being modeled, the choice of the degree of delay in the definition of flows is made.

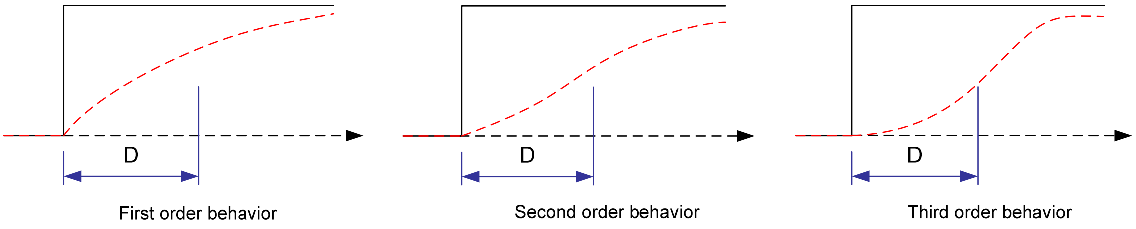


Figure 2.12 Behaviors of SD stocks due to various delays (Sterman, 2000)

The above description of the SD model shows a relatively simple approach that gives it an advantage over DES in modeling larger systems. Besides the minimal needs of data makes SD more appropriate than DES at the aggregate management levels. Further, SD by definition targets top management levels (Forrester, 1965) offering a strategic systemic view.

Industrial and economic systems are closed-loop feedback information systems. SD particularly recognizes the role of feedback information in creating system behavior. It offers a quantitative approach for relating organizational structure and corporate policy to growth and stability. Besides, such a closed-loop system exhibits behavior as a whole that is not evident from the examination of the individual parts and components of the system (Sterman, 2000). Major executive decisions represent a continuous process. Decisions are reached after a period of consideration. Actions are not taken immediately after decisions. Decisions are interpreted and smoothed and they then produce gradual changes as they overcome the resistance and inertia of the business units in the organization.

In any industrial system, there are usually considerable levels of aggregation. For example orders arrive as separate pieces of paper, but they are represented as a continuous order flow. The executives' interest, anyway, is above the level of individual transactions. A continuous flow model helps to concentrate attention on the central framework of the system structure, which is more orderly and unchanged than what would be thought. Diversion of attention toward separate isolated events tends to obscure the central structure of the system that we are trying to define and maintain running. A model should represent the continuously interacting forces in the system. The frequency with which measurements on real systems may happen to have been taken is not relevant to the frequency with which internal dynamic performance must be calculated (Sterman, 2000; Lyneis, 1980; Forrester, 1965).

Certain modeling requirements of the manufacturing system that SD can support are listed below:

1. A number of subsystems can be integrated to give a holistic system view. Manufacturing systems are made up of several units for which SD can offer an umbrella for integrative interactions.
2. It is appropriate as a system thinking approach, for modeling large scale systems and the higher levels of decision making where aggregation is preferred.
3. It focuses on the policy decisions that are embodied in the feedback loops, not on individual localized decisions.
4. It focuses on system structures not on hypothesized data and much less data is required than in DES
5. Strategic issues can be analyzed over long time horizons without difficulties with the statistical assumptions
6. Stability of the system can be analyzed for long time horizons even with minimum data.

7. It is easily generalized and generic concepts already exist for the different types of systems.
8. A model is an intuitive dynamic picture of the perceived cause-and-effect relationship among the real system components that is easy to present to top management personnel.
9. The complexity of the models increases linearly (Sterman, 2000) so that more complex systems can be modeled with relatively simple models.

2.4.2.3 The stock management model

It was predicted by Forrester (1991) that about 20 generic SD models would be developed to represent 90% of situations encountered by managers in enterprises. In fact, the majority of the SD models reviewed for this research uses some of Forrester's concepts he included in his early models in the 1950s. Forrester built models for a simple supply chain (Forrester, 1965; 1968) and for the whole world's economical dynamics (Forrester, 1973) using the same few modeling tools of SD. Sterman (1989) developed the stock management model (SMM) as a generic structure for modeling business functions. He combined Forrester's concepts as well as the works of Lyneis (1980) and Morecroft (1985). Sterman used SMM in building a comprehensive organization model in Sterman et al. (1997) and in his book Business Dynamics (Sterman, 2000). Lynies (1980) also explained a number of generic model concepts that were closely similar to Stermn's.

The SMM is a generic structure of the decision making problem concerned with the regulation of a system state. Decision makers facing such a problem seek to maintain the stock level at a particular target value. But stocks cannot be controlled directly and have to be influenced through the flow rates. The decision maker adjusts these flows such that the stock is at its desirable level. What makes the problem difficult is the presence of time delays between the initiation of a control action and the effect of that action. Further, there are time lags between changes occurring in a stock's level and the perception of these changes.

SMM is divided into two sections: the stock and flow structure, which represents the physical structure of the real system, and the decision making rules by which managers act to maintain the physical flow in equilibrium. The basic physical flow structure is made up of two stocks and three flows (Figure 2-13). It can represent the ordering of materials in a production system and receiving them, the work-in-process level and the finished products level, the level of people being hired and the level of workforce, or the accounts receivable and the money in hand and many other cases. Order Rate is the rate of ordering materials from suppliers. Supply on Order is the materials that have been ordered but not yet arrived. Acquisition Rate is the rate at which the materials that have been ordered arrive. Stock is the accumulated materials that have arrived. Loss Rate is the rate at which the materials are taken from the inventory. It has to be dependent on the value of the Stock. Similarly the Acquisition Rate has to be dependent on the Supply on Order level. Order Rate is a function of any meaningful parameters in the system.

The Acquisition Delay and Loss Rate both include some external parameters in their definitions. Loss rate can be influenced by customer order rate, attrition rate of people, recovery rate of patients, etc. Management can try to influence its value. Similarly Acquisition delay can be influenced by the management by arrangements with suppliers or some worker agents for example.

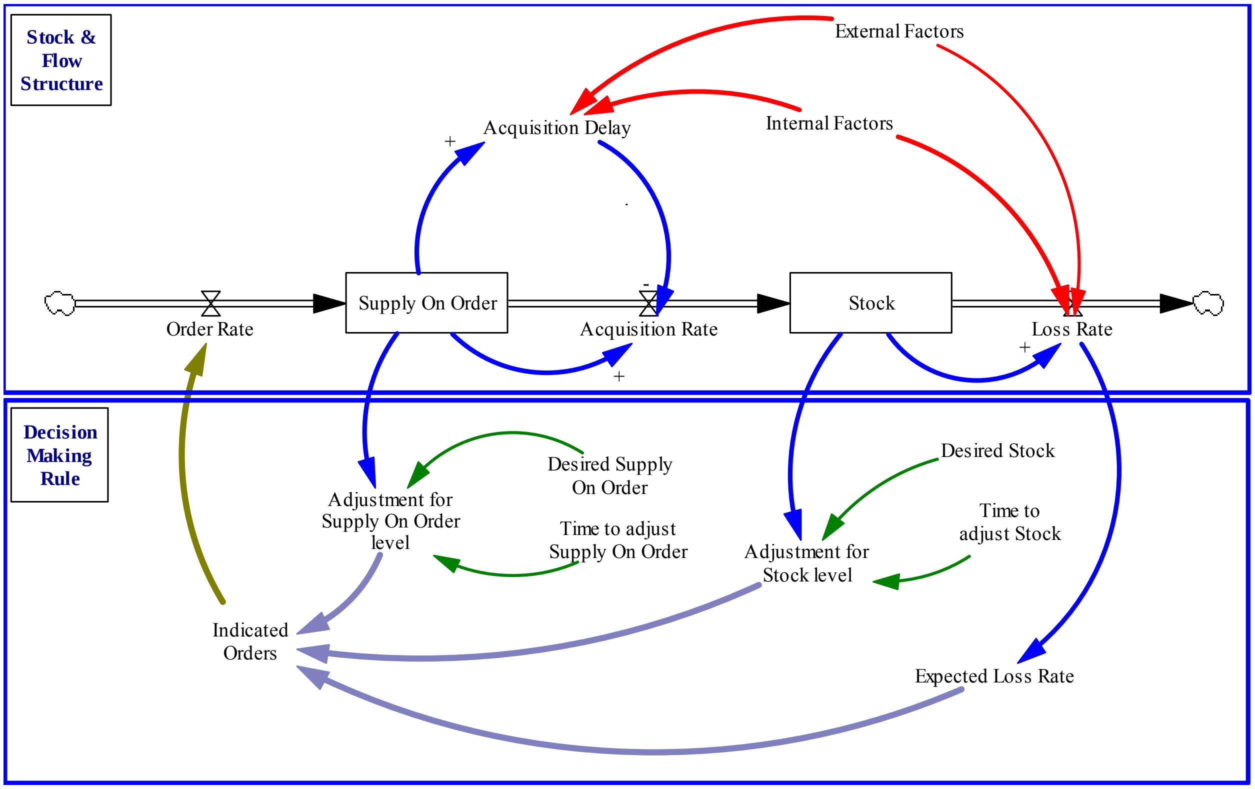


Figure 2.13 The stock management model structure

The management should set the policies to regulate the two state variables. There are desired levels for them that are decided by the management. As a control task, management monitors the actual levels and compares them with the desired levels to estimate the adjustments needed to maintain the target values. An adjustment however is over a period of time, not instantly. Some time is needed to move from the actual to the desired level. The action that the management actually takes to accomplish the adjustment is making new orders. So the adjustment policy will lead to estimating the Indicated Order Rate, which what the management believes the order rate that must be in effect to accomplish the adjustments, i.e. to maintain the system states at target values.

The Indicated Order Rate is the outcome of the policy setting process. Yet some input from other, mostly external parameters are needed. In the current example, it is the Loss Rate, i.e. the customer order rate or usage rate. The management should also estimate the expected loss rate so that its adjustment policy does not result in accumulating unnecessary stocks. This technically closes the feedback loop in which the adjustment policy is embodied. This feedback loop starts at the Loss Rate and ends at the Loss Rate. More examples of using the SMM are presented in Sterman (2000).

2.5 Hybrid Simulation

The world does not usually lend itself to using one form of abstraction at a time. Most, if not all real life systems; physical, industrial, business, social, environmental etc. are hybrid in nature. Whenever human decisions impact the system behavior and the environment, the hybrid systems can be better approximations (Lee et al., 2004; Lee et at., 2002b; Borshchev, et al., 2000; Zeigler et al., 2000). Using hybrid techniques is becoming a must as has been said by some (Levin and Liven, 2003). Modern technology applications; cars, robot, cell phones, digital watches, medical devices microwaves, washing machines, etc. are all areas for applying hybrid systems. By hybrid simulations we mean combined discrete-continuous simulations, which gives modelers the ability to reach better fidelity and fit the characteristics of all sections of the system being modeled. Approximating continuous behavior by discrete behavior cannot guarantee accuracy. Overestimates or underestimates will likely be obtained. An experiment made by Lee et al. (2002a) to compare modeling the inventory level in a supply chain system by DES and by continuous simulation showed that the DES model overestimated the level of inventory.

The previous two sections in this chapter highlighted the inherent complexity in developing discrete models and the simplicity in developing continuous models. The modeling of large, complex systems can be made easier if hybrid simulation of the two approaches is used. In addition this can accommodate all types of behavior in the system which, for being realistic, cannot be only discrete or only continuous. Two directions of interactions (Ziegler, 2000; Pritsker et al., 1997) can occur between discrete and continuous components in a hybrid simulation as shown in Figure 2-14.

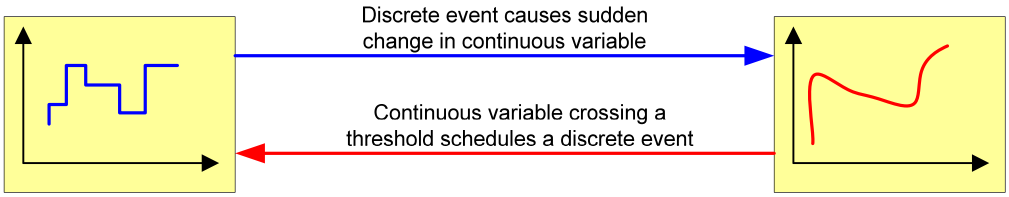

Discrete event causes sudden change in continuous variable
Continuous variable crossing a threshold schedules a discrete event

Figure 2.14 Types of interactions between continuous and discrete components

Hybrid simulation models combine discrete and continuous behaviors, or as expressed by Maler et al. (1992) have non-trivial mixture of discrete and continuous components. Research related to this field has been more popular in the area of real-time control and reactive systems. Reactive systems are event-driven systems that are normally interacting with external and internal stimuli. They maintain ongoing interaction with the environment rather than giving results upon termination. These systems are generally discrete in nature but have to interact with environments that are continuous. Definitions used by researchers have been conceptually the same. Most researchers who are interested in hybrid systems came from the areas of control systems and the theoretical computer science and they viewed the hybrid system as the system that combines the discrete and continuous state changes; usually in distributed and embedded control systems (Gheorghe et al., 2006; Lee et al., 2004; Lee and Hsu, 2002; Alur et al., 2000; Chouikha, et al., 2000; Pepyne et al., 2000; Kowalewski et al., 1999; Maler et al., 1992; Harel 1987). Common examples of hybrid systems in literatures are systems such as the digital controller of a continuous environment, air traffic management systems, guidance of transportation systems, embedded automotive controllers, real-time communication networks, control of process and manufacturing plants, chemical processes, robot planning, and the like.

Researchers also have used hybrid approaches for business systems, including supply chains and some manufacturing applications. In most cases, decision making situations were simulated using discrete simulation with few differential equations for some continuous variables under the control of the discrete parts of the simulation model (Umeda and Zhang, 2008; Lee et al., 2004; Gregoriades and Karakostas, 2003; GroBler et al., 2003; Levin and Levin, 2003, 2002; Lee et al., 2002a; Zulch et al., 2002; Pepyne et al., 2000; Baines and Harrison, 1999; and others).

Hybrid systems research in the area of simulation modeling of the business, environment, manufacturing systems started from the recognitions of the limitations of the discrete event simulation approaches. This was particularly significant as the business, supply chains, and manufacturing systems have become more integrated, complex, and larger in size. Still, this review shows that even when the system control is not the focus in the simulation, hybrid simulation are based on the discrete controller of the continuous system elements. The next section describes the two main approaches to describe the dynamics of the hybrid continuous discrete simulations.

2.5.1 The dynamics of hybrid systems

There are two main approaches to develop hybrid simulations:

1. The hybrid state transition machine (Maler et al., 1992; Harel, 1987).
2. The DEVS&DESS formalism (Ziegler et al., 2000; Ziegler, 1976)

Fundamental similarities between the two approaches can be observed:

1. Both were developed based on a control-system mentality; that is a digital (discrete) system controlling a continuous environment.
2. Running a hybrid simulation is a process of alternating between a discrete phase and a continuous phase. In the discrete phase the state of the system changes and time does not advance. In the continuous phase the time advances but the system state does not change.
3. Events drive the simulation model and only events update the system state.
4. Continuous calculations are performed in the continuous phase between the discrete events, starting with the new state after the event occurrence.
5. The impact of the continuous calculation is communicated to the discrete components by a discrete event, which is triggered by the continuous variable value crossing a predefined threshold level

6. Both require the use of small-sized objects for which the states can be easily enumerated as well as transitions between states.

2.5.2 The hybrid state transition machine

The state machine/diagram is one of the Unified Modeling Language (UML) tools (Jacobson et al., 2001). Called the state chart diagram in UML, it addresses the dynamic view of the system by showing the sequence of states that an object goes through during its lifetime in response to events, together with its responses to those events. Most of the characteristics of the state machine as used currently in simulation modeling were described by Harel (1987). Maler et al. (1992) modified Harel' state machine to incorporate the continuous behavior.

The state diagram is a directed graph in which nodes represent states and arrows (labeled with triggering events and guarding conditions) represent transitions between states (Figure 2-15). It works by following this rule: If event a occurs while the system is in state A and if condition P is true at that time, then the system transfers to state C. The symbol $a(P)$ indicates that the event a cannot cause the transition to be taken unless condition P is true. Condition P is a guarding condition in the sense that it prevents the transition if it would lead to a wrong or illogical state. For example, a machine cannot switch from idle to busy unless power is on. Events can be associated with conditions (e.g. event a) or be unconditioned (e.g. event x). If unconditioned the transition is taken once the event occurs.

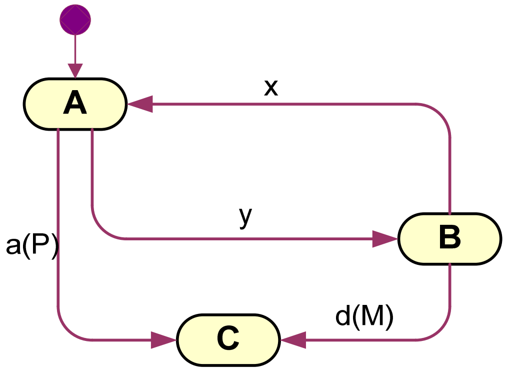


Figure 2.15 State diagram with three states

The state diagram as described above is a discrete event driven system. Maler et al. (1992) incorporated the continuous behavior into the discrete state diagram by using the concept of phase transition, by which the behavior of a system is the result of alternating discrete and continuous phases. The continuous phase takes positive time to allow changes in variables that are modeled by differential equations. The discrete phase consists of a finite number of discrete transitions that may cause abrupt change in the value of the variables. To incorporate the continuous behavior into the discrete system, the state (on a state diagram) is allowed to have differential/integral equations associated with it to describe the continuous behavior when the system is in that state. The behaviors of the variables modeled by the differential/integral equations (continuously behaving variables) are sensed at the state diagram transitions and based on the values of these variables they can generate events that would lead to transitions to be taken or at least enabled.

Because of the need to alternate between the continuous and discrete phases, a hybrid system can either advance time (the continuous phase) or update the state (the discrete phase).

Time advancement and state updating cannot be concurrent. In Figure 2-16, a system starts in state S_0 at time t_0. It may change to S_1 vertically then advance time horizontally to t_1 (following the dashed line path), or it may change time to t_1 horizontally then change the state to S_1 vertically (following the continuous line path). Diagonal advance does not tell when the change in state occurred or how long the system was in the state being left behind (Maler et al., 1992) and this can be necessary information that should be obtained.

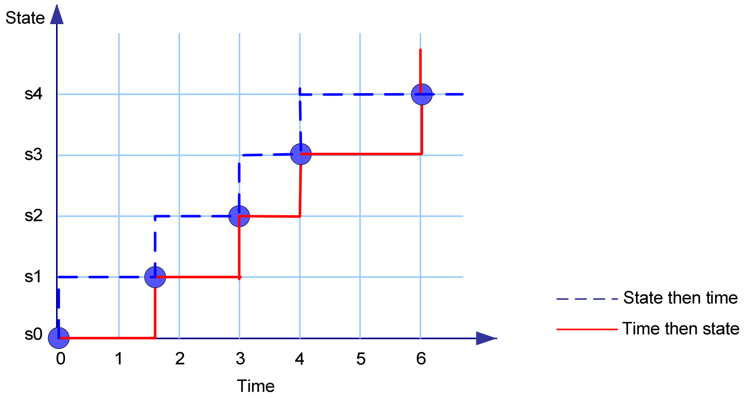


Figure 2.16 Advancing time or updating state in hybrid systems

The continuous calculations are performed during the continuous phase; between the discrete events. Assume that a system should visit the states (0,0), (1,1.5), (2,1.5), (3,6), (4,6), (5,6), (6,6), … where the first digit is the number of the state and the second is the time stamp of that state. This is shown on Figure 2-17, in which a line indicates time advancing (continuous phase) while a no-line is discrete phase. Notice that time stamp at the end of a line segment and at the beginning of the next remains the same while the state changes.

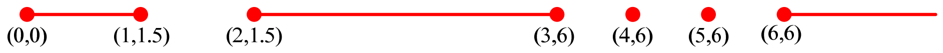


Figure 2.17 Continuous and discrete alternating steps in hybrid simulation

By combining the contents of Figures 2-16 and 2-17, the result can be as depicted in Figure 2-18. Following the discrete-continuous alternations, this system evolves by either of two ways: by advancing time then updating state (left in Figure 2-18) or by updating states then advancing time (right in Figure 2-18).

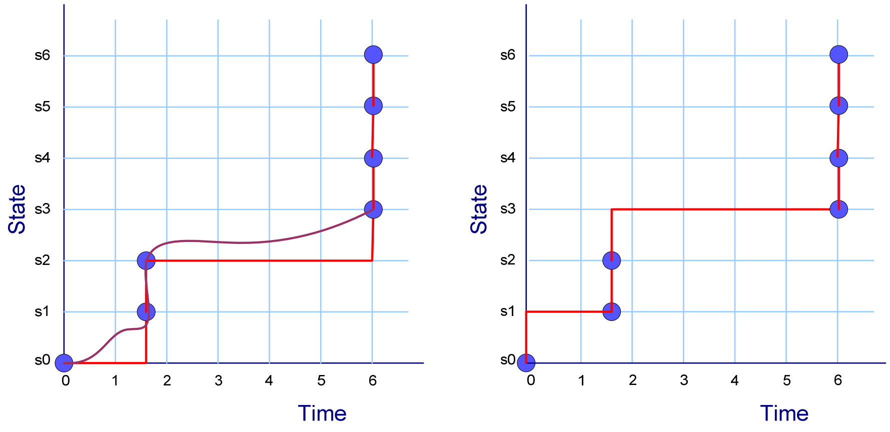


Figure 2.18 State and time alternations in hybrid systems

It is possible that the actual behavior of the system is continuous and should follow the curved line in the left part of Figure 2-18. Following this line is not likely in a hybrid system built as described above. Pure continuous models can achieve such behavior. The behavior of a continuous variable in a hybrid system can be as shown in Figure 2-19, where the pair (x, t) represent state x and its time stamp t. The continuous behavior when the state machine approach is utilized is in fact discontinuous and has to accept abrupt changes imposed by the discrete components. Discrete always dominates the simulation in this approach. In Figure 2-19, the State Event is a discrete event generated by the continuous variable crossing a predefined threshold value. This event is communicated to the discrete components and is then treated as any regular discrete event. This is how a continuous variable may attempt to change the system.

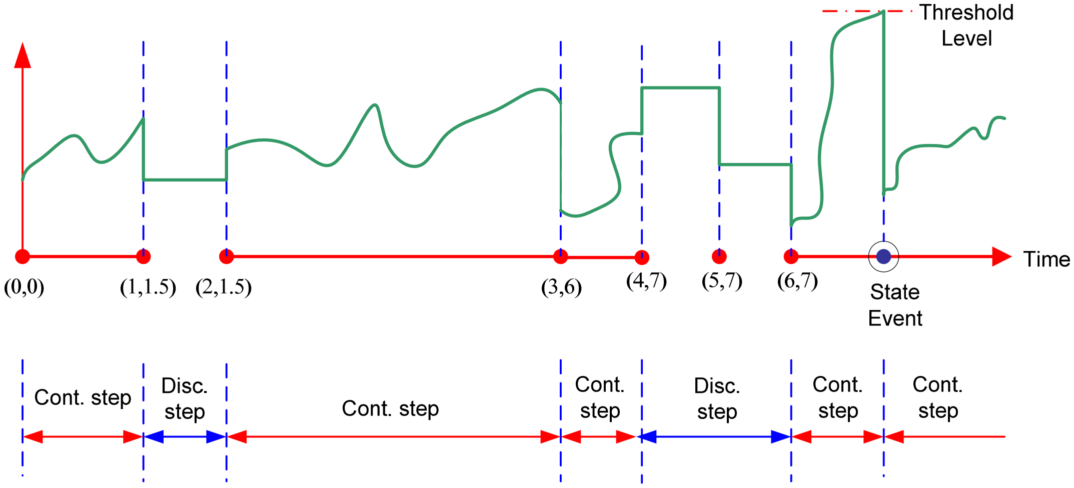


Figure 2.19 Intermittent continuous behavior in control-based hybrid simulation

2.5.2.1 The AnyLogic software package

The commercial software AnyLogic (http://www.xjtek.com/) is marketed as the only commercial software that combines DES and SD modeling tools in the same interface. It offers tools to build discrete simulation and system dynamics models as well as agent-based models in an object oriented environment. AnyLogic is an implementation of the concepts proposed by Harel (1987) and Maler et al. (1992) in the way it combines the discrete and continuous simulation units. AnyLogic uses an object oriented approach with state charts associated with the objects in the model. The state chart indicates the state space of the object and the events or conditions that cause it to take transitions from a state to another. It can also describe actions that result from state change. For instance, a state chart of an object from an AnyLogic model is shown in Figure 2-20, where a system is initially using the main generator. The transition from main generator to a standby generator (the left most arrow) is taken if a message arrives at the object that the main generator is down. The transition from using the standby generator to B (branch) can be timed or based on an event. If a message that the main generator has been fixed arrives before the end of the time interval then the transition will be to using the main generator state, otherwise the transition will be to the stop state to stop the system at the end of the time interval.

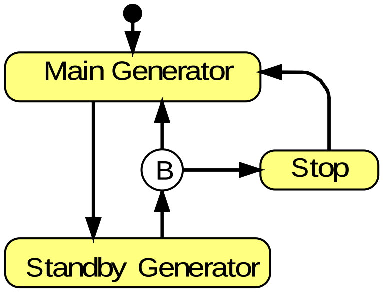


Figure 2.20 State chart in an AnyLogic object

A message arriving to take a transition is an event. Alternatively the transition can be set to react directly to the occurrence of events by writing a Java code that instructs the transition how to react. Events are all discrete and timeless. Thus AnyLogic allows discrete and continuous model objects to interact through the use of the state chart. The value of a continuous variable can be monitored to trigger an event that is sensed at a transition as defined in the Java code in it.

A special type of events (the dynamic event) is an object in AnyLogic that is used as a simple form of the state chart and can be used in the same way to react to events or act based on specified points in time. The dynamic event object allows the modeler to explicitly schedule a discrete event based on a condition associated with the value of some model variable that might be a continuous variable, or based on time. When the condition is true, the event is triggered and the system state is updated as dictated by the action defined in the event object.

Another way to interact continuous and discrete model parts depend on the fact that the continuous components in AnyLogic are treated as variables not objects. The DES components are objects. Since they are variable, the stocks and flows of a SD model can be referenced in the actions coded in the DES objects as well as in the state chart and the dynamic event code fields. It is also possible to reference the attributes of the DES objects in the mathematical formulations of the SD variables. For instance the size attribute of a DES queue object, which is modeling materials buffer between two processes, can be referenced in the definition of the work-in-process level in a SD model unit. This however can be misleading since the SD concepts do not allow stocks to be changed except by the effect of the flow rates. The contents of a DES queue should be added to a SD stock only through a flow rate variable. AnyLogic allows the simple algebraic addition of the queue contents to SD stock.

The users of AnyLogic need to be Java programmers. All actions or reactions in any object are stated as Java statements. Sophisticated object behaviors can only be defined in this way. The AnyLogic simulation engine is discrete but uses a numerical solver to solve the set of differential equations of the SD variables. Figure 2-21 represents the simulation engine architecture of AnyLogic. The discrete engine generates a set of global algebraic differential equations and sends it to the solver. The set of equations are solved to update the associated continuous variables. If a condition is met or a time delay in a dynamic event object or a state chart has elapsed, then a reaction is taken and the discrete engine updates the state appropriately. The check for the conditions is performed each time step (AnyLogic Users' manual). If no condition met or threshold values crossed then the calculations continue to update the continuous variables until the next discrete event. The system switches to executing the regular discrete events whenever these events are due to occur, at which time the continuous calculations stop. Thus similar to what was described in the previous sections, the AnyLogic simulation engine alternates between the discrete and continuous steps where the continuous calculations are only allowed between the discrete events and are reformulated after each event using the updated system state.

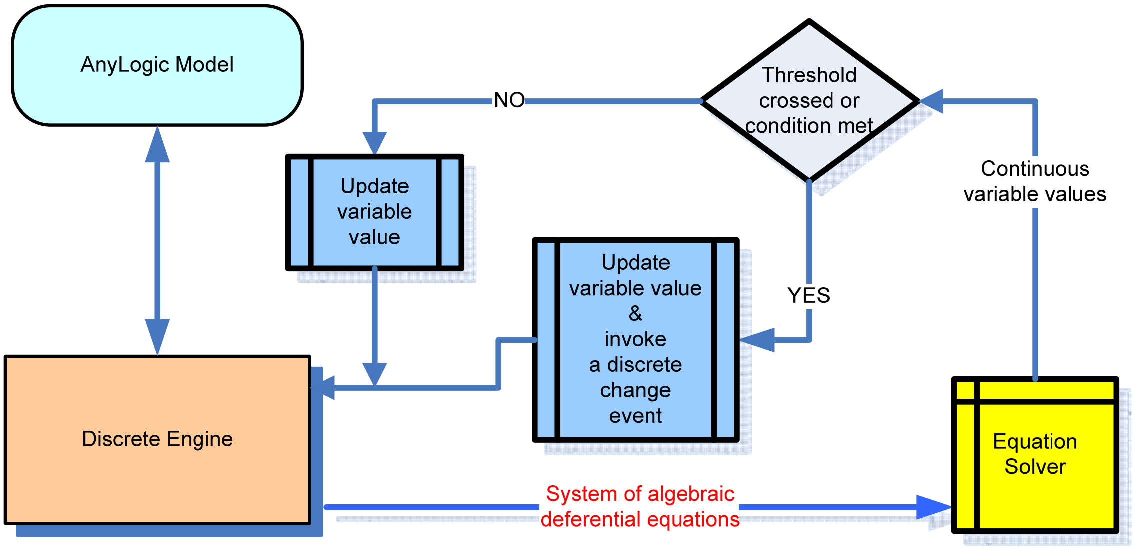
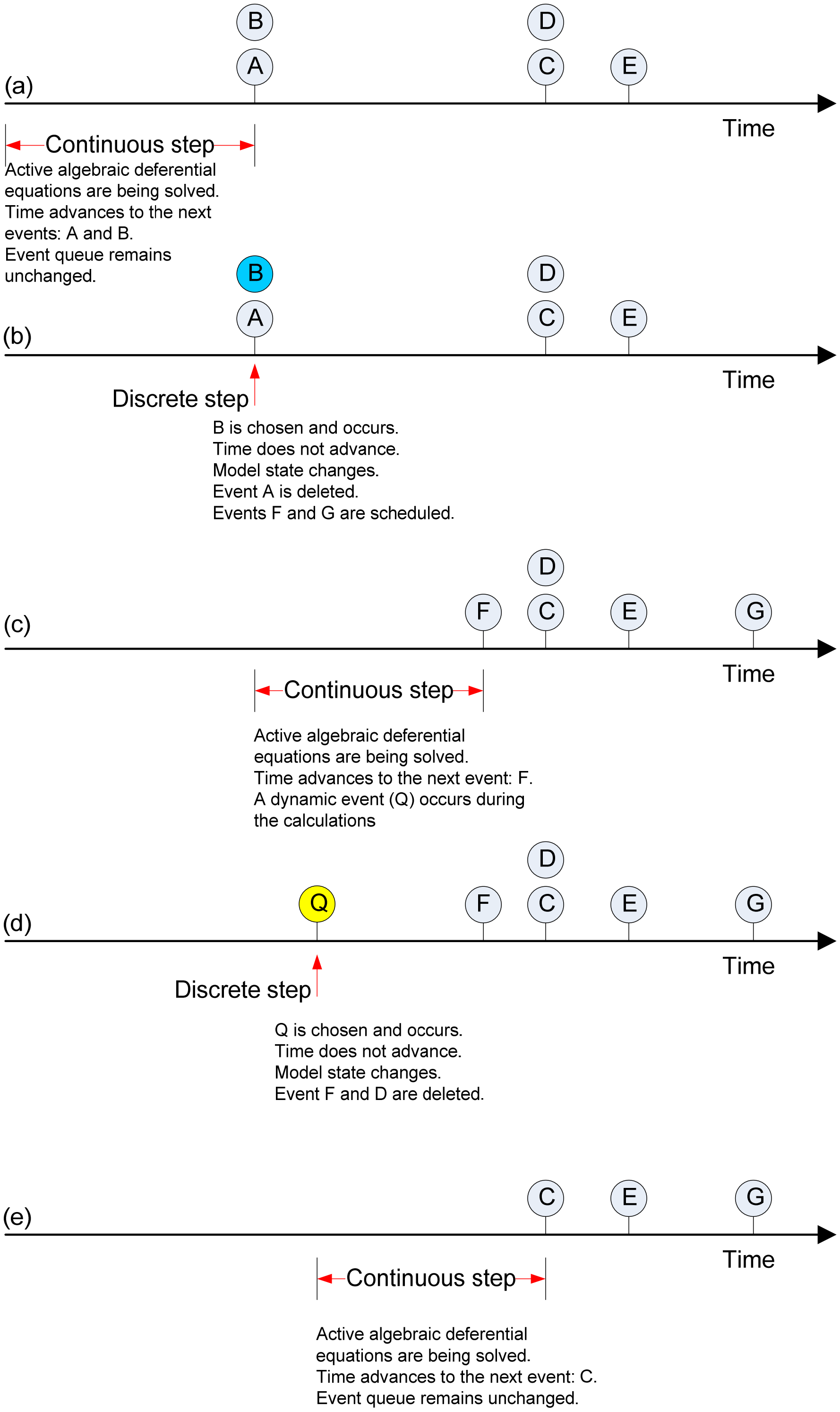

AnyLogic Model
NO
Threshold crossed or condition met
Update variable value
Continuous variable values
Update variable value & invoke a discrete change event
YES
Discrete Engine
Equation Solver
System of algebraic deferential equations

Figure 2.21 AnyLogic's hybrid simulation engine architecture

Based on AnyLogic's user manual, Figure 2-22 describes the alternating between the discrete and continuous steps. In the continuous step time advances to the nearest event (or events) in the events queue while solving the algebraic-differential equations (part (a)). At the next event's time the event is executed, the state of the system is updated, time does not advance, and the events queue may be changed by deleting and/or scheduling events (part (b)). The following continuous step (part (c)) is the same as in part (a) but an event (Q: called change event) defined by the use of the dynamic event object or the state chart occurs unexpectedly. The continuous event is stopped to execute Q (part (d). The following continuous step is same as that in (a) or (c). The sequence continues in the way to the end of the simulation run.

The discrete part of AnyLogic engine does not know when a change event would occur. It depends on the equations set being solved to read the time for that event. Once this happens, the clock is advanced to the time reported by the continuous-time equation solver, and the event is executed by the discrete part. Continuous behavior affects the discrete behavior in this way. On the other hand, each time an event is executed, the system state changes and the updated state is used in the continuous part as new initial conditions for the calculations and the simulation engine generates a new set of equations to replace the existing set. In this way the discrete part is impacting the continuous time behavior. This mechanism is comparable to Figures 16 through 19 in the previous sections.



Active algebraic deferential equations are being solved.
Time advances to the next events: A and B.
Event queue remains unchanged.

B is chosen and occurs.
Time does not advance.
Model state changes.
Event A is deleted.
Events F and G are scheduled.

Active algebraic deferential equations are being solved.
Time advances to the next event: F.
A dynamic event (Q) occurs during the calculations

Q is chosen and occurs.
Time does not advance.
Model state changes.
Event F and D are deleted.

Active algebraic deferential equations are being solved.
Time advances to the next event: C.
Event queue remains unchanged.

Figure 2.22 Continuous and discrete steps in AnyLogic

2.5.2.2 Commentary on using the state chart and AnyLogic

AnyLogic is the implementation of the hybrid state chart technology. This technology was originally developed for reactive and real-time control systems. Objects are preferred to use state charts and AnyLogic uses objects. In business and social systems the use of the state chart can be tedious as there is a need to enumerate all states that a system can be in during its life time. The number of the states can be infinite in general business and social systems. In physical and control system these states can be enumerated whereas in social system this task can be impractical, unless some accuracy or oversimplifying assumptions are considered. Lee at al. (2004) have recognized this difficulty even for the model of a digital controller of a single printed circuit board production process. Allowing one type of behavior to control the other is the disadvantage of the state chart. As mentioned by Frey et al. (1997) a central design issue in developing hybrid discrete-continuous simulations is which paradigm controls the other. Yet there is no answer to this question yet.

The continuous behavior of the hybrid state chart is discontinuous as was shown in Figure 2-19. In social and business systems an abrupt change in the value of a continuous variable is not realistic. The change in customer order rate, productivity, material arrival rate, the rate of increase of a population, the level of pollution, or may be the learning curve of a certain process are not expected to show such abrupt changes. In such situations, continuously changing variables are not normally influenced by such timeless events. For example, if the inflation rate in the market is crossing a threshold value, there is no way to just cut it. Government and market actors have to change their policies to influence the inflation rate over a period of time. Also if inventory is increasing at a certain rate, management may not empty the inventory suddenly in the normal operating circumstances. It may stop production and the inventory would go down gradually.

In addition, it is not likely that single simulation software can meet all needs of all modelers particularly if hybrid simulation is required. In that regard, AnyLogic users need to use Java to add needed object classes and extend existing ones. In that way, AnyLogic becomes an interface for a programming language.

An approach that can integrate different discrete and continuous simulation software can be advantageous as it would allow molders to keep using their expertise in the modeling approach they prefer. It would also offer the flexibility to use the simulation software that is most appropriate for the specific needs, then have it integrated to other software that were also chosen for specific advantages in them. This can also allow modular, scalable models which could simplify the modeling process. This is what this research work is proposing. One major feature of the proposed approach, unlike AnyLogic, is the ability to utilize the existing simulations (legacy simulations) without having to learn a new approach or resort to lengthy programming work.

2.5.3 The DEVS-based hybrid simulation

The DEV&DESS formalism is an approach to specify and describe the dynamics of the hybrid continuous discrete systems. It is a combination of the DEVS (Discrete Event System Specification) and the DESS (Differential Equation System Specification) formalisms. All of them; DEVS, DESS, and DEV&DESS are the works of Zeigler (1976) and Zeigler et al. (2000).

2.5.3.1 The DEVS formalism

DEVS is a general formalism for discrete event system modeling based on set theory. It describes the different sets in a simulation model and the functions that describe the relations between these sets. Three sets and four functions are used in the basic DEVS formalism:

1. The set of inputs
2. The set of outputs
3. The set of states
4. The internal transition function
5. The external transition function
6. The output function
7. The time advance function

Any system can have a set of states that it can be in during its lifetime. The system receives inputs through input ports and gives outputs through output ports. The ports are the communication channels through which the system interacts with other systems or the environment. The DEVS representation of the system is given as in equation (10).

$$DEVS = (X, Y, S, \delta_{ext}, \delta_{\mathrm{int}}, \lambda, ta) \qquad (10)$$

1. X is the set of external inputs (external input events)
2. Y is the set of outputs (output events)

3. S is the set of sequential states. S is defined before hand and each state $s \in S$ has a specified time point $ta(s)$ at which it expires.

4. δ_{ext} is the external state transition function. It represents the interactions between X and Q to describe how inputs cause state transitions. It creates a state trajectory over S. It can be defined by $\delta_{ext} : Q \times X \rightarrow S$ where Q is defined below.

5. δ_{int} is the internal state transition function. It describes how transitions between states in S are taken when their times come; i.e. how to transit from s when $ta(s)$ is reached. It can be described by $\delta_{\text{int}} : S \rightarrow S$

6. $\lambda$is the output function. It is defined for the active state only (active state is the state that has finite duration as opposed to passive states that has infinite time durations). λ is executed only when the elapsed time for the system in a state equals its life time duration. Output is generated upon internal state transitions only, just before the transition is taken. λ creates a trajectory over Y and is given by $\lambda : S \rightarrow Y$

7. ta is the time advance function. For a state $s \in S$ it represents the time until which the system remains in that state if no external events occur. It creates a trajectory of states over the positive time domain: $ta : S \rightarrow \Re^{+} \cup \{\infty\}$

Let Q be the set of total states. An element in Q is the pair of a state and the time elapsed since the system entered that state. If the elapsed time is represented by e , then Q is defined by Formula 11.

$$Q:\{(s,e)\mid s\in S,0\le e\le ta(s)\} \qquad (11)$$

Unless an external input causes a transition from s the system would internally undergo a transition when $e=ta(s)$. Upon the transition and reaching a new state the elapsed time counter; e is reset to zero.

2.5.3.2 The DESS formalism

DESS is a version of the DEVS formalism, for the differential equations models (continuous models) in DESS the state transition function of DEVS is replaced by a rate of change function that defines the rates of change of the state variables. Numerical techniques are used to perform the calculations at the preferred time step. Let $q_1,q_2,...,q_n$ be the state variables and $x_1,x_2,...,x_m$ be the input variables, then a continuous model is formed by the set of first-order differential equations of (12):

$$\begin{aligned}
\frac{dq_1(t)}{dt} &= f_1(q_1(t),q_2(t),...,q_n(t),x_1(t),x_2(t),...,x_n(t))\\
\frac{dq_1(t)}{dt} &= f_2(q_1(t),q_2(t),...,q_n(t),x_1(t),x_2(t),...,x_n(t))\\
&....\\
\frac{dq_1(t)}{dt} &= f_n(q_1(t),q_2(t),...,q_n(t),x_1(t),x_2(t),...,x_n(t))
\end{aligned} \qquad (12)$$

The DESS formalism specifies the differential equation simulation models with three sets and two functions (DEVS uses three sets and four functions) and can be represented by equation (13).

$$DESS = (X, Y, Q, f, \lambda) \qquad (13)$$

- $X = \{(p_c, v_c) \| \ p_c \in Inports \ , v_c \in \Re\}$ is the set of input ports and values.
- $Y = \{(p_c, v_c) \mid p_c \in OutPorts \ , v_c \in \Re\}$ is the set of output ports and values.
- $Q$is the set of states
- $f : Q \times X \rightarrow Q$ is the rate of change function
- λ is the output function, which can relate Q to Y or relate Q and X to Y. Thus it has two forms: $\lambda : Q \rightarrow Y$ and $\lambda : Q \times X \rightarrow Y$

DESS describes a time-driven approach that cannot easily capture the feedback structure of the continuous system. States have to be defined, which puts limits on the size of the system that can be specified.

2.5.3.3 The DEV&DESS formalism

To develop hybrid simulation models, DEVS and DESS are combined (Figure 2-23) to form the DEV&DESS system specification formalism.

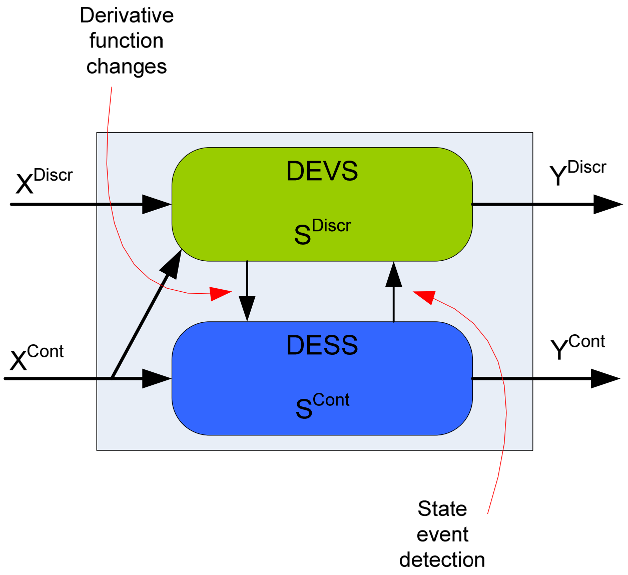


Figure 2.23 DEV&DESS combined model (Zeigler et al., 2000)

The DEV&DESS formalism uses five sets and six functions to specify a hybrid model. It is represented by equation (16).

$$DEV\,\&\,DESS = (X^{discr}, X^{cont}, Y^{disc}, Y^{cont}, S^{disc}, S^{cont}, \delta_{ext}, \delta_{\text{int}}, C, \lambda^{disc}, \lambda^{cont}, f) \qquad (16)$$

- X^{disc} and Y^{disc} are sets of discrete event inputs and outputs.
- $X^{cont} = \{(x_1^{cont}, x_2^{cont}, ...) \mid x_1^{cont} \in X_1^{cont}, x_2^{cont} \in X_2^{cont}, ...\}$ is the structured set of continuous inputs with input variables x_i^{cont}. Being a continuous in nature this could be a list of values that are changing with time. It could be a step function input to a continuous system, a formula describing a flow rate of increase or decrease defined over a certain period of time. The period of time may be as small as an integration step.

- $Y^{cont} = \{(y_1^{cont}, y_2^{cont},...) \mid y_1^{cont} \in Y_1^{cont}, y_2^{cont} \in Y_2^{cont},...\}$ is the structured set of continuous value outputs with output variables y_i^{cont}. This is again a set of values over time. The output can be the behavior of the continuous state variable over a period of time, not just a value at a certain point in time.
- S^{disc} and S^{cont} are sets of discrete and continuous states respectively. To combine them $S = S^{disc} \times S^{cont}$ is the set of states as a Cartesian product of discrete and continuous states
- $\delta_{ext} : Q \times X^{cont} \times X^{disc} \to S$ is the external state transition function, where Q is the set of total states; defined as $Q = \{(s,e) \mid s \in S, e \in \Re_0^+\}$
- $\delta_{\text{int}} : Q \times X^{cont} \to S$ is the internal state transition function
- $\lambda^{disc} : Q \times X^{cont} \to Y^{disc}$ is the event output function; executes only when an event occurs.
- $\lambda^{cont} : Q \times X^{cont} \to Y^{cont}$ is the continuous output function
- $f : S \times X^{cont} \to S^{cont}$ is the rate of change function
- $C : Q \times X^{cont} \to Bool$ is the state event detection condition predicate

The DEV&DESS system behaves following combinations of the following three cases over its life time, assuming an interval $< t_1, t_2 >$:

1. **No events during the interval:** f and λ^{cont} specify the continuous behavior. There is no state transition since there are no events. But new values for the continuous state variables are calculated. This corresponding to the time phase in the hybrid state chart approach.
2. **A state event at time t during the time interval:** A state events implies that $C_{\text{int}}(s(t), x^{cont}(t))$ is true. A continuous state variable has crossed a threshold value so a new value is calculated and in addition δ_{int} is executed to define a new state.
3. **A discrete event at the external input port at time t during the interval:** δ_{ext} is executed to define a new state at t.

The semantics in part 2 above implies that the state event affects the discrete part. In part 3 the time event in the discrete part also affects the continuous part through changing the value of f. This makes DEV&DESS another form of the same concepts of the hybrid state machine approach.

2.5.3.4 Commentary on the DEV&DESS formalism

DEV&DESS follows the same approach used in the hybrid state diagram approach. The DESS part (the continuous) is allowed to cause state events to occur and those events are detected at the discrete part. This takes place in the same way it does in the hybrid state machine approach. In the intervals between events, the DESS input, state, and output values change continuously until a condition specified on the continuous element becomes true. Typically, the condition is a continuous variable reaching a certain threshold or whenever two continuous variables meet (in which case, their difference crosses zero). In such situations, a state event is generated. This is represented by Figure 2-24 by Ziegler et al. (2000).

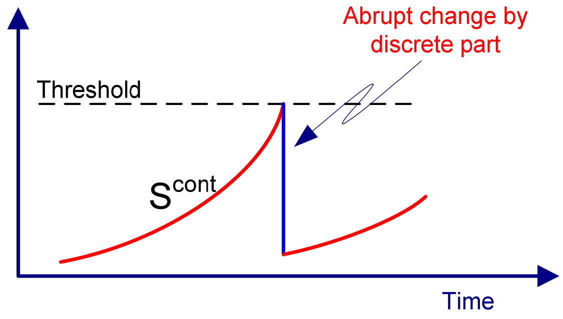


Figure 2.24 State event generated at crossing a threshold by continuous variable

The illustrative example that Zeigler et al. (2000) used to illustrate the use of the DEV&DESS was a barrel filling process. As depicted in Figure 2-25, the discrete input on/off causes the external transition function to open the valve variable (assuming it was off at start up). This event changes the rate of change function f at the continuous side, which allows the inflow to start filling the barrel. The continuous variable Contents represents the level in the barrel. It is also reflected by the continuous output C_{out} via the continuous output function. If Contents reaches the level of 10 the condition is satisfied and a state event is triggered in the discrete side. This causes the internal transition function to change the state of the discrete (variable Valve) to off. Also the state event triggers the output function to indicate a barrel finished at the discrete output barrel.

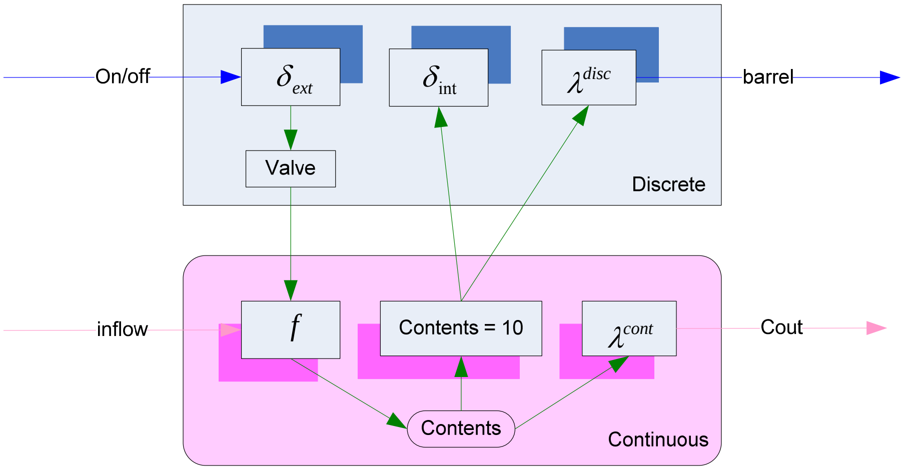


Figure 2.25 DEV&DESS hybrid simulation model of a barrel filling process

Such a situation can be modeled as a control process. Temperature in a furnace can increase until a certain value where discrete action is taken. A robot would move until a distance is covered then it is stopped. These are examples where the threshold approach is applicable. But as we argued earlier, it is not realistic to expect all continuous systems to be increasing or decreasing until crossing a threshold value. In fact the oscillating behavior (Figure 2-26) of continuous parameters such as inventory or production rate, or capacity, is more expensive and dangerous in a manufacturing system than a trend in any of them. A threshold cannot be used to control such a behavior. Management would work to smooth out the oscillation and achieve stability not to prevent a certain critical value if a critical value could be defined.

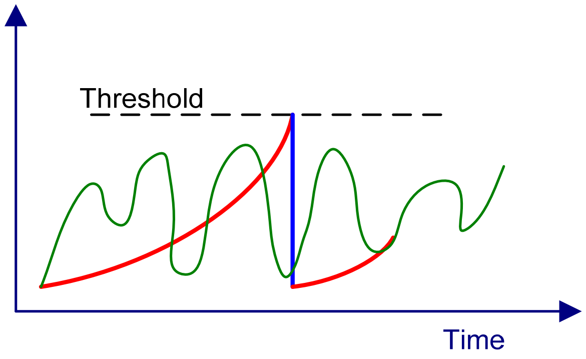


Figure 2.26 Oscillating continuous behavior not detected by threshold technique

DEV&DESS also requires the definition of states for the continuous components. The use of objects where each has a specific task to perform would make that possible for only needing a small set of states and transitions. But this is not likely to be the case for all continuous systems.

The simulation of a continuous system involves the simultaneous solution of a set of differential/integral equation. The simultaneous solution implies that the system would be performing actions for all of variables at the same time. Unlike discrete simulation where events are handled one at a time, continuous simulation acts concurrently for all elements in it. The point here is that defining states for continuous behavior is not practical or useful. Control situations are easy in that regard but not all continuous simulation situations are.

This becomes even more significant with SD. SD follows a system approach to recognize the impact of the structure of the system and the set of causal relationships in it on its behavior. Dividing a SD model in small objects and allowing them to interact indirectly would violate the fundamentals of SD regarding capturing the feedback structure of the system.

This implies that in a business system modeled in SD, the definition of states to support integration to DES models does not offer useful results. The inability to define states makes it difficult to define a pattern for interactions between a SD model and DES model. The only way to start defining the interactions between SD and DES is by recognizing when data is needed from one to the other. These needs for data sharing follow the nature of system being modeled. In DEVS and state chart approaches, the need to an interaction is signaled by an event. As there are no events in SD models then the needs to share data should be decided logically based on the overall function of the system being modeled.

2.5.3.5 Using the DEV&DESS formalism

Few implementations of DEV&DESS could be found in the literature survey in this work. Ziegler at al. (2000) described a pseudo code for a DEV&DESS simulator that uses messages between the DEVS and the DESS units to do three tasks: detection of the state events, reporting the state events, and the execution of the state events. That is events drive the simulation. Choi et al. (2005) and Choi et al. (2006) modeled the software development process as a hybrid process but using the DEVS formalism, not DEV&DESS. They connected the DEVS objects to build a feedback structure and made the simulation advance time in steps rather than by event occurrences. Their goal was replicating an earlier SD model (Abdel-Hamid and Madnick, 1991) of the same process. They approximated the continuous behavior by time steps execution of a DEVS-based model. In their second paper they utilized the condition function of DESS to detect the state event occurrences. They did not use DEV&DESS; only picked the condition function to use with a DESS model. In our assessment, the difficulty faced them was the need to define states for the continuous parameters in DEV&DESS. They kept the original SD model's logic, which did not allow practical definition of the states for the continuous parameters when the approximated the process by a DEVS model.

Gheorghe et al. (2006) used the DEVS formalism (the coupled version as described by Zeigler et al. (2000)) to describe interfacing discrete and continuous models. They approximated the continuous model by DEVS as well. No use of DESS or DEV&DESS was mentioned. They only classified the DEVS objects' ports into ports to receive data from the continuous variables and ports for receiving data from the discrete components. All units of the system were specified in DEVS as coupled units. They however proposed a synchronization mechanism to interface discrete and continuous components, which will be described in Chapter 4. The synchronization mechanism could detect the discrete or the state events generated in any part of the model, which is the core task in DEV&DESS simulator of Zeigler et al. (2000). The coupled DEVS version of DEVS was the framework for their hybrid simulation system, not the DEV&DESS.

2.5.4 On the current hybrid simulation approaches

The discussion of the hybrid state machine and the DEV&DESS approaches to hybrid simulation as well as the way that AnyLogic works can support the following comments:

1. Both approaches assume a discrete (digital) controller controlling a continuous environment. The continuous calculations have to be bounded by the discrete events and be allowed only in segments between events.

2. The continuous variable must accept abrupt changes in their values by the occurrence of the discrete events. A segment of continuous calculations between two events may not be a natural continuation of the previous segment.
3. DES dominates the hybrid system transforming it into stochastic-like system even if the deterministic dynamics are of significance. Pepyne and Cassandras (2000) argues that this shifts the paradigm of analyzing continuous systems from the mature differentiable calculus to the less mature non-smooth calculus field, which is based on Lipschitz's continuity condition.
4. Continuous components do not change the state of the hybrid system except by signaling the discrete part of reaching a pre-defined threshold value. Discrete events drive the simulation and only events can update the system state.
5. Defining states for a continuous system, which is controlled by a discrete controller, is not practical. A continuous variable in fact has an infinite number of states and identifying them in a simulation model is not practical. Crossing a threshold value is the only state recognized for continuous variables.
6. The SD methodology offers the ability to understand the system behavior and how it evolves over time. In the core of the methodology is the use of averaging and smoothing techniques to identify the trends in the behavior. Using SD in the state chart-based or the DEVS&DESS-based hybrid systems with the averaging and smoothing will filter out the exceptional occurrences that may not allow accurate definitions of the thresholds values that can be used in communication with a discrete system.

7. In business and social systems, where continuous behavior is observable, the use of the state chart can be tedious as there is the need to enumerate all the possible states and the transitions between them. The same is true for the DEV&DESS formalism as all states must be stated and transition functions have to be defined.
8. It is not likely that all continuous behavior will be either increasing or decreasing over time until reaching a threshold value. Fluctuations and oscillatory behavior can be more expensive and dangerous than a decreasing or an increasing level.

2.6 Distributed Simulation

Distributed simulation implies loosely coupled simulations (Fujimoto, 2000) that interact intensively at certain points in time. Yet both; parallel and distributed are concerned with issues introduced by distributing the execution of DES programs over multiple processors and computing platforms. The technologies of the parallel and distributed simulation were motivated by the needs of the military applications to integrate the geographically distributed systems (simulations and others). By the mid 1990s the Distributed Interactive Simulation (DIS) Standard (IEEE 1278-1995 and the Aggregate Level Simulation Protocol (ALSP) were developed and used. Currently the High Level Architecture (HLA) has replaced DIS and ALSP as the framework for developing distributed simulations. Still the military uses are main drivers (Bodoh and Wieland, 2003; Borshchev *et al.*, 2002; Fujimoto, 2001; 2000).

HLA is a standard (IEEE 1516) that describes the rules that should be followed to accomplish the integration of disparate simulations. The individual simulations in HLA are called federates while the collection of federates that are incorporated together is called federations. The software realization of the HLA framework is called the Runtime Infrastructure (RTI) and it implements the HLA rules and provides methods that can be called and used by federates. Figure 2-27 is a representation of the HLA structure.

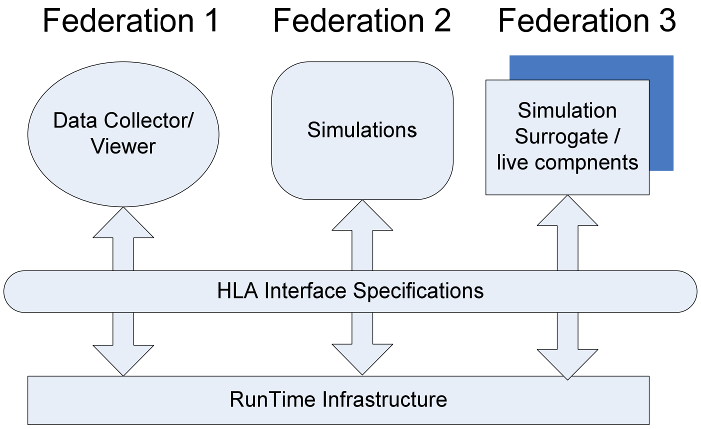


Figure 2.27 Structure of HLA implementation

HLA consists of the three components (Kuhl *et al*., 2000; Fujimoto, 2000):

1. The HLA rules that federates follow to comply with the HLA standard.
2. The Object Model Template (OMT) that specifies what information is communicated between federations and how it is documented.
3. Interface specification that defines how HLA members interact with the RTI library. It defines the RTI services and the application programming interfaces (API) to allow different programming languages and computing platforms.

RTI is responsible for providing support to distributed objects' interactions, attributes' ownership, and other optimistic and the time management policies (Bononi *et al.*, 2003). Specifically, RTI is active in the following areas (Fujimoto, 2000):

1. Federation management, which includes services to create and delete federation executions, allow federates to join or resign from federations, and pause or resume executions.
2. Declaration management, which allows simulations to establish the intent to publish attributes and interactions, and subscribe to be updated about attributes owned by other simulations.
3. Ownership management, which enables the transfer of ownership of attributes during executions.
4. Time management, which coordinates the advancement of logical time.
5. Data distribution management, which controls the distribution of state updates among federations.

2.6.1 Distributed simulation in industry

Distributed simulation usage is very limited in industry (Boer et al., 2006a; Lendermann, 2006). A recent survey on the use of distributed simulation in industry (Boer et al., 2006a; 2006b) has given some explanation where it showed that industry practitioners depend heavily on the "commercial-off-the-shelf" simulation packages, which offer very limited support for the HLA standard. Vendors do not see direct benefits in offering HLA support in their packages, given that HLA is still military-directed and too complex for industry applications. Unlike military applications, industry wants fast and direct result at the lowest expenses, for which HLA as well as the concepts of distributed simulation would add too high overhead technically and financially. Vendors also do not see much economical benefits in collaborating with other vendors. Yet some benefits of distributed simulation have been recognized. These included the possibility of speeding up the model development process by modularizing models and utilizing the synchronization techniques.

In manufacturing applications, Saad et al. (2003) suggested that using distributed simulation for manufacturing system does not require strictly synchronization; only loose level of synchronization is required in which a model in a distributed arrangement would pause its run if it detects that it is ahead of other simulations. No more complicated approaches should be needed according to them. However, this could be true for the specific case they considered where several models (built by the same tool; Arena) communicated by sending messages using the Microsoft Windows' Message Queuing tools. The models represented several processing operations that communicated with an assembly facility. In the case of simulating the enterprise in SDDES more considerations must be taken in synchronizing SD and DES models since each method of simulation works in a different way.

Chapter 4 will review the existing synchronization approaches used in distributed simulation arrangements. In Chapter 5, we propose a new synchronization mechanism for the synchronizing SD and DES.

2.7 Simulating the Manufacturing Enterprise

DES is the most commonly used approach in modeling the manufacturing system since the 1960s. Usually the manufacturing activities are simulated. DES as a detailed, stochastic approach is suitable for simulating manufacturing processes that are highly stochastic and need to be monitored closely. SD is not widely used in manufacturing applications. But the integrated manufacturing system is challenging DES and indicating opportunities for exploiting the potential of SD.

Few surveys have addressed the use of simulation in manufacturing applications. Banks et al. (2005) and Smith (2003) have surveyed and discussed the applications of DES. Another limited survey by (Baines and Harrison, 1999) assessed the use of SD in manufacturing systems. A recent two-part survey (Boer et al., 2006a; 2006b) assessed the use of the distributed simulation concepts in industry in general. The findings of these surveys are discussed in the following sections. In addition, cases of applications of simulation in the manufacturing domain will be discussed. Table 2-3 summarizes representatives of these cases. A discussion follows after the table.

Table 2.3 Simulations of manufacturing systems

Reference	Tool	Scope	Commentary
Sterman et al., 1997	SD Represent physical & institutional structure, market behavior, & deal with multiple levels of analysis.	Marketing – R&D – competition – pricing – quality – financial accounting – manufacturing performance A manufacturer implemented a total quality management (TQM) program. Operational level performance dramatically improved. Financial performance dramatically declined	Comprehensive model at aggregate level. Focus on financial performance and balance in allocating resources & intangible management support. Manufacturing measured by level of commitment to TQM, learning curve, inventory levels, rate of change in productivity. Quick success in manufacturing fueled more support on the expense of other business units and the moral. Offered understanding of cause-and-effect-relationships in aggregate terms.
Mandal & Sohal, 1998	SD For policies and system structure, strategic analysis over long range horizon, Capture cause-and-effect and feedback structure	Capacity planning – Production – Customer orders – Sales Decline in fabricated metal industry in Australia.	Study the impact of economical policies and governmental regulations on the industry as a system over ten years. Typical use of SD for holistic view of an industry. Comprehensive model built with limited data. Diagnostic ability of SD
Ashayeri et al., 1998	SD For modeling strategic level efficiently including market and affiliated companies.	Production planning, capacity, inventories, market demand, forecasting, production, shipping.	SD not needing detailed or exact information can model strategic business level. SD offers designed experiments at the business level, which is traditionally possible at the operational levels. SD is a very useful for assessing business process reengineering projects.

Reference	Tool	Scope	Commentary
Fujii et al., 1999	DES	Physical materials flow: Processes & transportation Computer Integrated Manufacturing (CIM) system	Distributed simulations arrangement Only physical materials flow in CIM controlled by MRP
Reid & Koljonen, 1999	SD Captures dynamical feedback structure	Abstract representation of lead time, inventory levels, management capacity to deal with problems, Delayed orders Analyzed the theory of constraints' approach of ignoring financial inputs at manufacturing processes level	Too abstract and over simplified System stability cannot be maintained without continuous coordination with feedback of financial level with the operational level.
Brennan and O, 2000	DES With agents	The machine loading and scheduling in a manufacturing system. Agents represented shop floor components and communicated with Arena model that offered the simulation interface	Discrete model with some flexibility and distributed components through the use of agents. Programming is needed to develop agents and achieve communication with Arena Limited scope to shop floor scheduling
Fujii et al., 2000	DES	Bill of materials – processing – storage – assembly – distribution – activity based costing (ABC) calculations Analyze ABC costing in the push and pull approaches	Distributed simulations arrangement Only physical materials flow in the system Discrete simulation consistent with ABC costing

Reference	Tool	Scope	Commentary
Pepyne & Cassandras, 2000	Queuing model with continuous enhancements	Processing workstation Optimize trade-off between desired quality and processing makespan.	A single workstation For optimization not the what-if type of simulation uses.
Ritchie-Dunham et al., 2000	SD Policies and resource management	Enterprise system: Customer base - , human resources, supplies inventories, financials, technologies, customer support Evaluate ERP and BSC for integration, functionality, visibility, and standardization that are difficult to quantify for lack of good data and high costs.	SD could be used even with lack of good data. No details about the structure of the system or the experiments. Service system with no production facilities. Suppliers are not included.
Barton et al., 2001	DES - EMI Extend DES model scope by EMI to communicate operational performance to finance.	DES for operations – EMI: customer orders, design, MRP, production planning and control, accounting, suppliers. Evaluate scenarios to introduce new products using DFX criteria	DES not suitable to communicate operational performance to financial level. DES use is too limited compared to EMI. Basically static. Assume existing EMI models.
Ma et al., 2001	Continuous simulation tool controlled by a programmable logic controller (PLC) in a distributed simulation arrangement	Control of a loading/unloading robot in a manufacturing process or similar control tasks in manufacturing settings	Limited to control applications. Customized PLC rules for each process. Specialized continuous simulation tools (IGRIP)

Reference	Tool	Scope	Commentary
Johnson & Eberlein, 2002	SD More efficient than DES/spreadsheets	Equipment capacity – failure modes – related financial measures Evaluate investment decisions in an oil and gas company	SD could replace DES (used for technical aspects) and spreadsheets (used for financial aspects) High level management friendly approach. DES could not model financial parameters efficiently. Spreadsheets were used. DES rejected by higher management for too much detail.
Lee et al., 2002a	SD - Discrete Improve discrete simulation accuracy using SD	SC partners in SD, communicating by DES SC modeling	DES only overestimated inventory levels. Abstract model; considers flow of orders in one direction and flow of info in the opposite direction Not enough details given on using DES for communications
Lertpatarapong, 2002	SD Semiconductors manufacturer. Analyze long range behavior and stability of the system.	Capacity – Inventories – Demand – Competitors - Market share Analyze oscillations in system behavior.	Aggregate representation Manufacturing is by inventories and production rates
Zulch et al., 2002	Discreet objects Separate aggregate planning from scheduling by hierarchical structure	Customer order arrival - Production planning & sequencing - Processing	Easily becomes huge and complex with possibility of thousands of object in a very simple situation Traditional DES in sub models structure
Bezemere and Akkermans, 2003	SD Semiconductors manufacturer Stability of the system	Demand, order flows, capacity, inventories, and customer services.	SD captured the feedback structure easily. Only flows of order and products studied. Studied oscillations due to delays and how to stabilize them.

Reference	Tool	Scope	Commentary
Gregoriades & Karakostas, 2003	SD – discrete objects Simplicity of SD and scalability of objects	The organization system. Mapping business objects to SD simulation	SD models interact only indirectly through the business objects, which would affect the integrity of the feedback loops of SD. Objects are developed and validated first, then SD models are tailored to fit. Discrete and/or static objects control SD.
Goddeng et al., 2003	DES and agents Semiconductors manufacturer	Materials flow data and decision flow and their interactions.	Failed to use SD for lack of sufficient granularity. DES difficult to model decision flows. Agents were used to communicate DES units. Java tools had to be developed to customize agents.
Keenan & Paich 2004	SD Model feedback structure of an auto manufacturer's enterprise system Various improvement initiatives implemented successfully but combined outcomes not as expected	Enterprise system: macro-economic variables, financial ratios, market share, investment decisions, resource utilizations, market behavior, competitors, customer behavior, segments of products and factories	Macro level variables were modeled. Individual processes could not be incorporated. Detailed operations of dealerships could not be included in desirable level of details. Could not reach desirable individual household level analysis, which is an important point of analysis. Model offered senior management a holistic view across geographically distributed operations.

Reference	Tool	Scope	Commentary
Venkateswaran & Son, 2005	Hybrid SD and DES Investigate using HLA	An implementation of the HPP model Aggregate production planning and scheduling tasks. Production rate from SD and cycle time and feasibility from DES	Production planning function only. Integer programming makes decisions → Static Simulations only test the IP optimization output. Arbitrary daily data interactions
Adamides, 2006	SD	A simulator to design strategic policies in manufacturing system	SD models intangible assets whereas DES models tangible assets Strategic level modeled in SD. Resource planning and allocation decisions
Lavoie et al., 2007	DES enhanced by a set of differential equations	Optimization of production rate, work in process, and surplus rate in a highly stochastic system. Differential equations estimated demand and represented control policies by a threshold to signal the need for a control action.	Process is highly stochastic due to high equipment failure rate, which results in inability to meet planned production while increasing the inventory levels. DES was used for processes to capture the stochastic behavior and provide detailed monitoring of equipment units. DES provided input parameters to control policy modeled by a set of differential equations, based on a feedback structure allowing management to react to unexpected occurrences in a systemic manner based on a set of preset rules. DES with differential equations is faster that DES only simulation as many events are replaced by fewer binary variables in the differential equations
Rabelo et al., 2007	Hybrid DES and SD	Manufacturing value chain. Investment decision, demand, customer satisfaction, staffing, profits, and other business level units in SD Manufacturing processes and product service facilities in DES	Detailed estimates of production and service costs, lead times, and productivity from DES are inputs to SD. SD estimates demand, satisfaction, investments in quality improvement for inputs to SD Profits and enterprise growth over future 5 years considering outsourcing alternatives.
Umeda & Zhang, 2008	Hybrid SD and Discrete	Manufacturing supply chains, to incorporate shop floor (from discrete) data in estimating customer satisfaction and ordering (in SD)	Suggesting the integration of SD and DES (which what is studied in this dissertation) without providing any explanation of how to achieve that.

Table 2-3show that Des is mostly used at the operational level where the models represent the shop floor level activities and the physical flow of the materials and products (the manufacturing activities). When going beyond the shop floor level, usually some aggregate production planning activates is considered and SD becomes popular. It is widely accepted among researchers that most of the processes in manufacturing are stochastic that makes DES the appropriate choice. The main concern as expressed by some has been the flow of materials, inventory levels, and resource utilization rates. The manufacturing system in this context is viewed as a collection of interconnected processes; machines or servers, reservoirs, buffers, queues, and delays. The simulation models are defined to consist of elements to represent these components of the manufacturing systems as analysts are concerned with determining the key performance indicators at such detailed levels. (See also Sadr and Sorensen, 2003; Bonder and McGinnis, 2002; Lee et al., 2002a; Wu, 2002; 1992; Law and Kelton, 2000; Kosturiak and Gregor, 1999; Greene, 1997; De Souza et al., 1996; Pegden et al., 1990; Towill and Edghill, 1989; Carrie, 1988). The interactions with the business level/non-manufacturing functions are not simulated by DES. DES was in fact considered not suitable for modeling financial computation for higher management (Johnson and Eberlein, 2002; Barton et al., 2001).

Cases have shown the value of simulating the total system. In Wu (1992) DES was used to compare a British manufacturer of mining equipment with a German manufacturer who used the same technologies and produced same quality in their final products. Yet the German company was noticeably ahead of the British, which was due to the ability of the Germans to respond faster to the customers and deliver and install in about two thirds of the time that the British needed. The manufacturing functions in the two companies did not offer them the competitive advantages. It was the other supporting functions by professionals, sales, customer relations and services. Analyzing the manufacturing lines could indicate promising performance but for the company to comprehensively evaluate its performance, the manufacturing functions should be put in place among the other non-manufacturing functions. In other words, an enterprise view is needed to correctly assess and evaluate performance.

For a specific motivation, capital equipment are more expensive currently than before. Careful consideration at the business level of investing in them as well as ensuring the economic utilization of them at the operational level can be addressed if business and operational level functions are integrated in the simulation model. But financial measures are not used at the production line levels. This may be attributed to the lack of realizing the impact of the feedback structure in business systems (Lertpatarapong, 2002; Sterman, 2000). The inability to recognize the effect of the feedback relationships and their dynamics leads managers to create oscillations by themselves in the system, in attempting to react to observed changes. Frequent changes in production line performances causes lower levels managers to react. If production processes are integrated in an overall feedback loops-based model, the managers' reactions can be assessed before they are in effect. There are many ways to describe the goal of the manufacturing enterprise. Nevertheless, the core is to create money and increase the wealth of the owners. All activities within the enterprise must be streamlined in this direction. The integration of the non-manufacturing functions and manufacturing function in simulating and analyzing the enterprise system is the logical framework to achieve that goal.

This is related to achieving stability in the enterprise system. Stability implies the robustness of the system to sources of variations (equipment failure, performance variation, product changes, sales variations, competitors actions, market changes, etc.). It is more important to analyze the dynamic stability and frequency response of the system than the study of the optimal operating conditions. Detailed approaches (e.g. DES) at the operational levels can not address the problem of stability (Rabelo et al., 2005). DES models allow analysts to evaluate the system performance for specific values of decision variables or control policies. The complex, nonlinear cause-and-effect relationships with the impact of the feedback loops and time delays cause the system to respond to variations in input data disproportionately and with tendency to amplify them as well as with fluctuations (the bullwhip effect). Such fluctuations must be recognized and dealt with through the underlying causes, not the apparent consequences.

The interest in the study of the stability of the system has started with the application of the control theory concepts to industrial systems by Forrester in the mid 1950s (Edghill and Towill, 1989). The study of stability and reactions to exogenous inputs must be done before any detailed analyses and should be done over a long range. This gives an advantage to the continuous simulation approaches that model aggregate levels. The assumptions of statistical distributions in DES should not be considered fixed over long periods of time (Morecroft and Robinson, 2007). DES also faces other challenges that continuous simulation and hybrid approaches of discrete and continuous can handle. This is discussed in the following sections.

Manufacturing functions are normally under financial constraints and pressure, for instance for better resources utilization and less needs for expediting. Such pressure would force managers to increase utilization of resources by allowing more materials in order to keep them running. This results in increased inventories in the system as well as imbalance and possibly longer lead times. Yet, if such pressure is eliminated the system cannot maintain stability if changes in demand or unexpected changes in capacity or customer requirements occur. Reid and Koljonen (1999) have shown that the theory of constraint (TOC) thinking process' approach of focusing on the physical system without the " ..cost world .." interactions leads to chaotic system performance. Only when the two levels are coordinated within a feedback structure is the stability achievable.

Wu (1992) in his analysis used DES but he found that that aggregate levels are better simulated using continuous simulation. No attempt, however, he made to use continuous simulation, or extend the use of DES to incorporate business level functions. Instead, and believing that the feedback structure in the manufacturing system is too complex, he suggested following a hierarchical top-bottom approach to analyze the system. This starts with an aggregate view of the system and based on it detailed levels should be designed for a better performance. For that regard the EM techniques (IDEF, GRAI) were mentioned by Wu (1992) and by Barton et al. (2001) and others. Nevertheless the analysis of the manufacturing system that Wu did was for the production planning function and did not attempt to include any business level tasks. In addition, DES was not linked to the IDEF model that he used.

A definition of the manufacturing system by Bauer et al. (1982) signals clearly the need to attempt the simulation of the manufacturing system as a whole (manufacturing and non-manufacturing). They defined it as an organization of men, machine, and procedures (this is the manufacturing function aspect), acting under physical, legal, and economic constraints (this is the non-manufacturing aspect). Bauer et al. attempted to simulate the micro and the macro levels of a semiconductor company that has two plants in two cities. They attempted that by using SD. Their focus was on the logistics of the manufacturing system and the exchange of orders and order status data among the two plants. SD has failed to model the details of the processing procedures and was abandoned in favor of DES. Their conclusion was to use detailed DES models in a bottom-up approach to model the entire manufacturing system. This seems to be inconsistent with the basic concepts of classifying the management levels in strategic, tactical, and operational in which the higher levels provide the guidelines to the lower levels. Besides, data collection and preparation for DES simulation is a tedious task. Starting at the operational level when the system is still experiencing problems would make building DES with its huge data requirements a difficult task. If aggregate data were to be collected, this should be easier. And when a model of the macro level is developed, detailed versions of parts of that model can be developed. Such detailed models should be easier to build as they are focused and within the guidelines for the macro level model. The author sees that their comments on the difficulty of detailed discrete simulation do not support their bottom-up recommendation. Yet, since the use of SD did not provide the expected results, DES became the only choice and since DES is detailed in nature they wanted to start at the micro level. The simulation project, however, was a pilot project and was not implemented.

In another case reported in Wu (1992), a capital equipment manufacturer invested and installed a flexible manufacturing cell (FMC) which was dedicated for the manufacture of a critical type of valve. After a huge investment in the FMC, the result was a remarkable increase in WIP. The explanation was that the FMC had a high productivity that was not matched by the other departments that used that valve. The FMC however, was very specialized and not useable for other uses. If a long-range horizon simulation model that incorporated the production process and the finance and equipment management business functions was used in evaluating the investment, the increase in inventory expenses would have been avoided. This could have been by not taking the investment in favor of other less costly productivity methods, or by modifying the policies to increase the internal demand. This would also have involved advertising and marketing efforts or triggered a major capacity planning project.

Baudin (1990) was not dealing with the simulation of manufacturing system but with the analysis of the operations of such a system. He recognized the role of integrated system approaches in better system performance but said that the use of dollar sign as a measure disappears as we move towards the operational levels of the manufacturing organization and he concluded that the decisions made at this detailed lower level of management do not have direct impact on funds flow in the organization. On the other hand he recognized the contradictory relationship between the accountants and the manufacturing analysts in the manufacturing organization where accountants work to limit spending while analysts want to spend. This type of trade-off relationships obviously signal the need to include the two parties as well all others in a feedback integrated approach if the system was to avoid the conflicts among the business units.

This is not limited to the financial and accounting aspects in relation to operational productivity. In fact the accounting and financial metrics can represent all level performances. Strategies such as Design-for-X, Total Quality Management (TQM) and the like, are supposed to be evaluated at the enterprise-wide level (Barton et al., 2001) since they encompass the entire system, by definition for some of them.

The trade-off was obvious in a leading semiconductor manufacturing company that implement a TQM project with a dramatic level of success (Sterman *et al.,* 1997). Yield doubled, on-time delivery rose from 70% to 96%, cycle time fell from 15 to 8 weeks, and defect rate fell by a factor of 10. However during the same period the company's share price fell by more than 60%, return on equity fell from 7% to 4% and the company was forced to lay off workers for the first time ever. It is again emphasized that the productivity improvement at the manufacturing functions and the financial results are more complex than the perception that financial benefits would follow successful process improvement. Productivity improvement programs are tightly coupled with the other activities within the firm, along with the customers, competitors, and the financial market. The couplings among various system parameters at the factory floor level were weak and the TQM teams dealt them relatively independent of each other. On the other hand such couplings and interactions with the business levels were strong. The rapid benefits at the manufacturing level motivated the management to increase the support at manufacturing at the expenses of other areas such as product development, R&D, and sales and marketing. Thus the increased production capacity could not be matched by market demand. Personnel at areas other than manufacturing lost confidence in TQM and believed it would not be helpful, but a threat to them. This created unbalanced system. In addition the management, pressured by the need to boost its share price, has shifted its focus to new financial endeavors, which stressed the system even more and intensified the imbalance and eventually distorted the company's cost estimating structure. The TQM program had to be stopped.

Despite the trade-offs between financial measures and the shop floor productivity measures, it is only possible to estimate the impact on the total system of equipment loading, or a batch size decision at a certain machine, through the use of the financial and accounting indicators. Accounting can play the role of the system integrator (Umble and Srikanth, 1996), which implies that only using the financial performance measures to judge the health of a manufacturing enterprise can be misleading. Also, it is not unexpected that good financial measures of performance can be the result of cost cutting programs or, as Viswanadham (2000) indicated due to underachievement over the long-term value creation. The fact is that financial performance measures reflect the performance of the enterprise over the past few months, let us say, not even the current performance. A conclusion out of this is that an integration of the operational and financial levels should help control the trade-off.

Logically, the local focus on the individual processes often leads to local improvements, which just may cause the shift of problems from a business area to another, e.g., moving a bottleneck from a production step to another up or down the stream. An enterprise must cope with the increasing competitiveness and rapidly changing technologies, which necessarily requires reducing cycle times, cutting costs, and upgrading to better technologies. But as seen above achieving these goals can have negative consequences.

Given the large scale and complex systems of today, a simulation model would be too complex to use, let alone to build. It is difficult and time consuming to interpret the results of a simulation, especially a model that includes large number of stochastic elements. It has been argued by Forrester (1965) that the cognitive limitations of human mind would prevent managers from understating how complex dynamic systems operate. Still the need to use system views to develop simulations of the manufacturing organization is necessary.

Attempts to develop comprehensive simulation go along with the adaptation of the integration concepts in managing the enterprise system. A system was described in Love and Barten (1996) and Barton et al. (2001) which was meant to model the total enterprise system for the purpose of testing various Design For X (DFX) strategies. DES was attempted and found inadequate for communicating the manufacturing indicators (utilization, throughput, etc.) to the financial planning levels. To achieve the comprehensiveness and combine the business and financial level with the manufacturing process level, enterprise modeling techniques were combined with DES. The system, however, turned to be complex, and few DES modules could be included to approximate the production facility in relation to the business objects designed by the enterprise model. The system was modeled in object oriented approach that had within each object a DES module that interacts with others by a driver. For instance a CAD sub system would interact with a CAPP sub system via the two drivers of the two sub systems.

Only aggregate model could be built while the details of the processes were missing. The enterprise model controlled the structure and limited the flexibility of using DES. The detailed approach of DES was not appropriate with the aggregate nature of the static enterprise model. The system, in addition, was tailored to test DFX technologies not to assess the performance of the enterprise. As was indicated in Barton et al. (2001) the enterprise modeling techniques were not likely to support the operational level analysis. For instance, a design change in a product would ease a capacity problem, but no operational details about the impact of that change could be obtained. Further, the stability of the system could not be assessed. Only estimates of specific values were obtainable.

Another attempt to achieve comprehensiveness in simulating the manufacturing system was described in Zulch et al. (2002) where they adopted a hierarchical structure that can be represented as in Figure 2-28 in which orders arrive, accepted or rejected, and if accepted they are further analyzed for the manufacturing decision. One customer order can result in many production orders that can be different in their processing requirements.

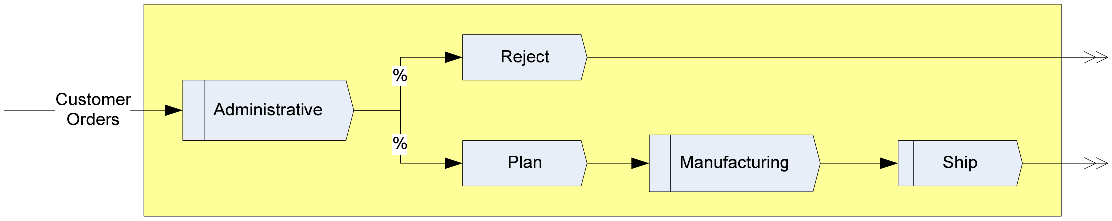


Figure 2.28 Aggregate manufacturing system representation

The manufacturing object is decomposed to have the processing facilities. The details of the manufacturing are actually modeled separately and communication is carried out by a messaging system. An object is actually the representative of the detailed manufacturing model. Data are collected and aggregated here for aggregate decision making. Each production order requires a detailed manufacturing object to be created. The system creates the object to fit the processing requirements of the order. Given that, the system easily becomes too complex since 1000 orders, for instance, would require 1000 manufacturing modules to process them. Each module requires sending and receiving messages and data with the aggregate level. Objects offer scalability but the potential for complexity are significant. The level of comprehensiveness, in addition, was limited to handling orders from receiving them until shipping them; that is the production planning and control functions at the order and material flow levels, which were modeled as discrete objects.

2.7.1 Contrasting DES and SD

The core differences between DES and SD stem from the scope and nature of the problems studied by each, being mostly stochastic, operational, and detailed with DES and deterministic, holistic and strategic with SD. The reason for that is the different ways each paradigm views and represents a system and the associated level of complexity involved. Important conceptual differences between the two approaches were addressed by researchers as summarized by Morecroft and Robinson (2007). A summary of these and other identified differences between the two approaches are given in Table 2-4.

Table 2.4 Conceptual differences between DES and SD

	DES	**SD**
Perspective	Analytic emphasizing detail complexity	Holistic emphasizing dynamics complexity
Underlying philosophy	Vague	Well-defined
Resolution	Individual entities, attributes, events	Homogenized entities and emergent behavior
Nature of model	Stochastic	Deterministic
Level of model complexity	Increases exponentially	Increases linearly
Data	Numerical with some judgmental elements	Broadly drawn
Problem scope	Operational	Strategic
Time advance	Unequal time slices matching events	Equal time steps
State changes	At discrete points in time	continuously
User perceptions of model	Opaque	Transparent
Outputs	Point estimates and detailed performance measures	Understanding of sources of structure behavior modes

DES has been successful in building simulations of manufacturing systems. Yet it is being is faced by serious challenges in simulating integrated systems. The credibility of DES cannot be denied. DES works effectively with problems of narrow scopes, but it is "…

incompatible with a global point of view" (Lin et al., 1998). A Survey (Smith, 2003) of the applications of DES in manufacturing system simulation showed that DES has been used in the design of the manufacturing system more than in the operation of the system. Facilities design and layout of flexible manufacturing systems was the most common, where materials handling systems are the core concerns. Further in the system operation, most applications (more than 90%) have been in the real-time control and scheduling. Less than 10% of the applications were in analyzing policies. The survey showed that generic DES simulators that can cover different systems are not satisfactory. Too much programming and customization must be preformed to model a system.

DES has been very successful and effective as a manufacturing systems modeling tool. It is widely considered the most appropriate for handling the stochastic dynamical nature of manufacturing systems and sometimes the only feasible tool. In the negative side, DES relies on statistics and only statistical inferences can be made, and it is expensive and time consuming to develop (Lee *et al.*, 2004; Rabelo *et al.*, 2003, Morecroft and Robinson, 2007). And as indicated by Sadar and Sorensen (2003) DES does not offer closed loop solutions to describing the dynamics of the manufacturing systems.

The developers of Arena recognized two main issues facing enterprises as they try to exploit the capabilities of simulation. The first is broadening the use of simulation effectively throughout the enterprise in a consistent coordinated way. The second is concerned with enhancing the value of the simulation initiatives to the enterprise by leveraging investments in tools and methodologies (Babat and Sturrock, 2003). The implication here by the Arena maker statement is that is that DES simulation software are faced by difficulties in modeling integrated enterprises[1]. Another implication of this statement by the vendors of Arena is that integrated business systems created a need for simulation approaches that are comprehensive yet cost- and effort-effective (i.e. simple while the systems being modeled get bigger) and these are not yet available as desirable.

Major points of criticism regarding DES are its detailed approach and the huge data requirements that are not suitable for aggregate levels of decision making, its limitations in modeling continuous system variables, the increasing complexity of the models for integrated systems, and the high cost in terms of time and money for building the models.

DES can model any kind of system at any level of details. But when it comes to the strategic issues in manufacturing systems, where details are not required or available then SD has distinct advantages. The SD enterprise model of Sterman et al. (1997) was a comprehensive model that captured the physical and the institutional structure of the enterprise, representing the decision making processes at the different levels of management. It was a model of the structure of the enterprise rather than a model of the business units in relation to the TQM project. But it did not include the details of the implementation of the TQM at the shop floor level, where the increase in machine and workforce productivity were realized. It did not include the parameters of WIP or other inventory types. The company produced many different products and all had to be summed together to allow for the model to be built and presented to top managers. SD was used for its ability to deal with the different levels of analysis at the different levels of management and the interactions with the market and economic environment dynamics. The

[1] A major theme park in Orlando, FL approached Rockwell Software to develop a simulation of the roller coaster system and its controller system. Rockwell (vendors or Arena) rejected the job for not being consistent with Arena tools. This indicates that the support for continuous simulation in Arena is marginal.

outcomes of using the model were better understanding of the cause-and-effect relationships that created the trade-off between manufacturing and accounting and allowed top managers to identify the problems they have created.

The ability of SD to model the vertically integrated enterprise is in fact the fundamental concept of SD as a system thinking approach that targets top management. Johnson and Eberlein (2002) showed that SD can replace the use of DES and spreadsheets to communicate the financial computations to the higher management levels. The outputs of the model are usable at that management levels. It also requires little data. Mandal and Sohal (1998) modeled the Australian fabricated-metal industry using SD even with limited data. The model was useful for policy design and evaluation at the holistic level.

In addition to evaluating the performance at an enterprise level, it is necessary to recognize the levels of excess stock, quality, expenses, utilization, or productivity. Such measures of performance represent results more than they represent causes. A low level of productivity, for instance, is a result of taken policies and system's reactions to them. Improving productivity starts with identifying such policies as well as the structure of the system that allowed that (Sterman, 2000). This is fundamentally where SD acts.

SD captures the causal relationships that are not captured by other approaches that are based on the flow diagramming approaches; DES as well as object oriented techniques (An and Jehn, 2005). Further SD offers the ability to model qualitative and *soft factors* as was showed by Sterman et al. (1997) who modeled the management's attitude towards various departments in the company after implementing TQM. Factors such as the level of commitment of workforce, level of management support, and level of job security perceived by workers where modeled.

The use of delays and interactive feedback loops in mathematical formulations allowed modeling such parameters in a satisfactory and relatively easy way. At the aggregate level, policy modeling and analysis, data availability is not the constraint. Recalling that DES by nature requires large amounts of data, it becomes apparent that SD has an important advantage over DES.

Data related to manufacturing activities in manufacturing systems are always available and at very detailed levels whereas data for the non manufacturing functions, usually at the higher levels of decision making are only available as rough estimates and expert guesses (Zulch *et al.,* 2002; Mandal and Sohal, 1998; Anthony et al., 1989). The strategic level is the least systematic process and because of the long time horizons only rough estimates and approximations are feasible. Operational level decision making uses current, detailed, accurate data. The tactical level falls in between. This obviously has to do with the expected quality of the simulation results that can be obtained if a data demanding technique such as DES is used at the higher levels of management. SD also facilitates conducting designed experiments at the business level (Ashayeri et al., 1998); something that has been available at the detailed levels using DES. DES would need good quality data to conduct such experiments if models could be built and validated. This gives credit to using SD at the higher levels of decision making. It also gives credit to using DES at the operational levels.

If highly specific results are expected from simulation then detailed models should be built for the entire system, which is usually impossible or impractical. The level of details in the model has to be decided and fixed for the entire model in advance. If varying levels of details used in different parts of the model then inconsistent results would be obtained. A reasonable approach to avoid inconsistency would be by dividing the model into separate components in a modularized, hierarchical structure, which was suggested by Zulch et al. (2003). For example, customer orders are handled for all departments in the production system at the same activity network node at an aggregate level. Orders are then accepted or rejected. The resources and processing durations for the customer orders are modeled in a detailed model that offers a detailed version of the order handling aggregate model. Similar approach is used for each manufacturing process in the system. This approach, in addition to only using discrete modeling, can be inefficient to build. The real model is the detailed level. Data for the aggregate layer are collected from the detailed layers. The aggregate layer can be considered a process flow diagram of the production system that offers no useful quantitative results. Besides, the system creates object to fit the processing requirements of the orders and it easily becomes too complex since 1000 orders, for instance, would require 1000 manufacturing modules to process them. Each module would require sending and receiving message and data with the aggregate level, making it too complex system.

The continuous variables are better modeled using continuous techniques. The inability to reflect the continuous nature of the process or the interactions among continuous components, in addition to the growing complexity with less accuracy is some important problems. As Lee et al. (2002a) demonstrated DES would overestimate the behavior of continuous variables. This research also argues that approximation of continuous variable by discrete tools can be misleading.

On the other hand if SD has an advantage at the aggregate levels where details are not normally needed, it has a problem at the operational detailed levels. SD could not prove effective to be used for the more detailed operational level activities. In fact it was stated by Lin et al. (1998) that ".. SD lacks a modeling platform" for applying it to manufacturing problems and that managers found it hard to correspond the stocks and flows to manufacturing system components. Wiendahl and Breithaupt (1998) experimented with simulating manufacturing systems using techniques based on direct use of the automatic control theory. They concluded that such continuous simulation approaches (of the control theory) do not lend themselves easily to model the discrete nature of the manufacturing functions in the manufacturing enterprise. Also, the use of continuous simulation based on the control theory is successful only at the planning level where the microscopic behavior of the individual process disappears behind the macroscopic view of the system. At the planning level (higher management levels) the individual event is not of interest, but rather mean values of the performance measures are observed in aggregate terms. SD is based on control theory concepts, which make these findings applicable to it.

With a similar attitude, the Manufacturing Systems Research Group at Cranfield University, UK (2000) recognized that using DES limited the scope of the simulation model to a detailed analysis technique, which is suitable for some users only and cannot be consistent with the integrated systems approach. SD was investigated as a replacement to DES for simulating manufacturing systems. But they found that the stocks and flows of SD are not suitable for the manufacturing system facilities as are other representation ways in DES. This was taken as an explanation why SD is not well-known in manufacturing applications. The Research Group investigated customizing SD-based tools for manufacturing functions simulation. To the best of our knowledge these efforts had not provided such SD-based tools for manufacturing systems simulation.

Another attempt was reported in Lin et al. (1998) who attempted to develop SD-based manufacturing system modules library; each element in it is a small SD model that correspond to a component in a manufacturing system (e.g. a module for a machine, queue, etc.). This can be criticized for:

1. Complicating SD's intuition advantages by introducing too many mathematical-based attributes of the elements that should be customized for the specific applications.
2. Introducing too much details not consistent with it being a system thinking approach
3. Approximating DES capabilities while DES already exists and is proven to be effective.

For instance, a module in that library was the converting activity module. It has inputs (materials), outputs (products) and time (labor). It is used as a process in a manufacturing line. Inside the module a stock variable accumulates time allocated to the process while a flow variable represents the passage of the allocated time. Further, this module is a part of a bigger system for which a global time is observed and the passage of time is executed at different levels. This was applied to a job shop where they tested the addition of new equipment; an application where DES has been effectively applied for decades. The manufacturing system was not viewed as a whole; to include the aggregate level. Thus SD did not contribute much.

Although SD was initially developed for industrial systems and the first application of it was for a production planning and distribution system, it has found the greatest success in other areas rather than manufacturing. Few researchers, since Forrester have used SD for manufacturing systems applications and little has been done in this direction (Bainess and Harrison, 1999; Mandal and Sohal, 1998). Manufacturing systems modeling was considered a *missed opportunity* for SD modeling, especially in the higher levels of decision making. The integration in systems and the adoption of system views support that.

Keenan and Paich (2004) used SD to model General Motors (GM) and the North American auto industry. An enterprise model of GM was built to assist senior manager assess the existing policies and the number of improvement initiatives that had been implemented. The initiatives were considered successful but concerns were made that the combined impact of the initiatives could not meet the performance objectives in terms of market share and profitability. SD offered management the ability to capture the feedback structure of the organization and address the leverage of the improvement initiatives. The enterprise model attempted to be as comprehensive as possible; including the macro-economic variables, market, dealerships, customer behavior, and the processes at the various manufacturing facilities located at geographically distant locations. Yet SD as a methodology failed to offer desirable levels of details. Particularly the model could not include the customers' behavior at the household level, which is an important aspect of the auto market given the high competition and the many brands and models offered every year. The model also could not reach the details of the manufacturing processes and the operations of the dealerships.

Only overall measures and indicators were collected regarding the potential policy alternatives. The question that was raised by the senior managers was about where exactly should they intervene and how specifically should the resources be allocated. The trends and the macro level indicators needed to be extended to become actionable. The use of discrete agent-based models was suggested to model those aspects that SD could not capture as desirable.

This has been the case with other researchers. Godding *et al.* (2003) found that the modeling and numerical simulation methods that are offered by SD environments do not provide the needed level of granularity to model the complex stochastic material flows and associated control algorithms for a semiconductor supply network without significant extension. Consequently they chose to use DES instead. Similar decision was made by Donizelli and Laziolla (1996) who used discrete event simulation to model the activities in the development process and he used continuous mathematical equations to express the resources allocation and utilization as functions of time. Bauer et al. (1982) also found SD limiting their abilities to model the processes at a semiconductor manufacturer.

In a different situation, Martin (2001) found that SD can model the environment of the software development process, but for modeling the process itself DES was used. They commented that:

> "… we cannot ask a SD model questions about the size or complexity of a module of code, because code modules are modeled as individual entities … we cannot ask a DES model about the behavior of continuous variables and feedback loops".

Baines and Harrison (1999) made a review for the uses of the SD in modeling the resources, manufacturing, and service sectors and they found that SD is not widely used in manufacturing applications but whenever used it is mostly in activities closer to the operational level functions. They also found that most of SD manufacturing applications are related to the SC model developed by Jay Forrester in the late 1950s.

Using SD for operational levels applications is unexpected because SD is supposed to be an overall modeling approach that targets top management. But since DES is the dominant manufacturing system simulation approach, modelers tried to use SD in the same way they used

DES. It is something we call the *DES mentality* in conducting simulation studies that make modelers expect other simulation approaches to work in the same way DES does and it is not giving the expected outcomes. Thais could be why SD in manufacturing applications is not popular.

As can be implied by now, each of SD and DES should be assigned certain uses in the manufacturing enterprise. Gregoriades and Karakostas (2003) and Chang and Makatsoris (2001) suggested limiting the use of DES to certain problem areas, which implies that they do not recommend using DES to develop comprehensive models or using SD for the operational levels. Huang *et al.* (2003) did not believe a single DES model can be used for all of the three levels of management. Lee *et al.* (2002a) recommended using analytical models for the operational level activities, DES for the tactical level activities, while for the strategic levels they recommended hybrid discrete/continuous simulation models. This classification was also supported by the Manufacturing System Research Group of Cranfield University (2000) where DES is recommended for the situations where few alternatives are considered and detailed analyses are needed. This usually happens at the operational levels of manufacturing systems and at some tactical level activities.

Hannet (1999) recommended continuous simulation for the higher level, aggregate planning processes for simplicity due to the broader range of impact such planning decisions have on the entire system. Yet when the aggregate decisions are disaggregated for implementation at the operational levels, and as the time horizon for planning is made shorter harder constraints and conflicts start to affect the planning process. In these circumstances Hannet considered continuous variables and models less appropriate.

In similar approach, SD was used in Son et al. (2005) to model the hierarchical production planning (HPP) process at the aggregate level while DES was used at the operational level. The motivation to use SD and DES was accommodating the levels of details between the planning and the scheduling levels. Plans, generated by an integer programming model at the aggregate level, are validated in a SD model of the production system. They are then communicated to the operational level scheduling techniques are used to breakdown the plans into shorter range segments. DES is used to validate the expected output at the operational level. They used HLA's RTI protocols to synchronize the simulation models. The integer programming optimizer at each level is invoked for a rerun when the simulation results show significant deviations from the expected performance. Simulation models were built validate the optimization results with the HPP framework.

The philosophy behind SD is that people can describe structure and local behavior of a system well, but fail to predict global behavior, especially if feedback loops of different lengths and complexity are part of the system (Jarke *et al.*, 1997; Bradl, 2003). SD can predict global behavior and it recognizes the feedback information as the first concern. By focusing on the system structure SD can help reaching a common understanding of how the system works, which is very important step toward achieving solutions for problems in more details later.

2.7.2 Attempts for more comprehensiveness

Attempts to build comprehensive simulation are many and in different directions. Some researchers used objects to facilitate the building of component systems that involved DES and

SD sometimes. Others, aiming at overall view of the enterprise, have utilized the enterprise modeling systems (GRAI, IDEF, etc) in conjunction with DES mostly. This shows first the growing need and interest in comprehensiveness, and second, but not less important, the inability of one tool or approach to offer all the required outcomes. Not many business and manufacturing uses of the hybrid systems were found in the literature review.

An approach to utilize SD in a way that makes it usable for all levels was suggested by Gregoriades and Karakostas (2003) in which they encapsulated SD models inside the business objects. They mapped the business objects to SD models on a one-to-one basis such that each business function is represented by an object, which is mapped to a SD model. The objects were developed first where each includes a recorder for managing interactions with other objects, set of business rules, methods and attributes of the object, and a SD interaction interface. Small SD models were built and their mathematics was hid within object structure to simplify using the models by non-mathematical managers. Objects must be developed and validated first. Then SD models are developed for each. Although not stated explicitly in the paper, the objects were built as discrete and/or static objects that will be controlling the use of SD. This reduces the data preparation needs but it has the potential of undermining the feedback structure of the SD model. It could even be more complicated to interconnect small SD models that are isolated inside customized objects than building a single SD model for the entire system.

Attempting to address the integrated system Kosturiak and Gregor (1999) utilized DES in a system engineering design and analysis methodology. They put simulation as needed in during the steps of the design process of the system. But static analytical tools rather than simulation were used for the goal setting of the design and at the strategic thinking levels. Further they had to accept rough simulations at the early stages of the design processes that will be refined in later steps. Objects were the tools they considered to implement their approach to total system simulation. In fact they introduced their approach as a simulation of the integrated manufacturing enterprise while it actually was an attempt to introduce many simulation models at the various steps of the system design process life cycle. The applications for their approach were at the production line levels.

A comprehensive supply chain simulation framework was suggested in Umeda and Zhang (2008) using discrete and continuous simulations. DES was used for the operational process inside the supply chain, while SD was used for the environment outside the supply chain that included the market behavior. The objective was to extend the analysis of the supply chain performance to include the market dynamics rather than quantified market indicator defined statically at the discrete simulation. This argument, however, ignored the history of using SD in modeling the supply chains for decades.

At a larger scale, Rabelo et al. (2007) used SD and DES to model the value chain of a construction equipment manufacturer who was evaluating outsourcing alternative of the manufacturing facilities. Optimizing the performance of the value chain (Porter, 1985) system is achievable via cost optimization, which required high resolution modeling of the manufacturing and service operations and their associated costs and impacts of overall system performance. DES was used to model the manufacturing and service facilities for each outsourcing option. The SD model was used to represent the value chain system at the strategic decision making level, including demand forecasting, customer satisfaction, profits and investment to improve quality at the operations level. Quality and demand are exported to the DES models to estimate the productivity, lead times, and costs. These are feedback into SD to update the system performance. All outsourcing alternatives were evaluated similarly and the decision could be made.

In Lee et al. (2002a) a manufacturing supply chain (SC) was modeled using a hybrid approach. The motive was the fact that manufacturing SC are neither completely discrete nor completely continuous. The product and information flow can have continuous factors. At the strategic management level, continuous approaches are more suitable for the lack of data, for the qualitative considerations, and for the unsuitability of the detailed, stochastic nature of the discrete simulation approach. In building the model a SC of a supplier, manufacturer, distributor and retailer was modeled. Information about customer orders, decision making at each of the SC partners as well as their inventory levels were modeled using mathematical formulation to reflect continuous behavior. Interactions among the SC partners (exchanging the input/output data from each other to each other) were discrete. They compared the results of the model with the results of a purely discrete model of the same SC. The comparison showed overestimation of the inventory levels at all SC partners by the discrete model.

A more sophisticated approach to build a hybrid simulation model of a SC was used in GroBler et al. (2003). They built an agent-based model that consisted of a supplier and three manufacturers. The behaviors of the manufacturers' agents were modeled in SD to reflect the continuous behavior or their systems. Every SD simulation step (0.125 month) the SD inside each manufacturer's agent generates the demand which is passed to the supplier. The response of the supplier is used as an initial value for the next SD simulation step. To control the SD models to run in a step by step fashion, they used the gaming capability of the Vensim SD tool. No efforts were indicated to decide on the step size. Too much programming was needed to build the agents (using Java) and communicate with the SD engine. The output was discontinuous.

2.8 The Gap in Simulating the Manufacturing Enterprise

Based on the discussion in the previous sections, the following statements can represent the gap perceived in this dissertation in the simulation applications in the of the manufacturing domain:

1. Managing the modern manufacturing enterprise system demands a systemic approach and a holistic integrative view that recognizes the inherent feedback structure of the system while accommodating the characteristics of the decision making processes at each management level.
2. This integrated manufacturing enterprise system poses challenges to the available simulation tools.
3. DES suffers several shortfalls in meeting the needs of simulating the such complex integrated manufacturing enterprises due to the difficulties in offering holistic models from the perspective of the aggregate management level for the long range planning horizon.
4. SD assumes the aggregate level perspective in a systemic integrative approach, yet it falls short in adequately modeling the detailed, short-term decision making levels.

5. Hybrid continuous-discrete simulation approaches offer the ability to accommodate all types of behavior in the integrated system. Yet the existing approaches are based on assumptions of control situations and tend to suppress the continuous behavior.
6. Distributed simulation approaches offer favorable features that could improve and facilitate the building of large-scale simulation models of the integrated manufacturing enterprises, yet are not yet exploited in such area due to technical complexity and high overhead.

It is concluded that there is a need for a comprehensive, simple, yet scalable and effective approach to simulate the modern integrated manufacturing enterprise system. This approach should accommodate the differences between the operational and aggregate management levels while bringing them together in a coordinated structure. A combination of SD and DES simulation paradigms has the potential of satisfying the needed characteristics in the simulation model of the manufacturing enterprise.

The integration of SD and DES as proposed in this work offers an inexpensive technique that maintains the existing simulation expertise in simulating the manufacturing systems. Legacy models can be utilized and no new programming skills are needed. The proposed SDDES has the potential to maintain the integrity of the two simulation paradigms; and allow no paradigm to dominate the other. The literature review provides the justification to stating the following as the research directions:

1. Managers of the integrated manufacturing systems need new simulation tools that can accommodate the differences between management levels in a holistic, enterprise-wide perspective.
2. Simulation models of modern manufacturing systems should incorporate in the same simulation arrangement, the operational and the aggregate management levels in a dynamic feedback-based structure
3. Current discrete and continuous simulation approaches; used separately, fall short in meeting the challenges created by integration in the manufacturing enterprises
4. The simulation of the integrated manufacturing enterprise should be approached using new hybrid continuous-discrete methodologies
5. The existing frameworks to implement hybrid simulation are inadequate for meeting the needs of managing an integrated manufacturing enterprise
6. SD and DES can complement each other for simulating the large scale, dynamic, integrated manufacturing enterprise system

CHAPTER 3: SYNCHRONIZATION IN DISTRIBUTED SIMULATION

SD and DES advance time differently and update the system state differently. A synchronization mechanism is needed to integrate them. This chapter reviews the synchronization algorithms used in the distributed simulation systems. A new synchronization mechanism for integrating SD and DES will be presented in Chapter 5.

Distributed simulations interact by exchanging messages. Messages indicate the occurrence of events and the consequences of them as well as the timestamps associated with the events just occurred and those that are expected. Since models could be running on different platforms and they interact, it is expected that some causality relations might be violated. Synchronization works to ensure no causality relations are violated. The principle of causality requires that the time delay between an event and any reaction to it be greater than or equal to zero (Ma et al., 2001). The distributed structure and the problem of synchronization were first described independently by Bryant (1977) and Chandy and Misra (1978). They developed conservative approaches to deal with it. Jefferson (1985) then investigated the concept of the optimistic synchronization and developed the time wrap (TW) algorithm.

Synchronization deals with advancing local simulation time in each of the models in order to ensure correct global simulation time across all of them. The conservative and optimistic mechanisms of synchronization were developed for the discrete simulations. Synchronizing models running on different operating platforms is a complicated problem and there is no consensus so far (Fujimoto, 2001) on which of the conservative or the optimistic approach is better. If the hybrid dimension is added an even more complicated situation arises.

Traditionally, hybrid system are dominated by the discrete components (and are mostly in control situations) where the occurrence of events indicates the points in time when a synchronization action could be due. In business and some other social systems where continuous parameters are the basis for the behavior of the system, there are no special instantaneous occurrences such as events to use. Such parameters are better modeled using continuous simulation tools. A time advancement step has to be decided and this step must be coordinated with the times of occurrence of the events in the discrete parts when discrete tools are used to model the appropriate parts of the system. The concept of a time bucket has been proposed by researchers (Stienman, 1991) as another approach in addition to the optimistic and conservative approaches. The time bucket concept was inspired by the MRP systems that breakdown a long range plan into smaller time buckets. Many variations and alterations of the time bucket approach were proposed. Table 3-1 summarizes and compares the synchronization mechanisms, where Cons. in the Type field means conservative and Opt. means optimistic approach.

Table 3.1 Synchronization approaches in distributed simulation

Method	Reference	Type	Concept	Commentary
Null message / Lookahead	Chady & Misra, 1978	Cons.	Original conservative mechanisms idea. Take precautions not to violate causality. Advance time only if causality not violated. Lookahead for safe time advancement. Null messages to avoid deadlock.	No causality violations. Slow simulation. Less parallelism. Designed for discrete events. Rely on application specific info
Time Wrap	Jefferson, 1985	Opt.	Advance local time freely. Rollback if causality violated. Anti-messages to execute rollbacks GVT for minimum timestamp for rollbacks	High calculation overhead. Possible avalanche of cascaded anti-messages leading to instability High memory needs Greater parallelism Designed for discrete events Special memory management tools
Time Bucket	Stienman, 1990	Cons.	Minimum time interval (TB) between events is time step to advance time. Models interact by the end of TBs only	Little computational overhead Designed for discrete events BT size is an issue Inefficient if not enough events in TB. Small TB not practical regarding MRP links Possible zero time between events
Breathing Time Wrap	Stienman, 1993	Opt.	Breathing Time Bucket with Anti-messages	Messages sent at the end of TBs only Less anti-messages than TW Designed for discrete events For SPEEDES environment

Method	Reference	Type	Concept	Commentary
Phased Time Bucket	Fujii el al., 1994; 1999	Cons.	Fixed TB size in all simulations TB relates but not necessarily same of MRP Central coordination unit is one simulation Time advance by alternating between all processes simulations then the central unit Interactions at the end of TBs only	Simple Designed for CIM / materials flow Not particularly designed for discrete events No specific approach to decide on TB size Inaccuracies if events do not match with the end of time buckets
Minimum Time Step	Frey et al., 1997	Cons. / Opt.	DES controlling continuous process Events indicate synchronization points Continuous process run between events and generates state events if threshold crossed Time steps in continuous calculations as small as nanoseconds TW to synchronize discrete simulations	Control application in natural sciences Computationally expensive - Not practical for industrial application of continuous processes. Difficulty in detecting next event time for continuous process to stop or start No specific way to choose time step No guarantee of matching continuous steps with discrete event timestamps Possibly causality violations
PLC-Continuous	Ma et al., 2001	Cons.	PLC running several continuous processes. Fixed TB. Interactions allows during buckets but no responses until the end of TB for continuous processes, yet immediate responses possible by PLC. Time advances by alternating between all continuous processes then the PLC	Digital control of continuous process. No explanation for selecting TB size Specific for PLC testing and applications Possible inaccuracy due to delayed responses between continuous processes Actions of continuous process are time consuming (movement, processing) but actions by PLC are instantaneous (on/off)

Method	Reference	Type	Concept	Commentary
SQL-Based Synchronization	Lee et al., 2002b	Cons.	SQL coordinator sends queries to DES models about scheduled events to create a common events calendar. Event timestamps for queries sending	Designed for discrete simulations Particular for Arena Can be time consuming/inefficient Simple
Resource Reconciliation	Lee & Wysk, 2004	Cons.	ERP/MRP as coordinator an adaptor Fixed TB (based on MRP TB) Models run TB after TB Each model sends a message to the adaptor at the end of each TB Models send statistics to the adaptor, which consult with ERP/MRP for corrections and new assignment	Designed for discrete events For materials processing and flow Increased parallelism Complicated for using extra local databases at the models and the adaptor Inefficient for too many interactions with ERP/MRP
D/C Co-Simulations	Bouchhimaet al., 2005 Gheorghe et al., 2006	Cons.	Interactions between discrete and continuous simulations Synchronization at event times only. Continuous runs between events and generate state events if threshold crossed. Continuous must detect next discreet event timestamp Discrete must detect state events accurately Time advances from an event to the next by alternating between continuous then discrete	DES dominance Continuous is forced to behave as event-driven Control applications No specific guidelines for continuous time steps
Breathing Time Bucket	Stienman, 1991; 1992	Opt.	Variable TB size Event horizon to determine TB size Local rollbacks only GVT based on event horizons	Not for small scale simulations. Less accuracy than TW but less rollbacks Inefficient if not enough events in TB Designed for discrete events For SPEEDES environment.

3.1 Conservative Time Management

The conservative algorithms take precautions to make sure that no events can be scheduled with timestamps earlier than an event that has been executed. Models interact by sending messages to each other. Each message has a non-decreasing time stamp and they are received in the order that they were sent. Message order indicates the order of executing events. The simulation process picks the event from among all models that have the smallest timestamp. But if the message queue within any model is empty the process comes to a deadlock and cannot proceed. Null messages are used to avoid deadlocks. Null messages have timestamps but they do not create any events or lead to updating the system state. A null message of time t from a model is a promise that it will not send any messages with timestamps smaller than t. Knowing the status of its message queue and the state of the simulation so far, each model can determine the lower bound on the timestamp of the next outgoing message it will send (Fujimoto, 2000).

The main feature of the conservative algorithms is the lookahead concept. If a model can ensure that any message it will send in the future will have a timestamp not less than current time plus L then L is considered its lookahead period which indicates a safe time interval for advance. A disadvantage of the null message approach is the possibility of needing too many null messages if the lookahead period is short, which will make the process inefficient (Fujimoto, 2000). Another problem is that L can equal zero in some cases and the algorithm cannot proceed. The conservative methods are relatively inefficient by nature and they resist having more parallelism in simulation running.

3.2 Optimistic Time Management

Optimistic methods are complicated compared to the conservative methods. They allow models to advance time freely, and do not keep a global clock. This implies more parallelism and hence faster simulation runs. It also implies more potential for violating causality relationships. Yet, when causality relations are violated optimistic algorithms can detect the violations and recover from them. They are less reliant on application specific information that the conservative methods use to determine the safe events and estimate lower bounds on timestamps (Frey et al, 1997; Fujimoto, 2000). However optimistic methods require more computational overhead as the ability to recover from violations of causality relationships depends on saving the status of the system such that the system can be returned to any previous state when needed.

The time wrap (TW) algorithm (Jefferson, 1985) is the most well known optimistic algorithm. It allows free time advancement and if causality relations are violated then the TW rolls the system back in time and un-process any events that should have not been processed before a just-arriving event that has an earlier timestamp. Rolling back is initiated at a model but because of un-processing events at other models, it leads to a chain of rolling back actions at different models.

When rolling back, all messages sent out must be unsent. The anti-message is a copy of the message with the negative of its contents. When both messages are stored in the same queue at a model they are annihilated. When a roll back is needed and an event should be unprocessed, the anti-message to that message that executed the event is sent. Operations performed by users (I/O operations) cannot be canceled by anti-messages. The system consumes huge amounts of memory to store data on these operations. Memory is also needed to store the information that might be used in case roll backs are performed. These problems can be improved by using the Global Virtual Time (GVT), which is a lower bound on the timestamp on any future rollback. Any stored data for times before GVT can be safely discarded. GVT is estimated during the run.

TW, as mentioned has the drawback of sometimes being overly optimistic (Steinman, 1993) with limited guarantees that events will be valid and too many cancellations will not have to be made. It can become unstable due to the uncontrollable very large number of cascaded anti-messages that could be generated. It is also not supported by the existing commercial simulation software (Fujii et al., 1999, Le and Wysk, 2004). Frey et al. (1997) had to use a TW-based simulator (WARPED system; developed at the University of Cincinnati) to synchronize discrete models.

There is no consensus concerning which method is better: conservative or optimistic (Fujimoto, 2000). Yet, the lookahead concept of the conservative approach is getting considerable attention and much research has been devoted to improving its implementation. HLA is driven by the desire to reuse existing simulations and this makes the optimistic algorithms disadvantageous because they require adding mechanisms for state saving and memory management to allow rollbacks (Fujimoto, 2001). With HLA dominating the area of distributed simulation, conservative methods are getting more momentum.

3.3 The Time Bucket Approaches to Time Management

These are conservative synchronization approaches that are simple to implement. The concept of time bucket (TB) is very simple and intuitive. MRP systems use TB. MRP is the most commonly used planning system in manufacturing applications. MRP systems assume that time is divided into equal-length TB (typically weeks) and the system is observed at the end of each bucket. Orders are assigned to the time buckets. An aggregate plan, for instance, could be for the coming three month and then it is detailed such that orders are assigned on a weekly basis to available resources.

The choice of the time bucket in MRP is critical in production planning (Riezebos, 2004). If the bucket length is L then the throughput time can be estimated as nL where n is the number of time buckets the materials remain in the system. If demand in each bucket is D then the amount of materials released is DL . The average levels of inventory and inventory holding cost are determined to an extent by the size of the time bucket, which makes bucket length a design parameter in MRP systems.

Steinman (1990) proposed the time bucket synchronization algorithm, which was based on using the minimum time interval between events as the time bucket (time step) for advancing times in distributed discrete simulation models. Models interact at the end of each TB only which makes the algorithm require little computational overhead. However the bucket size must be large enough to allow models to generate reasonable number of events such that the interactions at the end of the TB are efficient. Still the bucket size must be small enough to maintain simulation fidelity. From an operational point of view a small TB creates difficulties in work load balancing. In discrete simulation events can be concurrent, that is the minimum time between events is zero. This also would make the TB algorithm not suitable for some situations.

Yet, considering the production planning situations where MRP systems are used, the use of the concept of TB can be useful. Since planning as well as reviews and re-planning activities in manufacturing system take place periodically, it becomes acceptable to utilize TB in developing a synchronization mechanism to synchronize distributed simulations of the manufacturing system. Fujii (1994; 1999, 2000) recognized that planning is performed at an aggregate level and then disaggregated at lower levels and for a decision to be made or revised feedback and status information from all lower levels must be provided (which is actually the typical approach in planning manufacturing activities). Based on that and for the development of distributed simulation of manufacturing systems, the aggregate level model and the detailed level models has to be synchronized and since feedback and revisions are typically done periodically then it is acceptable to utilize the MRP’s time bucket to develop a synchronization approach.

A CIM environment was considered in Fujii (1994; 1999; 2000) in which manufacturing cells interact through a transportation unit. The transportation unit organizes the materials flow as well as the exchange of messages among the cells. This represented the planning activities and the shop floor activities. Cells and the transportation unit were modeled by separate discrete simulation models in a distributed simulation arrangement. The focus is on the materials among and within the subsystems.

Time in all cells and the transportation unit is divided into time buckets. The plan is decided at the beginning of the planning horizon and communications among the cells and the transportation unit are performed at the end of each time bucket only. To allow better accuracy (while considering the unexpected events at the shop floor level) the time buckets tested where in hours. One, two, four, or eight hours time buckets were considered where a work shift was eight hours (Fujii, 1994). When a decision is due (being aggregate or local) all cell models have to be stopped until the collection of all data from all models is completed, decision is made, and messages with instructions are received. Decisions are made at the edges of time buckets only. Time buckets correspond to the time buckets in the MRP system. The shorter the time bucket the more accurate the results but the simulation run becomes slower.

To synchronize the models three different scales of times are used in Fujii (1999). These are the real world time (RWT), local virtual time (LVT) for each manufacturing cell and for the transportation unit, and the global virtual time (GVT) for the entire simulation. All models run one TB at a time. The bucket size is taken as one shift in synchronizing simulations. As indicated the decision of the bucket size is a function in the desired level of accuracy and speed of simulation. Yet bucket size is the same in all models. The time buckets in the simulation models add up to make the MRP time bucket.

Allowing interactions among the models at the end of time buckets only can cause inaccuracies when some occurrence take place before the end of a time bucket. Fujii et al. (1999)

rejected setting the bucket size as the minimum time between the events across all the models as computationally inefficient. Further when all models run concurrently there is no way to avoid inaccuracies. If the models are allowed to run in a phased approach in which they alternate then it is possible to improve the accuracy. Since the transportation process in the Fujii's work is different from other models in the distributed simulation, for being a transportation and communication hub, it was possible to make the transportation unit run after the models of the manufacturing cells have completed a bucket. This is described as the *phased time bucket algorithm* (Fujii et al., 1999) and can be represented as in Figure 3-1, where three simulations for two manufacturing cells and the transpiration unit are used. The time bucket is not in fact divided in two parts but the running of the models is carried out in an alternating way.

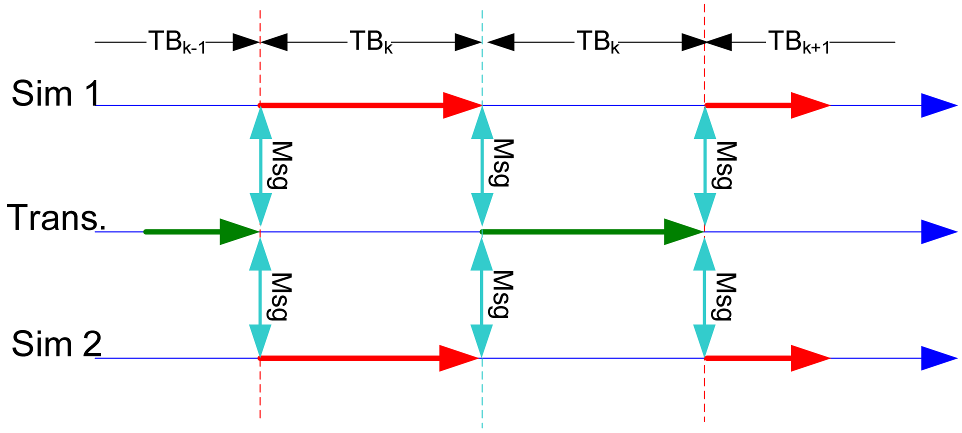


Figure 3.1 Phased time bucket mechanism

The algorithm can be described in the following steps.

1. Process simulators execute their simulations independently until the end of TB_k and then send messages to the transportation unit.
2. After collecting all messages and updating its event list, the transportation unit executes its simulation until the end of TB_k and then responds to each process model appropriately.
3. Process simulators update their status and data for the end of TB_k and then loop to Step 1 for the next bucket TB_{k+1}

In setting the size of the bucket, experiments have to be made to determine the best size with respect to accuracy and computing time. The bucket size however is fixed over the simulation run.

The distributed model of Fujii is focused on the physical material flows and all exchanged messages are requests for materials and confirmation of receiving or the readiness of the requested materials. This is in fact the implementation of the MRP decisions. This makes it easy to assume that the simulation models would run to the end of the time bucket then the transportation process would update each. MRP assumes that there is sufficient capacity to process all orders. Only revisions are made when expected productivity is not met or delays occurs, which is observed at the end of the planning interval. There is no unexpected occurrences that would require the simulation models to issue emergency messages. Only status information and progress data as well as requests and receiving signal of materials are of concern.

Setting a fixed bucket size is a simple approach and is already in use in the MRP systems. It facilitates the revision of the implementation of the MRP decisions using the simulation models since the MRP planning horizon can be divided into the buckets of the simulation models. In addition the simulation models in consideration are all discrete models. In summary, the scope of the simulation model in Fujii et al. (1994, 1999, 2000) allowed using a fixed time bucket approach and having the models run a bucket by bucket and interact only at the end of each bucket.

Another approach to synchronize distributed simulation of manufacturing systems was a control application that suggested the use of programmable logic controllers (PLC) to control simulation models of manufacturing process equipment (Ma et al., 2001). A conservative approach is used to synchronize time by allowing models to advance time in fixed TBs. Models are only permitted to advance if no local causality constraints will be violated. PLC is emulated using the SoftLogix control tool while the equipment are modeled using a continuous tool (IGRIP). PLC offers digital controlling actions thus a mixed time-driven and event-driven synchronization approach is used. The bucket size was chosen short enough for accuracy but not too short to maintain efficiency. No specific algorithm, however, was mentioned for how to set the bucket size.

Messages exchanging between the IGRIP tools and the PLC can occur at any time during the TB. But as Figure 3-2 shows there are different cases:

1. If at any time during say TB$_k$, IGRIP_2 sends a message to IGRIP_1, the sender can do that then continue to the end of the TB. The receiver adds the message to its incoming queue to process it at the end of the TB.
2. If at any time during say TB$_k$, IGRIP_2 sends a message to PLC, the sender should wait for a response and PLC must provide the response immediately.

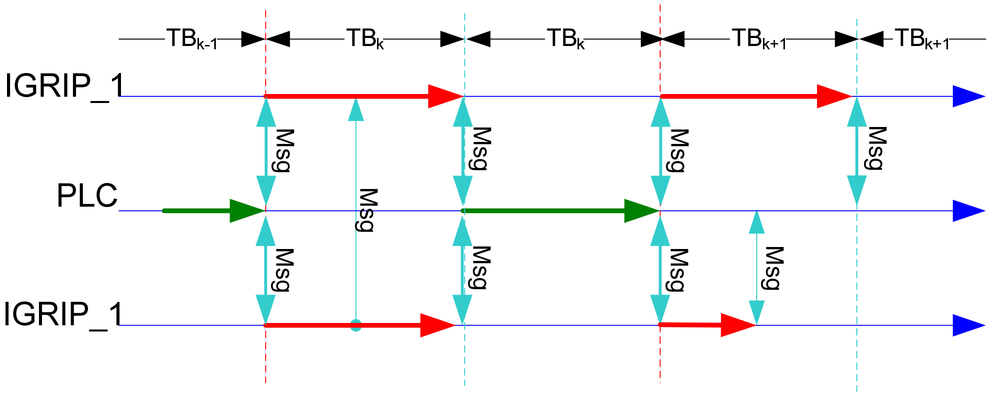


Figure 3.2 Synchronizing PLC and continuous processes

PLC advances its local time for a certain TB after all IGRIP processes have done so. Since PLC can respond immediately then no causality errors are expected, yet causality errors can happen among the IGRIP processes as they only respond at the end of TBs. The IGRIP actions can be time consuming (e.g. robot move, processing) while PLC actions are instantaneous (e.g. on/off events). The unique feature of this approach is that responses to message is possible during time buckets for some tools (PLC) as compared to other approaches that only allow interactions at the end of buckets.

Yet the choice of the bucket size is not explained in either case. The two considerations are the accuracy and efficiency of the simulation. The bucket size should achieve the balance between the accuracy and efficiency.

To synchronize DES models built in Arena, Lee et al. (2002b) developed a coordinator that uses SQL queries to obtain information on the next events in the Arena models and generate a common event list. This approach is specific to Arena models and for discrete simulation only. It uses event times to indicate when queries should be used.

Lee and Wysk (2004) proposed a conservative approach to synchronize discrete simulations where all models execute by advancing time independently for a TB after another. During a TB models run fast and only interact with each other at the end of it. This was meant to increase the parallelism. The simulation models are coordinated via the ERP/MRP system where an adaptor is used to map the simulation models to the objects of the ERP/MRP. Although discrete simulations are used, TBs that correspond (but not necessarily equal) to the time buckets in the ERP/MRP are used to guide the simulation time advance. At the end of each bucket:

1. Each model collects its statistics and sends a message to the adaptor
2. The adaptor (after receiving all messages from all models) check its methods for the appropriate response to each message:
    a. Check MRP/ERP and update models with corrections if any
    b. Obtain and send the assignments for next bucket to the model

Each model has an intermediate database for communication with the adapter. The local time in each model is reset at the beginning of each TB. Thus models only run for a number of connected TB-length runs.

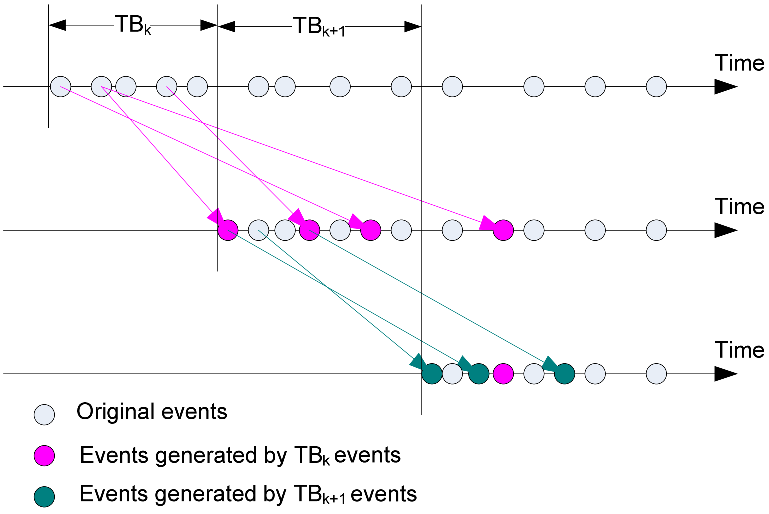
The choice of the time bucket is again controlled by the trade-off between accuracy and efficiency. Yet in this work of Lee and Wysk, a short TB means too frequent checking with the ERP/MRP system via the adaptor which would slow down the simulation more than what regular messages exchange between models would.

Since the simulations interact with the ERP/MRP systems then a starting bucket size can be suggested by the ERP/MRP then based on the system being modeled and the required granularity in simulation, the step can be adjusted to fit all models. Experimenting and observing the occurrence of events in the models should guide the analyst decide the bucket size.

3.4 The Breathing Time Bucket

The breathing time bucket (BTB) mechanism was proposed by Steinman (1991, 1992) for the use in the SPEEDES environment. BTB is an optimistic approach that uses local rollbacks instead of a centralized rollback, based on that the need for the anti-messages is eliminated. Further, BTB does not require the minimum time interval between events as the bucket size, as does the TB mechanism (Steinman, 1990). Instead the event horizon concept is utilized to determine the bucket size for each time bucket.

The event horizon is the time stamp of the earliest new event generated by the execution of an event in the current TB. Determining the bucket size becomes identifying the end of the current bucket. As represented in Figure 3-3, each TB contains a number of events and each of these events may cause the generation of other events in the future. The time of the earliest of these generated events is taken as the start for the next TB and the end of the current bucket as well.



TB_k
TB_{k+1}
Time
Time
Time
Original events
Events generated by TB_k events
Events generated by TB_{k+1} events

Figure 3.3 Defining bucket size by the event horizon

The next TB starts with the first event that was generated by an event that has been executed in the current bucket. This improves the efficiency of the synchronization process since the maximum possible number of independent events is executed in each bucket. Still the mechanism may not be efficient with small simulations. Also there is a need to save states for possible rollbacks. A GVT is determined as the minimum among all event horizons in all models. Thus some events will always be beyond the GVT. If events are far from the GVT they tend to cause the need to rollback.

However, the number of events in a bucket can be too small and the algorithm becomes inefficient. Further, the algorithm is designed for distributed discrete simulation and particularly for the SPEEDES (Synchronous Parallel Environment for Emulation and Discrete Event Simulation) environment and it utilizes the use of the communication hardware in SPEEDES significantly. SPEEDES (http://www.speedes.com) is a simulation engine that allows modelers to perform optimistic parallel processing on high performance computers and networks of workstations.

A version of the BTB algorithm utilizes anti-messages of the TW algorithm. This is the BTW; for Breathing Time Wrap algorithm (Steinman, 1993). BTW also works for discrete simulation and its goal is improving the efficiency of the BTB and reducing the calculations overhead and the memory needs of the TW algorithm. The sending of messages of the TW is performed more often in the BTW; specifically at the end of each time bucket and using the calculated GVT of the BTB approach. This reduces the possibilities of needing anti-messages since the events closer to the GVT according the BTB are less likely to be invalid. BTW is also meant for the SPEEDES environment (Steinman, 1993) and uses the techniques included in SPEEDES for state saving to even reduce the memory usage normally needed by the TW algorithm.

This review showed that discrete event simulation is usually considered in developing synchronization mechanisms for distributed simulations. Synchronizing discrete and continuous simulations is for control situations (as discussed earlier hybrid systems are usually developed for control tasks). The few existing attempts to synchronize discrete and continuous distributed simulations are usually approached by developing special languages and are not generic (Gheorghe et al., 2006; Bouchhima et al., 2005). Using special language ignores the capabilities of existing software and not encouraging for modelers.

Ma et al. (2001) have explicitly considered continuous simulation in their work as mentioned above. This was a PLC control of a distributed structure of continuous simulation processes. Another control situation was investigated in Frey et al. (1997) who synchronized a continuous process with distributed DES simulations using the minimum time step protocol. The DES part controlled the synchronization task as events were used to indicate the synchronization points. The continuous process runs only between events. The continuous time step is chosen small enough (could be as small as nanoseconds). This was meant to have the discrete events to occur at the end of these time step. The continuous process can generate events upon the crossing of threshold values. The continuous process is triggered to run upon the occurrence of an event and it runs until the next event in the DES part of until a threshold is crossed. The TW algorithm is used to synchronize the discrete models and identify the time of the next discrete event. The time interval until the next event is the minimum time step of the synchronization.

This approach is computationally expensive due to the necessity to use very small integration step in the continuous part. The authors did not suggest any directions to optimize the time step although they indicated the need for that. In addition this does not guarantee matching the timestamps of the discrete events with the integration steps so some causality relations may be violated in the communications between the discrete and the continuous parts. The TW algorithm cannot recover these violations of the causality relations as it only synchronizes the discrete models. And because of using the TW (optimistic approach) it is not possible to accurately predict the time of the next event time (as no lookahead is used). Further, the use in the simulation was a control situation where the discrete process is dominant, and it was for small scale applications in area of natural sciences.

In an attempt to develop a generic approach to synchronize discrete and continuous simulations, Bouchhima et al. (2005) also studied discrete and continuous simulation that interact in the traditional approach of detecting threshold crossing in the continuous side that generates a state event in the discrete side. The synchronization transactions are carried out at the event times. For that, models should detect the occurrence of events at each other.

- The continuous part must detect the next discrete event's timestamp
- The discrete part must detect the state events generated by the threshold crossing in the continuous part

This implies that the two types of simulation have to advance time from an event to the next. This is how DES normally works. The continuous part is actually forced to behave as if it was an event-driven simulator. The simulation time advances by jumping from an event to the next and this is done by alternating between the two simulators in a conservative-like approach. Formalism for the components of this distributed simulation approach was developed by Gheorghe et al. (2006). They used the coupled DEVS specification (Ziegler et al., 2000) to describe each component of the system. Although they mentioned the existence of the DESS formalism for continuous simulation systems, they did use it in any part, even for the continuous simulator. The synchronization approach can be described as in Figure 3-4 and by the following steps:

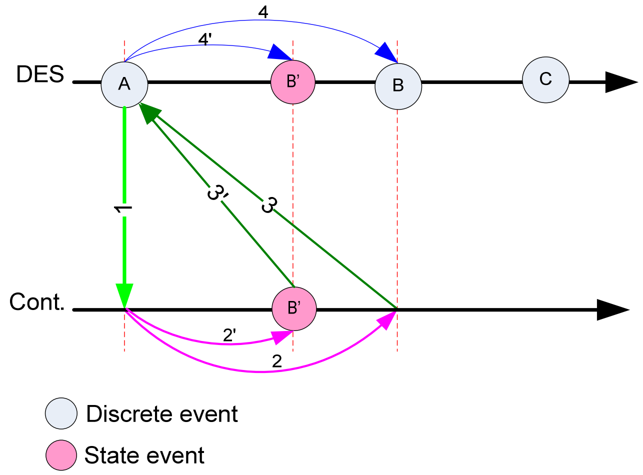


Figure 3.4 Time advance by alternating between discrete and continuous

1. DES executes event (A) and indicates next event (B)'s timestamp
2. Control switches to Continuous (Arrow 1)
3. Continuous advances its local time toward the time of event B:
    a. If no threshold crossing takes place before B then Arrow 2 is followed then control switches to DES (Arrow 3)
    b. If threshold crossing takes place before B then Continuous pauses, generates a state event (B') and signals it to DES, and then control switches to DES (Arrow 3')
4. DES advances its local time:

a. If Arrow 3 was used in Step 3 then DES advances to B (Arrow 4) and the cycle repeats starting from Step 1 with B replacing A and C replacing B.

b. If Arrow 3’ was followed in Step 3 then DES advances to B’ (Arrow 4’) and the cycles repeats starting from Step 1 with B’ replacing A.

DES updates the state of the system upon the occurrence of the discrete and the state events. It also controls the switching between the two processes. As mentioned the simulation was developed for a control situation where an electronic engine was used to run a manipulator arm in a CAD system. The position of the arm is sent to the discrete controller every 0.4 sec and based on it the DES controller adjust the speed. No explanation was given for the 0.4 sec interval, but it can be explained as being small enough to achieve satisfactory accuracy.

3.5 On Current Synchronization Approaches

Current synchronization and time management approaches were developed for discrete simulations or based on defining a threshold to schedule special types of events, if continuous behavior is involved. Either way the events guide the synchronization algorithm.

SDDES aims at avoiding the threshold approach where discrete components are dominant. The business level of the enterprise system is the dominant level in reality. SD is the appropriate approach to model that level and hence the synchronization approach that can be used with SDDES should not allow DES to dominate SD. Besides, there are no recognizable events in SD.

The TB approach seems to be appropriate for continuous/hybrid simulation. The TB approach is:

- Consistent with continuous' time-driven approach
- Not inconsistent with DES' event-driven approach

Thence the existing synchronization algorithms as presented in this chapter are not well-suitable for SDDES. However the TB-based methods have potentials that can be utilized with the SDDES. In Chapter 5 we present an SDDES synchronization mechanism.

CHAPTER 4: RESEARCH METHODOLOGY

The literature review in the previous chapters identified the perceived gap between the requirements of simulating the integrated manufacturing enterprise system and the offerings of existing simulation methodologies and tools. The current research proposes integrating the SD and DES methodologies in a hybrid approach to simulating the manufacturing enterprise and proposes a framework for its development.

This research uses the hypothetico-deductive model of scientific research that works to develop a theory to account for knowledge gained by the observations and experimentation, starting by one or more hypothetical assumptions (Popper, 1959). The hypothetico-deductive research method starts with the recognition of a phenomenon. Relevant observations are then collected and analyzed in order to develop a statement of the research premises, directions and assumptions that are then operationlized and tested. If hypotheses are confirmed a theory can be developed otherwise the hypotheses are revised or the research propositions are rejected. The hypothetico-deductive research method has been designed for social studies but it can provide useable guidelines to conducting the current research. The author’s view of the research as a process is depicted in Figure 4-1.

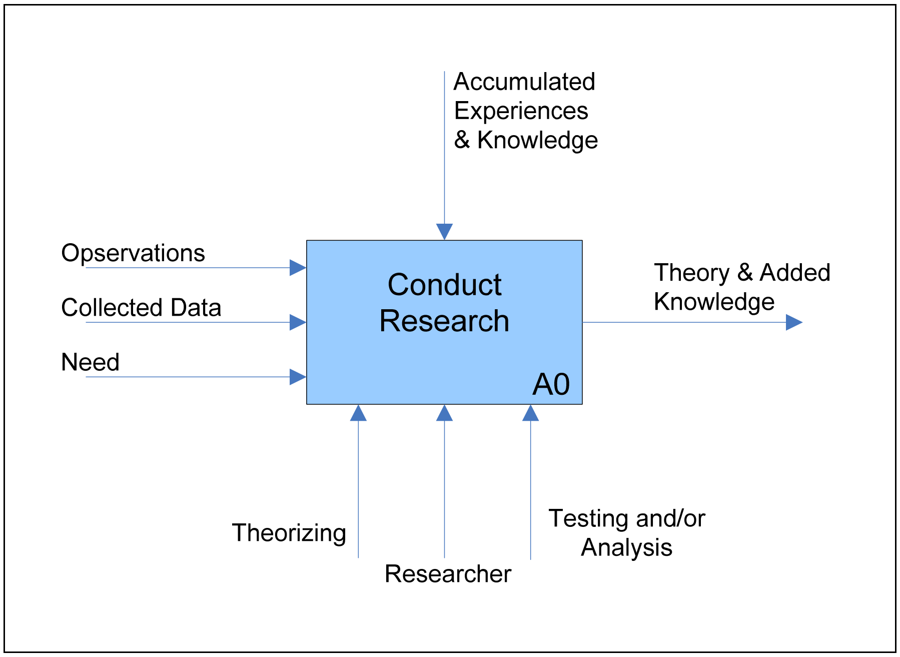


Figure 4.1 Generic view of the research process

The current research is an exploratory type of research. It sets the ground for further future research and developments in relation to the proposed simulation methodology and the simulation of the manufacturing enterprise system. The essence of the hypothetico-deductive is utilized within our view of the research process as described by Figure 4-2.

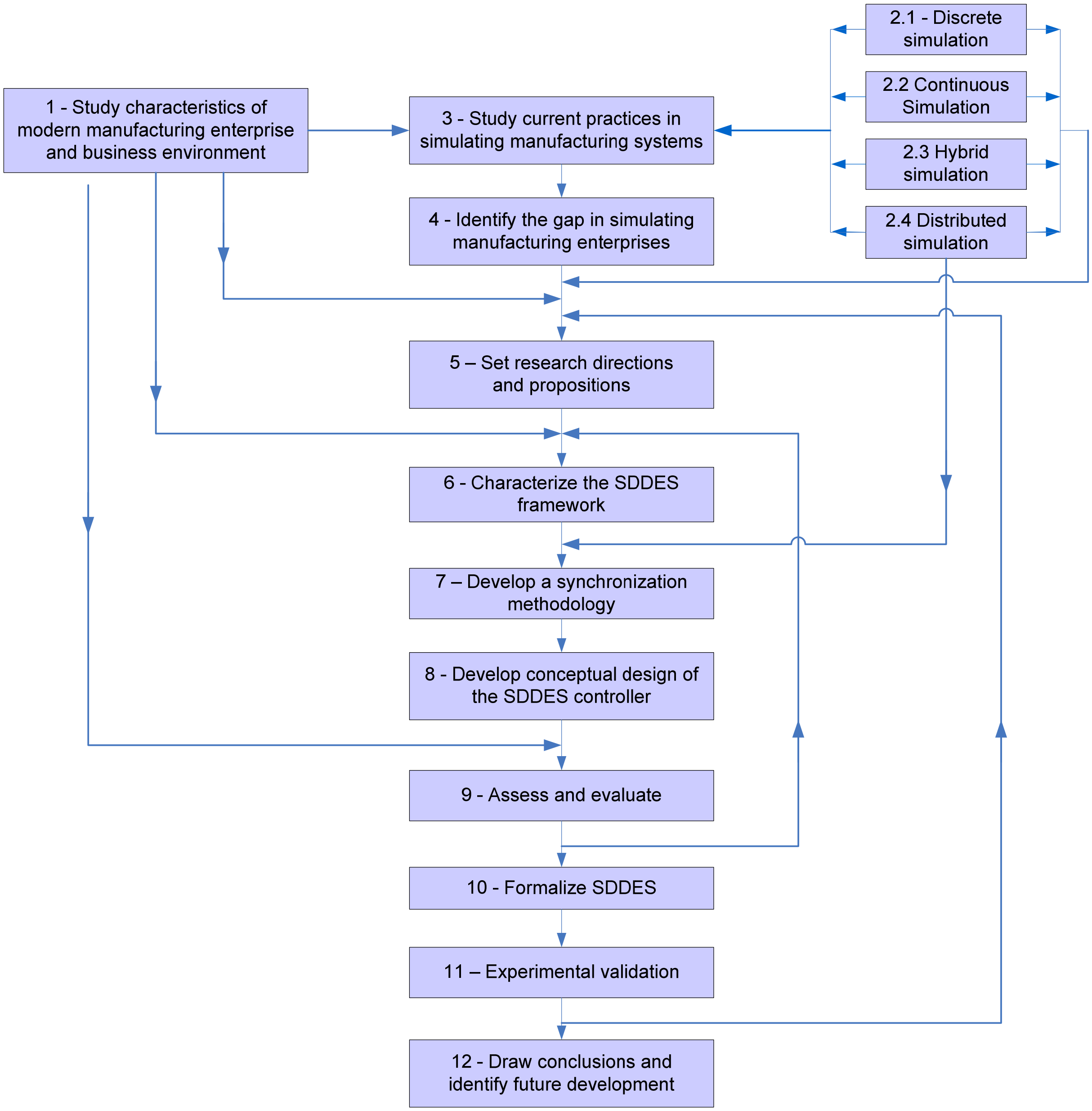

1 - Study characteristics of modern manufacturing enterprise and business environment
2.1 - Discrete simulation
2.2 Continuous Simulation
2.3 Hybrid simulation
2.4 Distributed simulation
3 - Study current practices in simulating manufacturing systems
4 - Identify the gap in simulating manufacturing enterprises
5 – Set research directions and propositions
6 - Characterize the SDDES framework
7 – Develop a synchronization methodology
8 - Develop conceptual design of the SDDES controller
9 - Assess and evaluate
10 - Formalize SDDES
11 – Experimental validation
12 - Draw conclusions and identify future development

Figure 4.2 Research methodology

The first five steps in the methodology have been covered in Chapters two and three. This work started with the observations of the changes in the business environment and the impact of the adoption of the new approaches and perspectives in managing the manufacturing enterprise; in particular the increasing adoption of the system and the integrative perspectives. The literature review explored that need and characterized it. The research premises and directions have been stated as follows:

1. Managers of the integrated manufacturing systems need new simulation tools that can accommodate the differences between management levels in a holistic, enterprise-wide perspective.
2. Simulation models of modern manufacturing systems should incorporate in the same simulation arrangement, the operational and the aggregate management levels in a dynamic feedback-based structure
3. Current discrete and continuous simulation approaches; used separately, fall short in meeting the challenges created by integration in the manufacturing enterprises
4. The simulation of the integrated manufacturing enterprise should be approached using new hybrid continuous-discrete methodologies
5. The existing frameworks to implement hybrid simulation are inadequate for meeting the needs of managing an integrated manufacturing enterprise
6. SD and DES can complement each other for simulating the large scale, dynamic, integrated manufacturing enterprise system

The study of the manufacturing enterprise system focused on the characteristics of the three management levels and how the adoption of an integrative approach impacts the way they should be simulated. The difference between the management levels are manifested in the levels of aggregation or details in the relevant decisions contexts, the planning horizons and scope of decisions, the availability, and need of the data used in decision making and for simulation as well. As the world is going flat, the enterprise system is also being flattened. The strategic level of management has to be more involved than before in the detailed level tasks. The challenges posed by the business environment are directed in the most part toward the strategic and aggregate levels of management. Thus requiring higher level management to get involved in the operational level tasks would be contradicting with its original responsibilities. And it would create more difficulties in simulating the system due to the differences in the nature of the data and situations each level is dealing with. Consequently, there is a need to maintain the autonomy of the management level while having them coordinated in a holistic, synchronized manner.

The ERP systems in fact have been an attempt to achieve this level of comprehensiveness. But having evolved from the original MRP system, ERP came to be a database system that could not satisfy the characteristics of the higher management levels in addition to other shortcoming: potential inflexibility, risk, lack of reliable dynamic planning tools, and being too expensive.

Simulation with no doubt is advantageous over other analytical techniques of modeling and analyzing systems. And it has been effectively applied in manufacturing applications for decades. Yet the changes in the environment and perspectives created challenges to the traditional simulation techniques. Each level of management is found to be more appropriate to one paradigm of simulation than the other; considering the discrete and continuous paradigms. The hybrid continuous-discrete approaches offered several advantages over the use of either the continuous or the discrete separately especially as the system gets more complex and larger. The proposed integration of the SD and DES (will be named SDDES) is both a hybrid and a distributed approach. The distributed aspect came from combining two different paradigms of simulation.

Published cases of simulating the manufacturing systems have been analyzed to confirm our assumptions on the adequacy of the existing simulation methods to simulate the integrated manufacturing enterprise. Based on that, we have identified the gap in simulating the manufacturing enterprise as have been listed above, and justified the research premises and anticipated contributions. The rest of the steps of our research methodology are designed to develop a viable design for the SDDES simulation framework and build a test bed to assess its potentials. Figure 4-3 offers details on the approach to develop the SDDES framework.

The study of the simulation methodologies and the current practices of using them in simulating the manufacturing enterprise have led to identifying a need that can be met by combining SD and DES. This is a hybrid simulation approach for the simulation of the complex manufacturing enterprise system. The scale and complexity can be dealt with by following a modular structure modeling the enterprise with the SDDES simulation model. Modules are better for communication and model management. Yet they have to be described in a formal way to support communicating them among modelers and to the SDDES controller. Modifying and extending the SDDES model with more modules also require a formal description of them. Modules also indicated the need for a communication/synchronization approach among them in the model. The need for synchronization is justified since SDDES combines two different paradigms of simulation; the continuous and the discrete, not only different simulation tools. This added the distributed-simulation dimension to the SDDES methodology. And to implement the synchronization mechanism and manage the simulation model and simulation run the SDDES controller is the core unit in the SDDES methodology.

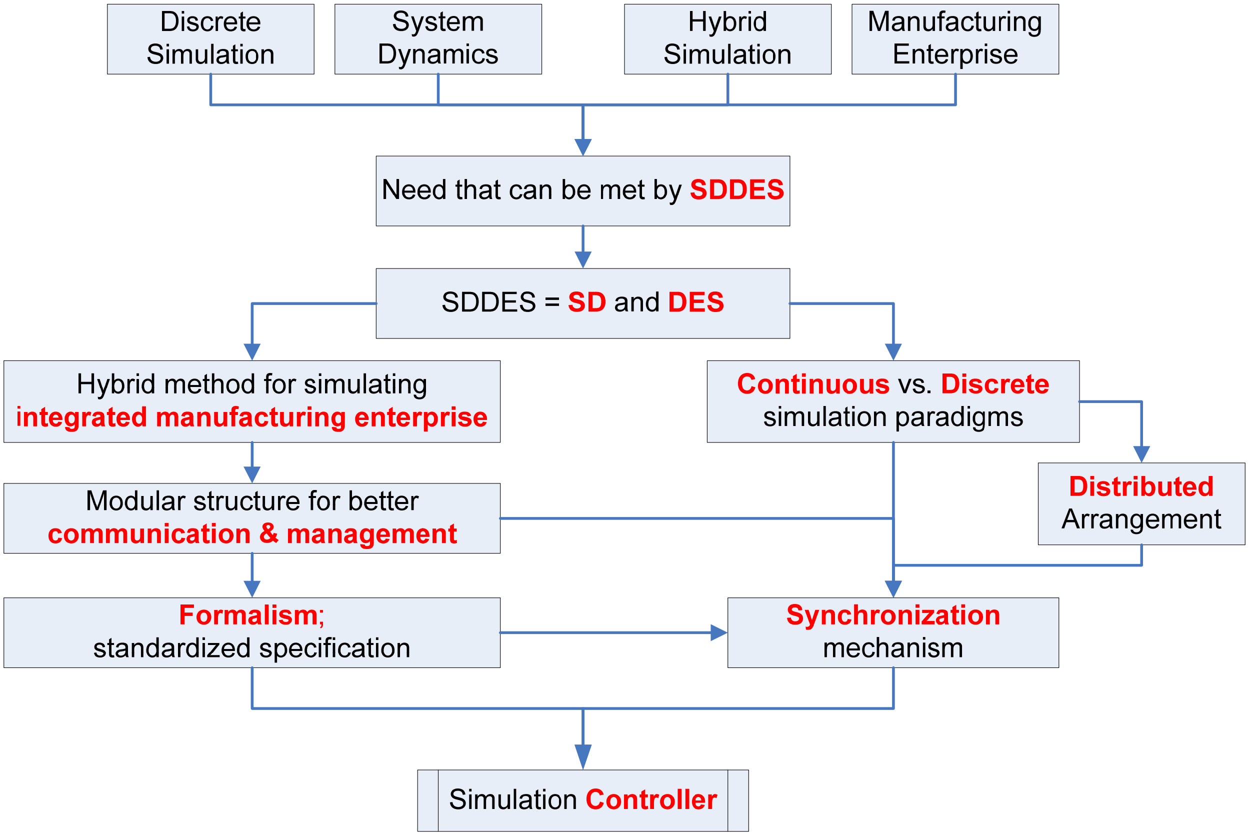

Discrete Simulation
System Dynamics
Hybrid Simulation
Manufacturing Enterprise
Need that can be met by SDDES
SDDES = SD and DES
Hybrid method for simulating integrated manufacturing enterprise
Continuous vs. Discrete simulation paradigms
Distributed Arrangement
Modular structure for better communication & management
Formalism; standardized specification
Synchronization mechanism
Simulation Controller

Figure 4.3 Road map to the development of the SDDES simulation methodology

4.1 SDDES and Its Modular Structure

Conceptually the SDDES simulation model consists of three parts:

1. An overall SD model of the enterprise system.
2. A number of DES models for selected functions in the enterprise that are decided based on the analysis needs.
3. The communication and synchronization coordinator (the SDDES controller) that manages the interactions between the simulation models.

The discrete and continuous simulation models used in SDDES will be defined as modules. Existing (legacy) simulations can be used with SDDES. New SD simulations will benefit from the generic constructs of SD. The stock management model (Sterman, 2000) as described in Chapter 2 will be utilized as a building block for the SD modules of the various enterprise functions. The DES modules will be developed according to the functions expected to be performed by each of them. No generic structure exists for DES models. The traditional model building processes for DES can be used. SDDES requires no special characteristics in the DES modules. In fact, since several DES can be integrated, there is no need to build large scale, complex DES models. A number of simpler models can be built and integrated. The scope of a module is defined based on the function it represents and the objective of the analysis. A process to develop SD and DES will be designed.

In the current work, modules do not correspond to objects. Instead a module is a complete functioning simulation model; defined on a functional basis to perform a complete function that would normally be performed by a business unit in the real system.

4.2 Formalism for the SDDES Modules

The system specification formalism offers a shorthand means of specifying a system. We develop a formalism to describe the SDDES model and its modules. Once specified, the modules can easily be modified and communicated. Managing them by the SDDES controller becomes easier. Users only need to provide the specific information to the generic formalism terms in order to modify an existing module or add a new one to the current SDDES model.

The SDDES formalism offers a generic description of the SDDES modules that reflects the characteristics of the SDDES model integration of SD and DES. The SDDES model in the SDDES formalism is made up of the set of all modules and the synchronization methodology. For every module, its type (SD or DES) should be indicated along with the sets of inputs and outputs the module uses and generates. Also the needed formatting of the data generated by one module is specified. This accounts for the differences between SD and DES. Also the timing of the data interactions should be specified such that the differences between decisions and data generated by different levels of management can be accounted for. Similar to other existing formalisms (DEVS, DESS, and DEV$DESS (Ziegler, 1987; 2000)) the SDDES is based on the set theory and basic finite state automata. Yet unlike the DEVS and the DEV&DESS formalism, there is no need to define or include the system states or the transition functions that map the system inputs to its outputs.

4.3 Developing SDDES Synchronization Mechanism

As SDDES is made up of two simulation paradigms, synchronizing the SD and the DES modules is critical if SDDES is to be effective and efficient. In Chapter 3, we discussed the synchronization mechanisms commonly used in distributed simulation. It has been found that events are vital in operationalizing these synchronization algorithms. It was also found that the time bucket (TB) -based approaches offer more potentials when continuous simulation are involved. We aim at developing a simulation approach that avoids the need to utilize sophisticated synchronization protocols and expensive computing resources. We also aim at avoiding having one simulation paradigm dominating the other. Thus the SDDES synchronization algorithm will allow simulation modules to run freely while exchanging data. The TB concept is consistent with the time advance mechanism in SD and with the event driven approach of DES. The DES modules will be run in run segments, the length of each is a function of the TB duration.

The DES will use replicated run for statistical validity. The SDDES synchronization mechanism allows the SD modules to have single replication runs of the length of the SDDES model simulation horizon. Each DES module will have its own run length. The SDDES simulation run length will be broken down into several run segments for each DES module. This is depicted in Figure 4-4. Each segment is a complete DES simulation run with replications. The length of the run segment is the TB for the DES module. The DES modules will have different TB values such that different functions can be accommodated in an efficient way.

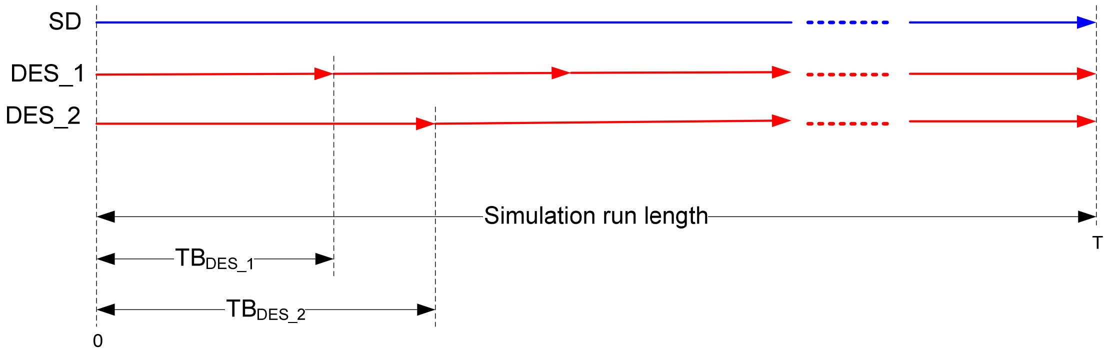


Figure 4.4 Run length structure for the SDDES model modules

4.4 The Functional Design of the SDDES Controller

The SDDES controller is the core part in the SDDES simulation approach. It is the director of the communications among the modules. It performs the time and data management functions during the simulation run. The controller also offers the tools to define the interactions ports between the models and to add new DES models if needed. In the core of it as well is the preparation of the data being exchanged between the model regarding the formatting of the data to be usable in the receiving model as well as performing aggregation and disaggregation of the data going upward or downward in the management hierarchy. The controller also provides the user interface to interact with the simulation model for the I/O operations.

A functional model of the SDDES controller will be developed to describe how it will perform its functions. The Integrated Definition (IDEF) family of modeling techniques offers adequate modeling approach to specify the functions of the SDDES controller. The first of the IDEF techniques (IDEF0) offers a hierarchal representation of a system that depicts the functions done within the system along with relevant inputs needed to perform these functions, outputs generated upon perfuming the functions, the controls that guide and constrain the functions, and the mechanisms needed in performing them. The most mature and usable IDEF techniques are the following: (http://www.idef.com/):

1. IDEF0 for functional modeling to represent functions, activities, or processes in the system
2. IDEF1 for information modeling to represent the structure and semantics of the information within the system
3. IDEF2 for dynamic modeling to represent the time varying behavioral characteristics of the system.

The IDEF0 can be used to model any system that can be viewed as made of "things and happenings" (Feldmann, 1998). A function is to be represented by a rectangular box that can have arrows pointing in or out of it as in Figure 4-5. The box can be decomposed into sub functions that are also represented similarly with the relevant arrows interconnecting the various boxes in the hierarchical structure shown in Figure 4-6. The methodology is described in details in the standard documents at the official site for IDEF; Knowledge Based Systems, Inc. (http://www.idef.com/).

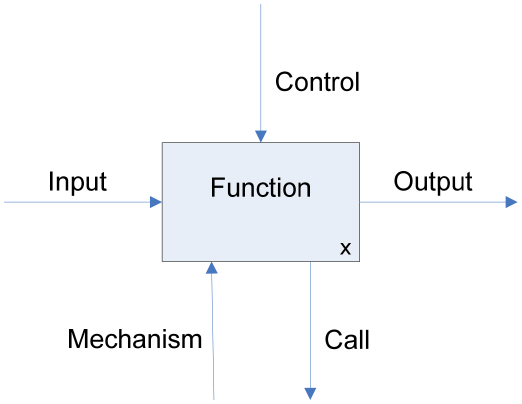


Figure 4.5 Generic representation of a function in IDEF0 models

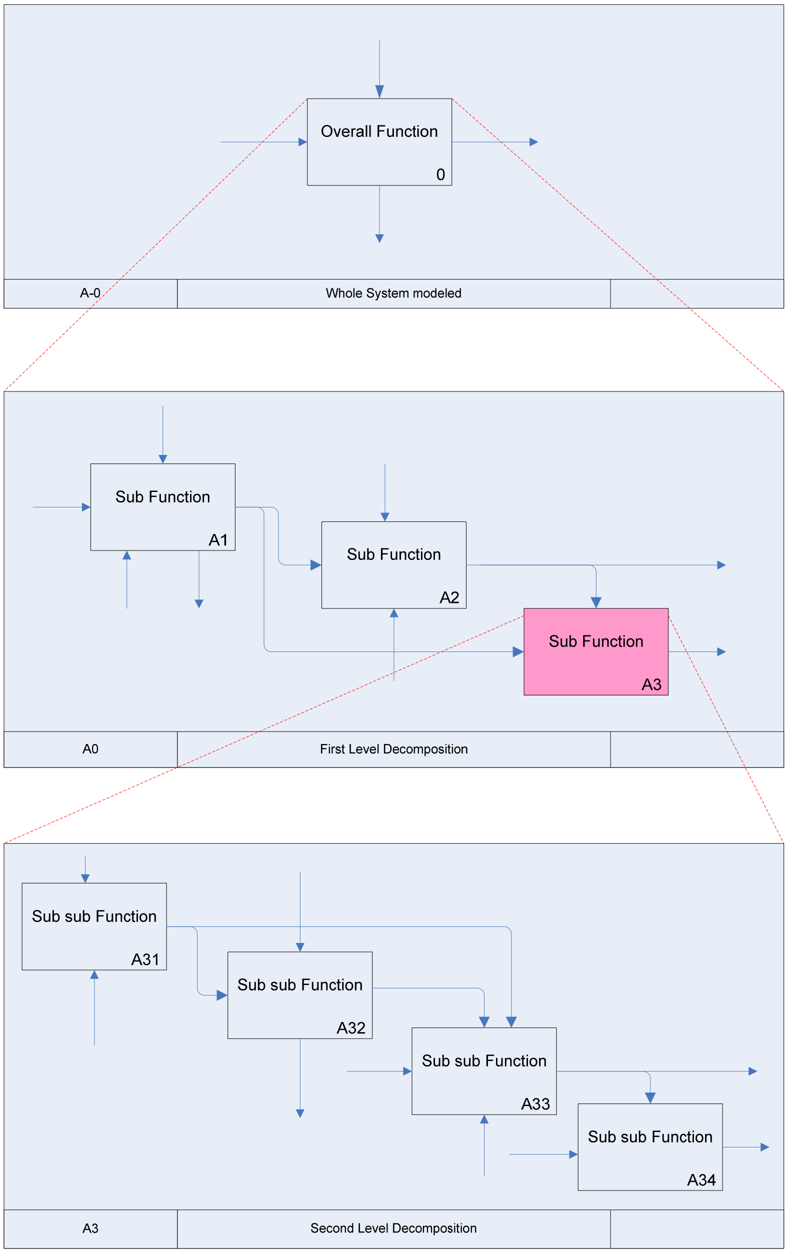


Figure 4.6 Hierarchical structure of IDEF0 models

4.5 An SDDES Prototype and Case Example

The SDDES will be experimented with using a testbed that will be built for the experimental part of this research. The SDDES test bed will demonstrate

1. Developing the SDDES simulation modules and model
2. Implementing the SDDES formalism
3. Implementing and evaluating the SDDES synchronization mechanism
4. The functions of the SDDES controller
5. Assessing the usefulness of SDDES

CHAPTER 5: THE SDDES SIMULATION FRAMEWORK

The SDDES simulation framework consists of four main processes as shown in Figure 5-1: modularization, formalization, DES modules resumption setting, and synchronization. SD and DES modules go through these processes to become modules in the comprehensive SDDES model of the enterprise system. The SDDES simulation model is managed by the SDDES controller. This chapter describes the processes and elements of the SDDES framework, but starts with defining the scope of the manufacturing enterprise as the basis for building the simulation model.

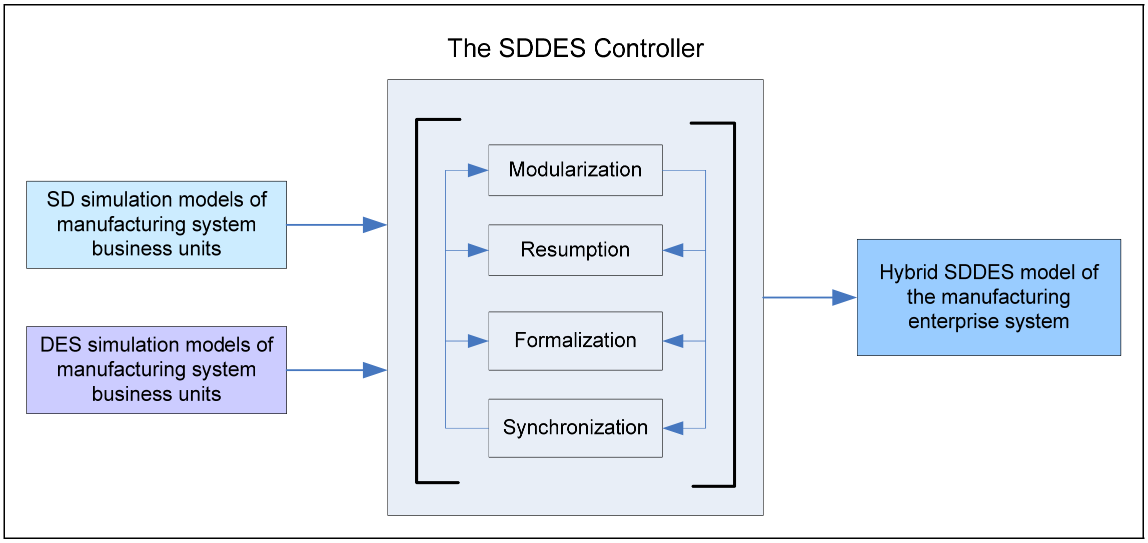

The SDDES Controller
SD simulation models of manufacturing system business units
DES simulation models of manufacturing system business units
Modularization
Resumption
Formalization
Synchronization
Hybrid SDDES model of the manufacturing enterprise system

Figure 5.1 The SDDES framework for simulating the manufacturing system

5.1 Scope of the Manufacturing Enterprise System

The SDDES offers a framework for modeling the manufacturing enterprise in a holistic system perspective (the SD contribution) while utilizing the effectiveness of the DES detailed approach at the operational managerial level. The main purpose of the SDDES model is the design and testing of management policies to confirm the estimated performance and expected behavior based on a comprehensive enterprise-wide feedback. Policies and plans are usually concerned with resource allocation and utilization decisions and actions. This involves all levels of management. Testing of plans comprehensively is critical to ensure realizing their outcomes. For launching a process improvement or a total quality program, enterprise-wide assessment and involvement are important. In addition, the model can be used as a comprehensive performance measurement system. Helal and Rabelo (2004) discussed the potential of using SDDES for building dynamic balanced scorecards. Based on that we recognize the following as the key components of the manufacturing enterprise model:

1. The internal supply chain of the manufacturing enterprise
2. Strategic decision related business units: resources allocation, rewarding systems, demand, financial measures, marketing, forecasts …etc.
3. External market and economy indicators
4. Suppliers as external aggregate indicators: supplier reliability index, supplier capacity, quality, costs, etc.
5. Customers as external aggregate indicators: demand levels, demand variation, satisfaction level, etc.

The internal supply chain represents the flow of materials within the system. As shown in Figure 5-2, it involves the activities related to the physical flow of materials and/or components from the external sources through the system until they are converted into finished products that are supplied to the market to satisfy customers' needs. Supporting functions include capacity management, marketing and sales, customer order and backlog management, forecasting, and inventory management. Inventories are more involved in the actual execution of the production activities than other supporting functions.

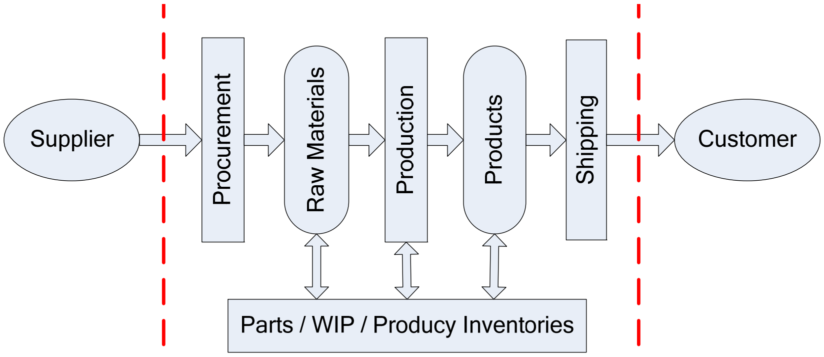


Figure 5.2 Core functions of internal supply chain of the manufacturing enterprise

Figure 5-3 shows the functional structure of the internal supply chain of the manufacturing enterprise and includes main supporting functions. The units included in this figure relate to the main flow networks that make up the enterprise system. The enterprise system consists of the overlapping set of networks of materials (physical goods; raw materials, final products, finished products, etc), orders (internal and external orders for goods, new employees, support, etc.), personnel (people as countable individuals), capital equipment (factory space, tools, production and other capital equipment), money (money in the cash sense), and the information network that interconnects the other networks. Information flows to other networks to impend decisions in these other networks. The rectangles in Figure 5-3 represent the materials, order, personnel, and equipment networks of the system. The other layers above the physical aspects include the resource allocation financial functions, which is more strategic in nature. Other sections include new product development that includes the research and development units. The model also should show the revenues and growth and market share related measures. Market and market share sub model include the advertising, sales, and customer relation management. It also acknowledges the status of the product in the market. It monitors the level of attractiveness of the product and the change in product life cycle to estimate the demand. When the information and money networks are added the scope of the enterprise simulation model can be represented as in Figure 5-3.

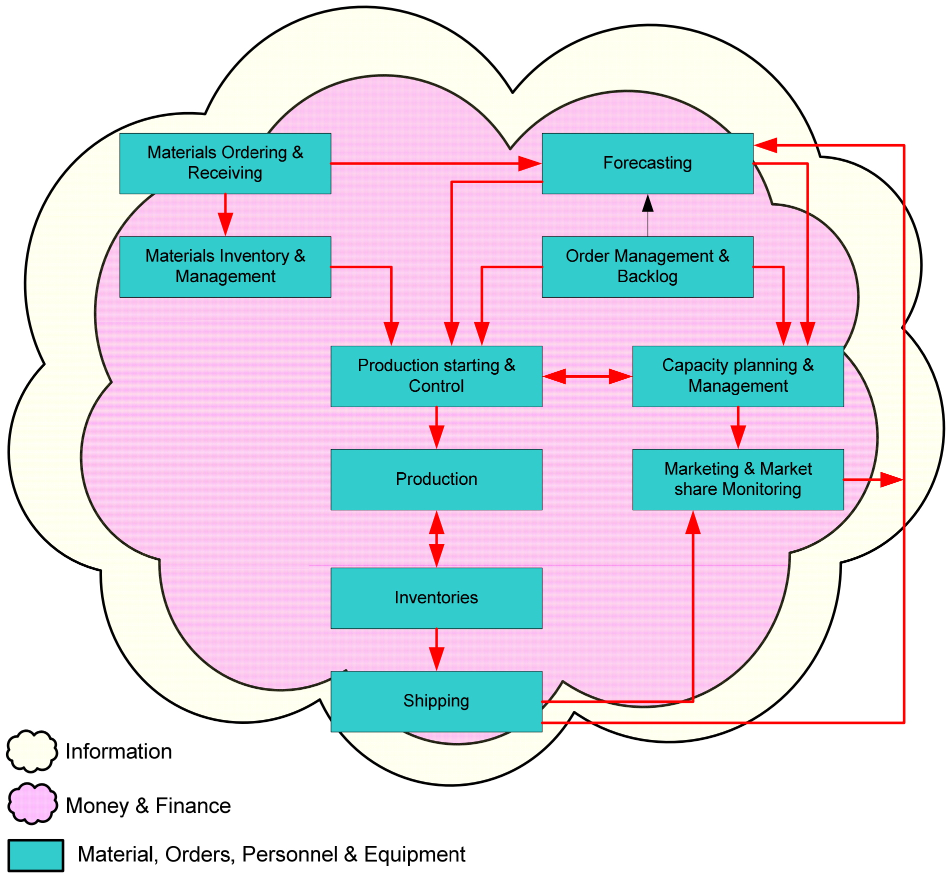

Materials Ordering & Receiving
Forecasting
Materials Inventory & Management
Order Management & Backlog
Production starting & Control
Capacity planning & Management
Production
Marketing & Market share Monitoring
Inventories
Shipping
Information
Money & Finance
Material, Orders, Personnel & Equipment

Figure 5.3 Abstract structure of a manufacturing enterprise

5.2 Outline of the SDDES Enterprise Simulation Model

Based on the scope of the manufacturing enterprise system presented in the previous section, the outline of SDDES simulation model is designed as shown in Figure 5-4. The boundaries of the simulation model are the internal box that contains the SD enterprise model, the DES models, and the SDDES communication controller. The SD model is a comprehensive model of the enterprise system. The DES models are developed for functions and parts of the system where detailed analysis is required; mostly at the operational level. The SD and DES models are interfaced in SDDES. They are treated as modules; each contributing to the comprehensive model of the manufacturing enterprise system. The SDDES may be made to interact with the enterprise's database (e.g. ERP). The communication controller is the core component of the SDDES approach. It coordinates, synchronizes, and controls the interactions among the models. The functions of the SDDES controller are described later in this chapter.

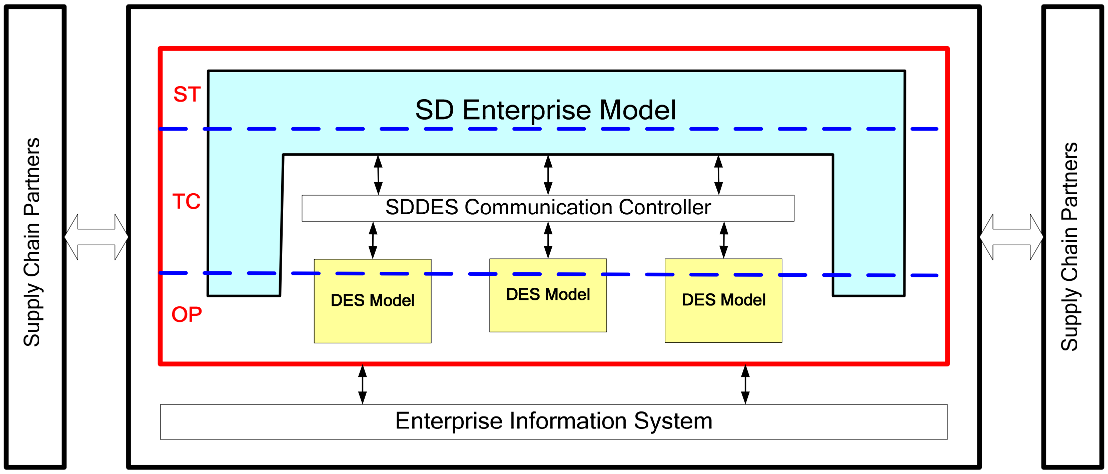


Figure 5.4 Outline of the hybrid SDDES enterprise simulation model

5.3 The Modular Structure of The SDDES Model

It is desirable to work with less complex simulation models. Objectives of modeling, however, dictate the level of details in a model. Less detailed models are easier to build and less expensive. Still, more detailed and refined models are needed to capture the complex dynamics in the real system units requiring that level of resolution for valid representation of their functions. SDDES promotes a modular, hierarchical structure of simulation models that consists of modules of different complexity levels, to minimize the complexity of the simulation model as a whole and validly capture its structure and dynamics. The modular structure can simplify the model building processes since relatively smaller modules of narrow scope need to be built. Several such modules interfaced together result in a comprehensive model. A modular simulation model is extensible and easy for communication and teamwork development.

The module is a simulation model of a certain system unit. It has a specific function and thus identifiable sets of inputs and outputs. Modules of the SD and DES components of the SDDES model are described in the next sections.

5.3.1 The SD modules

Each SD module is a unit in the comprehensive SD part of SDDES. An advantage of the SD methodology is having generic constructs that are usable for different system and applications. One such constructs is the SMM (Sterman, 2000) that offers a flexible template for molding various business and non business system units. The stock management model can guide the process of breaking down an existing model as well as the building of new SD modules. SMM was discussed in Chapter 2.

The process for developing SD modules for SDDES is shown in Figure 5-5. An existing SD model of the enterprise can be broken down into modules that have recognizable boundaries to represent the functional units or the scopes of decision making for the various decisions makers. Inputs and outputs of each module should be identified to assess the goodness of the module definition. The process is iterative. Narrow scopes of the modules are preferred to simplify model maintenance and use. Each module is to perform a certain function or to correspond to the organizational structure of an enterprise unit.

The module inputs are variables that are not normally under the control of the process owner of the process represented by the module. Inputs can be from any other module in the simulation SDDES model. Outputs are offered to the other modules. Once defined, modules are formalized according to the SDDES formalism, which is presented later in this chapter.

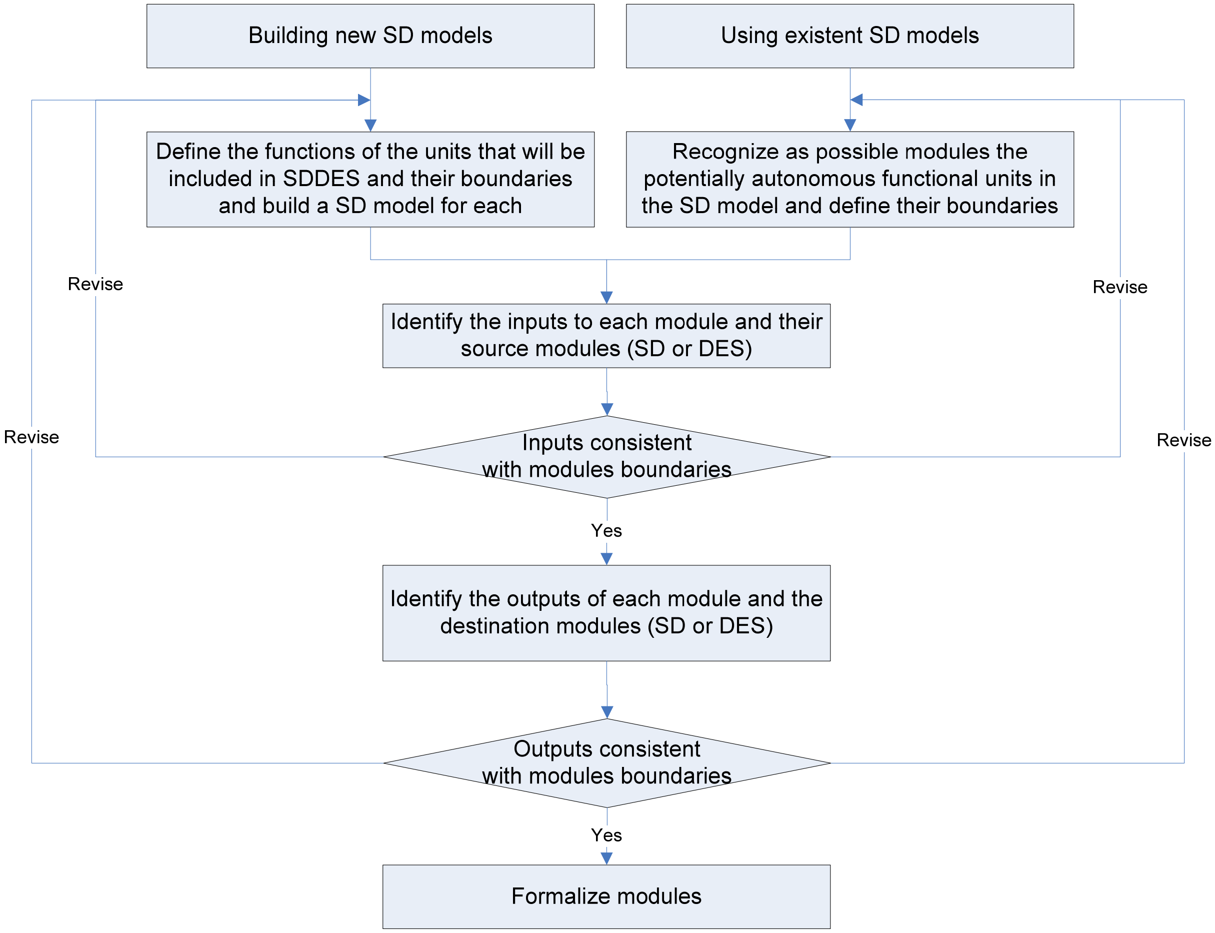

Building new SD models
Using existent SD models
Define the functions of the units that will be included in SDDES and their boundaries and build a SD model for each
Recognize as possible modules the potentially autonomous functional units in the SD model and define their boundaries
Revise
Revise
Identify the inputs to each module and their source modules (SD or DES)
Revise
Inputs consistent with modules boundaries
Revise
Yes
Identify the outputs of each module and the destination modules (SD or DES)
Outputs consistent with modules boundaries
Yes
Formalize modules

Figure 5.5 Defining SD modules for SDDES

Inputs to modules are received through the module input ports and the outputs are offered through its output ports. A representation of a SD module is shown in Figure 5-6. The module is shown to contain a symbolic SD module. The In_Port_x and Out_Port_x represent the input and output ports of communication respectively, where x is the number of the port.

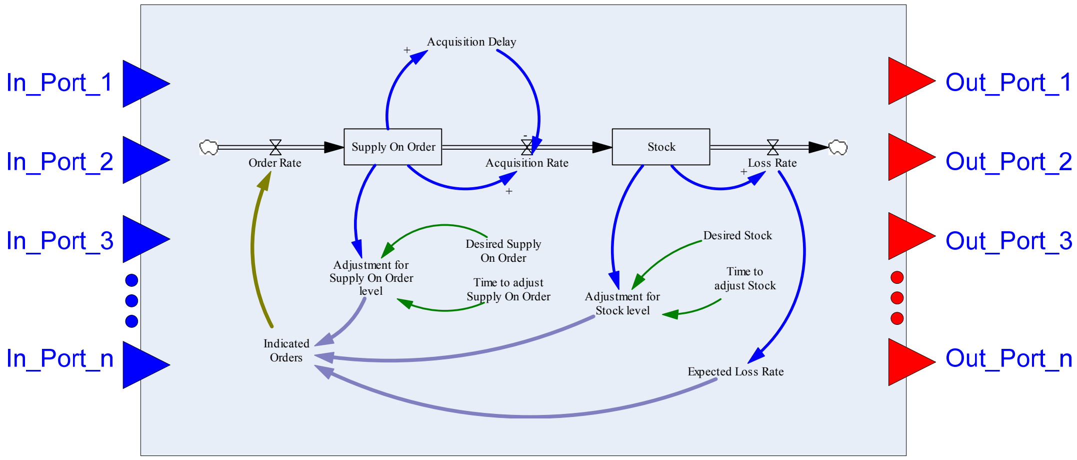


Figure 5.6 Symbolic representation of an SD module

5.3.2 The DES modules

Depending on the needs of the decision makers, DES modules are developed to be interfaced with the SD modules. DES modules can interact with each other as well. The DES modules are complete discrete simulation models that can be of narrow scopes. A process to develop the DES modules for SDDES model is shown in Figure 5-7. Module inputs and outputs should be identified along with the other modules it will interact with. Modules are then formalized according to the SDDES formalism.

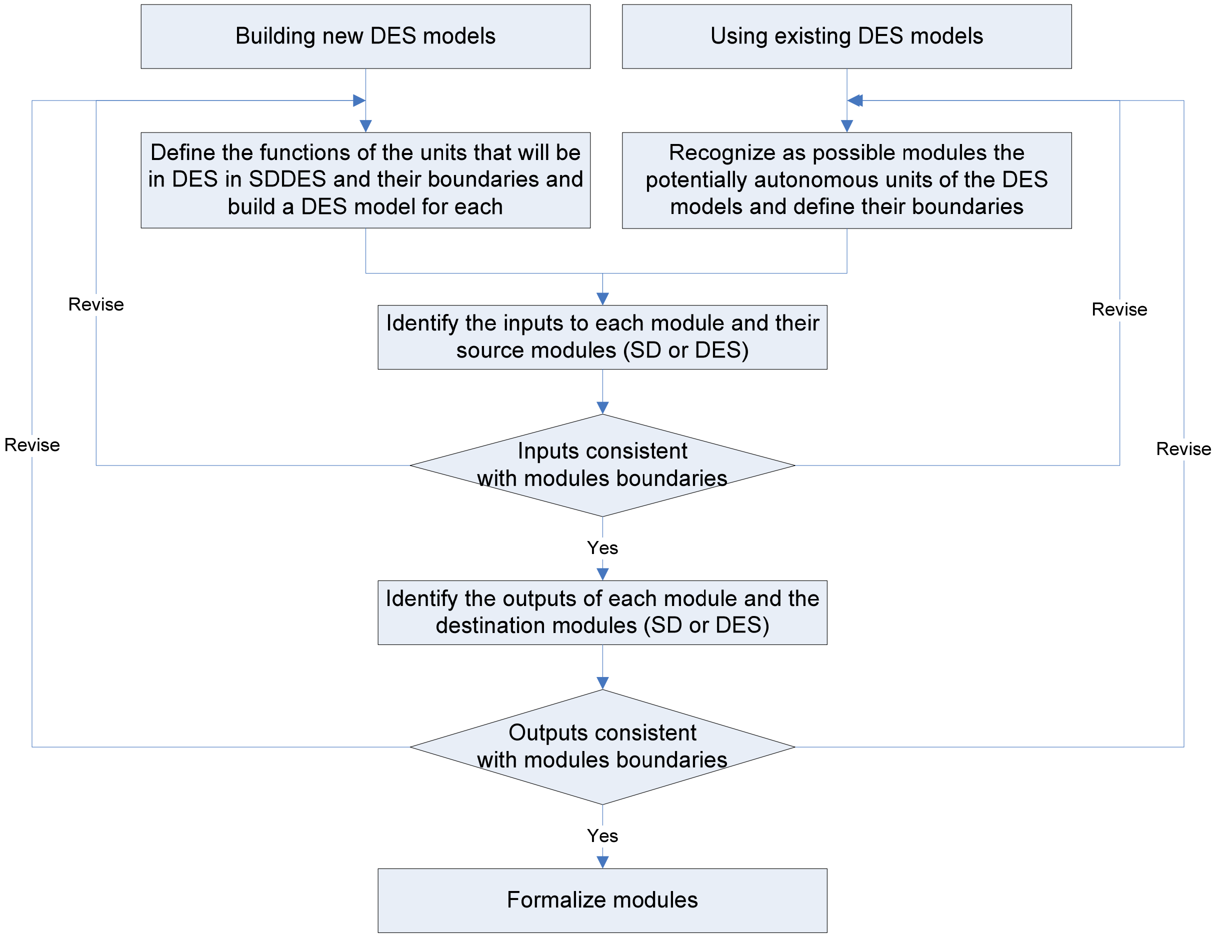

Building new DES models
Using existing DES models
Define the functions of the units that will be in DES in SDDES and their boundaries and build a DES model for each
Recognize as possible modules the potentially autonomous units of the DES models and define their boundaries
Revise
Revise
Identify the inputs to each module and their source modules (SD or DES)
Revise
Inputs consistent with modules boundaries
Revise
Yes
Identify the outputs of each module and the destination modules (SD or DES)
Outputs consistent with modules boundaries
Yes
Formalize modules

Figure 5.7 Defining DES modules for SDDES

Figure 5-8 shows a symbolic DES module. Elements inside the module boundaries are represent the DES simulation objects. The In_Port_x and Out_Port_x represents the input and output ports of communication, where x is the port number.

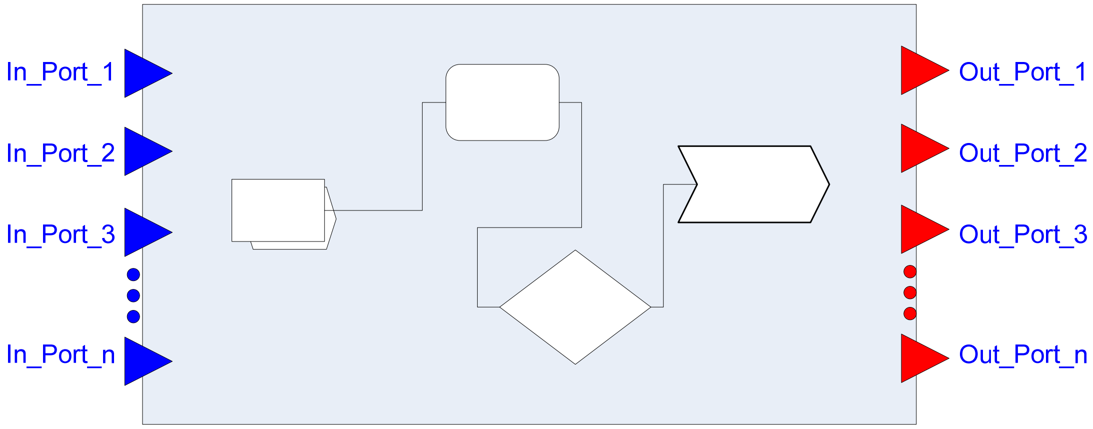


Figure 5.8 Symbolic representation of a DES module

5.3.3 Which simulation paradigm should be used to which business unit

The literature review and discussion made in Chapter 2 of SD's and DES' views of the world, potential, and applications in the manufacturing domain support the following criteria to guide the decision on which business units should be modeled by which simulation technique. This four-aspect decision criteria (See Figure 5-9) essentially recognizes the perspective within which the objective of simulating a system is defined and then analyzes three main system characteristics to assess which simulation paradigm can best meet the simulation objective. The various business units should be assessed with respect to each of the four aspects.

- **Perspective**: This implies the objective of simulating the business unit. An analytic perspective with an emphasis on the detail complexity of the system is more consistent with using DES. A holistic perspective with an emphasis on the dynamics complexity of the system is more consistent with using SD.

- **Resolution**: This refers to the contents and structure elements of the system given the perspective defined above. The system that promotes the individuality of its contents and structure elements is more consistent with using DES. The system that shows emergent behavior and emphasizes homogenizing its contents is more consistent with using SD.
- **Nature**: This describes the nature of the system behavior in reaction to exogenous or indigenous influencers. The system that behaves stochastically where randomness is emphasized is more consistent with using DES. The system that behaves deterministically is more consistent with using SD.
- **State Change**: The system whose state changes discretely due to countable timeless occurrences at specific points in time is more consistent with using DES. The system whose state changes continually, essentially due to time progress is more consistent with using SD.

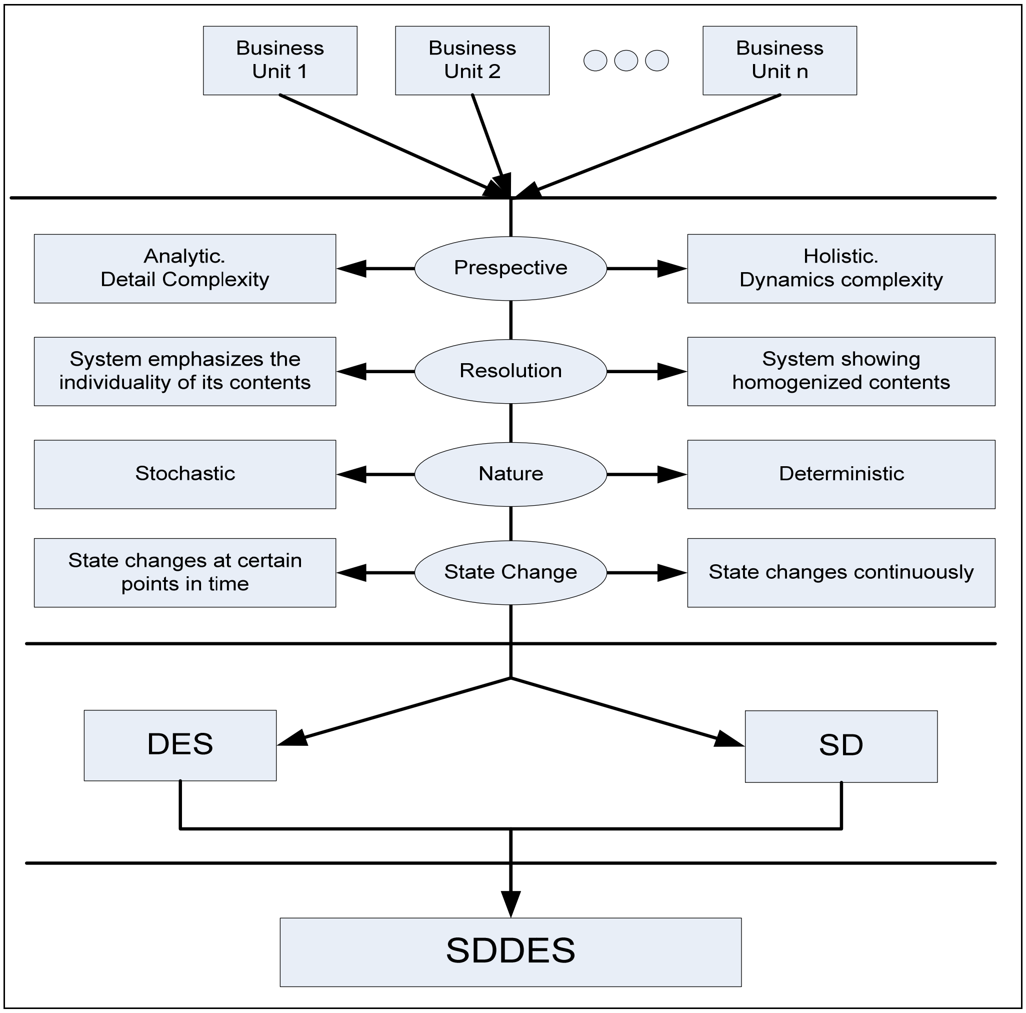

Business Unit 1
Business Unit 2
Business Unit n
Analytic. Detail Complexity
Prespective
Holistic. Dynamics complexity
System emphasizes the individuality of its contents
Resolution
System showing homogenized contents
Stochastic
Nature
Deterministic
State changes at certain points in time
State Change
State changes continuously
DES
SD
SDDES

Figure 5.9 Which simulation paradigm to use to model manufacturing system units

The decision to use DES or SD to model a business unit system is still subject to the feasibility constraints in terms of the data, financial, and time resources availability. Once built and validated, all DES and SD models can be interfaced according to the SDDES framework in order to develop a comprehensive simulation model. Besides flexibility, SDDES can overcome some feasibility limitations.

5.4 The SDDES Formalism

Formalisms are conventions of communications to provide abstraction of systems elements. The set theory provides the basis of abstraction (Fishwick, 1995). The SDDES formalism is a generic description of the SDDES modules. The formalism, based on set theory, is an abstract description of the modules. It offers a format to prepare for the interactions among modules and a language for modelers and users to interact with the SDDES model through the SDDES controller and among themselves as well. The structure of the SDDES formalism contains generic representation of each module type, inputs, outputs, and the formatting and timing functions.

Three sets and two descriptive elements are needed to describe a SD or a DES module in SDDES. A SDDES module; m, is described as in equation (17).

$$m = (\mathrm{T}, X, Y, P, TB) \tag{17}$$

where:

- T : type of the module; $\mathrm{T} = \{SD, DES\}$
- X : set of module inputs. For module m, X is defined by equation (18).

$$\begin{aligned} X_m = \{(m, vi, m_s, op_{ms}, U_m) \mid m \in M, vi \in aP, \\ m_s \in M - \{m\}, op_{ms} \in OutPorts_{ms}, U_m \subset P_m\} \end{aligned} \tag{18}$$

where:

  - m: current module

- v_i: the input variable
- m_s : the source module, from which $v_i$is obtained
- op_{ms} : the output port in $m_s$through which v_i is given
- U_m describes the users of input variable v_i in the m. An element in U_m specifies an input port in m, the variables in m that will use v_i, timing of needing v_i, and the formatting required in v_i. U_m can be described as in equation (19)

$$U_m = \{(ip, u, t, f) \mid ip \in InPorts_m, u \in P_m\} \tag{19}$$

where:

- ip : the input port in $m$through which V is obtained to be used u
- u : a variable in m that needs to use V
- t : timing of reading v into m to be used by u .
- f : data preparation action needed for v before it is usable by u .
- $InPorts_m$: set of all input ports of m

- M : set of all modules in SDDES model.
- aP: set of all variables in M less the current module; $aP = \bigcup_{i=1, i \neq m}^{M} P_m$
- P_m : set of all variables in m

- TB : time bucket of the module. It indicates the run segment length of a DES module and in case of a SD module it is set to $CONT$, for continuous, to represent the entire planning horizon. As shown later in this chapter, DES modules are run for different run lengths whereas SD modules are run for the entire planning horizon.
- P : set of all variables in the module.
- Y : set of module outputs; defined by equation (20) for module m:

$$Y_m = \{(m, op, vo, D_{Ym}) \mid m \in M, op \in OutPorts_m, vo \in P_m, D_{Ym} \subset M - \{m\}\} \quad (20)$$

where:

- o op : the an output port in m
- o vo : output variable given through op
- o $OutPorts_m$: set of all output ports in m
- o D_{Ym}: set of destination modules receiving vo . An element in D_{Ym} consists of the destination module identifier and the set of variables in the destination module that will use vo , as described by equation (21).

$$D_{Ym} = \{(m_d, V_{md}) \mid m_d \in M - \{m\}, V_{md} \subset P_{md}\} \quad (21)$$

where:

- m_d : destination module receiving vo
- V_{md}: set of variables in m_d that will use vo . More than one variable in m_d module can use vo ; each may have different timing and formatting requirements. An element in V_{md} consists of the variable that will use vo , the input port in m_d that it will receive vo through, and the timing and formatting settings, as represented by equation (22).

$$V_{md} = \{(ip_{md}, u_v, t, f) \mid u_v \in P_{md}, ip_{md} \in InPorts_{md}\} \tag{22}$$

where:

- ip_{md} : input port in m_d through which vo in obtained
- u_v : variable in m_d that will use vo
- P_{md}: set of all variables of m_d
- $InPorts_{md}$: set of all input ports of m_d
- t : timing of needing vo by u_v
- f: data preparation action needed for vo before it is usable by u_v

The timing and formatting settings for exchanging data between modules should be specified by the modeler for each input or output variable. Timing of data exchange is generally based on the TB settings for the DES modules. Let the SDDES simulation run length be *L*. The

SD module run is equal to L in length. The DES modules on the other hand are run for segments each of length TB , where TB can be different for the different DES modules. Data exchanges between modules are carried out between segments. Exchanging data can be at the beginning or the end of a segment. Frequency of data exchange transactions is a modeling decision based on the nature of the system being modeled. Data transactions at simulation run startup are used to initialize the modules. Data transactions at the end or beginning of a segment are used to exchange input and output data according to the designed feedback relationships. Timing settings for exchanging the variables include the following:

$STARTUP$	Data transaction at simulation run startup
TB_START	Data transaction at the beginning of a DES segment
TB_END	Data transaction at the end of a DES segment

Data preparation and formatting in the SDDES formalism implies transforming the data from DES or from SD to a format usable in the other paradigm as is explained in Section 5.6. The whole SDDES model is described to consist of the sets of model inputs, model outputs, modules included in the model, and the active synchronization mechanism as can be represented by equation (23). The sets of inputs and outputs in equation (23) refer to the user inputs to the SDDES model and the outputs the user receives from the model.

$$SDDES = (I, O, M, \sigma) \tag{23}$$

where:

- I : set of inputs to the SDDES model
- C: set of outputs of the SDDES model
- M : set of all modules in the SDDES model
- σ: the synchronization mechanism

The modular organization of the SDDES simulation model can be depicted as shown in Figure 5-10. Virtually any number of SD and DES modules can be interconnected. The SDDES controller provides the user interface and manages and synchronizes the interactions of the modules.

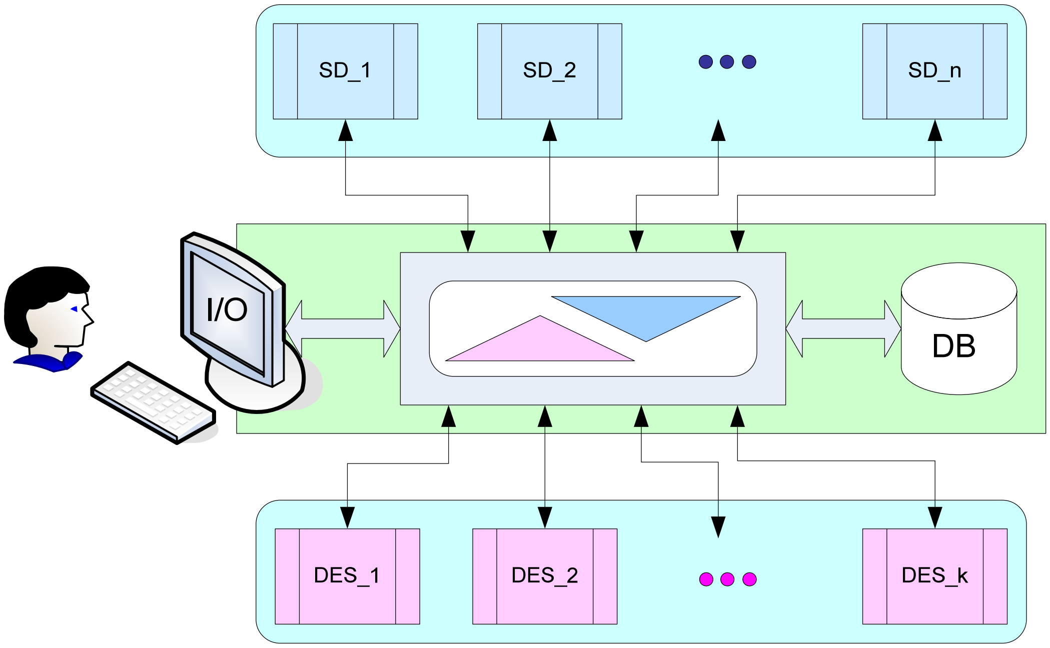


Figure 5.10 Layout of the SDDES system in modular form

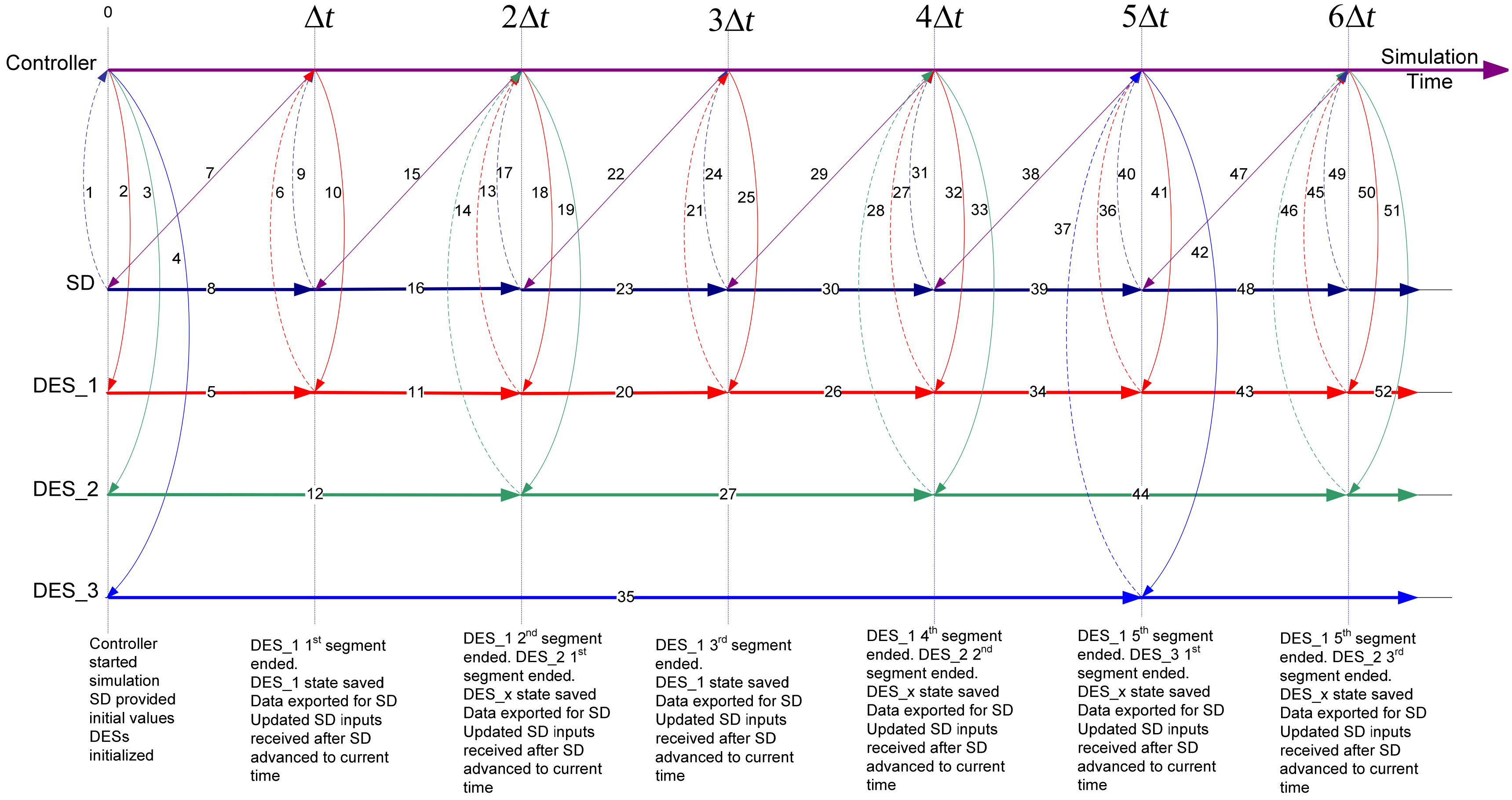
5.5 The SDDES Synchronization Mechanism

In Chapter 3 the review of the existing synchronization mechanisms for hybrid and distributed simulations showed that the conservative simulation approaches depend on using a lookahead interval to determine the safe time advancement step. The optimistic approaches use messages of the timestamps of the events to control the advancement of time and perform rollbacks when needed. They need events to act and they assume discrete simulations being synchronized, or a system that is dominated by discrete behavior. Continuous simulation does not generate events and does not have states that can be defined practically. Synchronization of the continuous simulations with each other or with discrete models can be approached using TB-based synchronization methodologies.

In this work we use the concept of the TB in synchronizing the SDDES modules. The TB is more relevant to running the DES modules and will be used to define the length of the run segment for each DES module. The SDDES synchronization mechanism requires DES modules to run not for the entire planning horizon for which the SDDES simulation will be used, but for run segments. A run segment is a complete discrete simulation run with the needed number of replications. At the end of the segment the DES modules export outputs to the SD and other DES modules and receive inputs from them. The choice of the TB size is a modeling decision that is made considering the desirable levels of accuracy and efficiency as well as the function modeled in the particular DES module. The SDDES simulation run length L is divided into integer number of segments for each DES module. The minimum size of TB is the SD computational time step (Δt). For a DES module, $m$the length of its run segment is $TB_m = \frac{L}{n\Delta t}$, where n is a nonnegative integer.

Figure 5-11 depicts the synchronization sequence of the SD and DES modules. It shows the sequence of the SDDES controller actions (numbered as shown on the arrows) in advancing each simulation module and performing the data exchange. All interactions are executed through the SDDES controller, which collects the data from all modules and distributes them to the requesting modules at the time data is needed after performing the needed formatting.

Figure 5-11 assumes three DES modules each with a different TB size. The base TB is equal to the SD computational time step. The first DES module (TB$_1$ = Δt) requires exchanging data at each SD computational time step. The second DES module (TB$_2$ = 2Δt) is slower than the first and requires exchanging data every 2Δt time units. The third DES module (TB$_2$ = 5Δt) is even slower and requires data exchanges every 5Δt time units.


0
Δt
2Δt
3Δt
4Δt
5Δt
6Δt
Controller
Simulation Time
SD
DES_1
DES_2
DES_3
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
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32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
Controller started simulation SD provided initial values DESs initialized
DES_1 1st segment ended. DES_1 state saved Data exported for SD Updated SD inputs received after SD advanced to current time
DES_1 2nd segment ended. DES_2 1st segment ended. DES_x state saved Data exported for SD Updated SD inputs received after SD advanced to current time
DES_1 3rd segment ended. DES_1 state saved Data exported for SD Updated SD inputs received after SD advanced to current time
DES_1 4th segment ended. DES_2 2nd segment ended. DES_x state saved Data exported for SD Updated SD inputs received after SD advanced to current time
DES_1 5th segment ended. DES_3 1st segment ended. DES_x state saved Data exported for SD Updated SD inputs received after SD advanced to current time
DES_1 5th segment ended. DES_2 3rd segment ended. DES_x state saved Data exported for SD Updated SD inputs received after SD advanced to current time

Figure 5.11 SDDES controller' synchronization action sequence

5.5.1 Characteristics of the SDDES synchronization

The following characterizes the SDDES synchronization mechanism:

1. SDDES is a time driven simulation where simulation time is tracked at the SD module.
2. The SDDES simulation run length is defined at the SD module as the planning horizon for the enterprise.
3. The SD computational time step (Δt) is the time advance step of the SDDES model.
4. There are no restrictions on setting the SD time step.
5. Each DES module's run is broken into several run segments. Each segment is a complete discrete simulation run with sufficient number of replications. Each segment is initialized with the status of the DES module at the end of the previous segment in addition to any adjustment received from the other modules.
6. Different DES modules can have different run segment lengths. Run segment length is equal to $n\Delta t$ where $n \in I^{+}$
7. The shortest DES run segment lengths is Δt

5.5.2 The SDDES time bucket size

The computational sequence in the SD methodology was described in Chapter 2 as shown in Figure 5-12. All values of system variables are known at the previous time moment; t_1 and given these values the current values at the current time; t_2 are calculated. The stock level at value t_2 is the present value of the stock that has resulted from the accumulated difference between its inflows and outflows. A flow rate value is the present instantaneous value of the flow between some stocks in the system. Thus the value of any SD variable is its present value estimated at the current point in time. The calculations sequence reduces the dependence of the state on the old states.

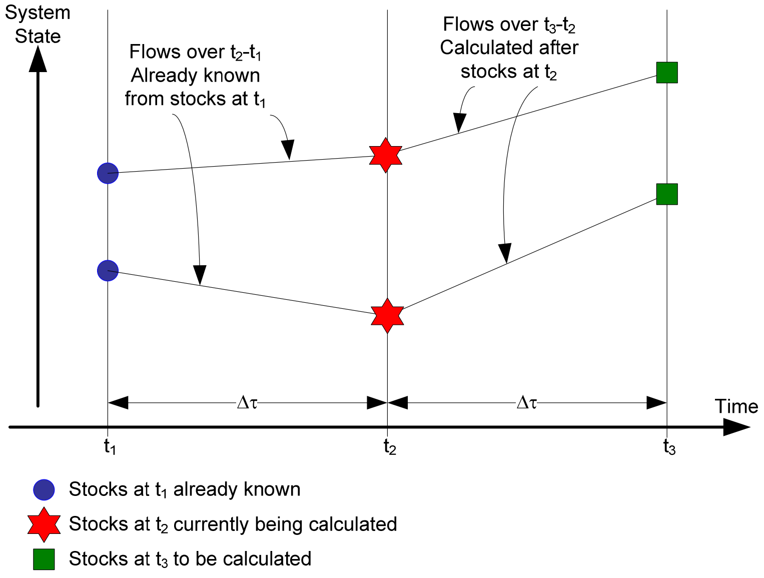

System State
Flows over t2-t1 Already known from stocks at t1
Flows over t3-t2 Calculated after stocks at t2
Δτ
Δτ
Time
t1
t2
t3
● Stocks at t1 already known
Stocks at t2 currently being calculated
🟩 Stocks at t3 to be calculated

Figure 5.12 Computational sequence in SD models

Figure 5-13 shows a casual loop diagram portion of a SD model. Production Start Rate is the rate at which raw materials are removed from parts inventory to start processing. It is also the rate at which raw materials are converted into Work in Process. Work in Process Adjustment, Finished Inventory Adjustment, and Parts Inventory Adjustment are the amounts of materials that should be made available to maintain equilibrium. The Indicated Materials Ordering is the estimated rate of ordering new materials to satisfy the adjustment needs and the scheduled production rate (not shown). Three balancing feedback loops in the diagram interact to maintain stable materials supply and production rate.

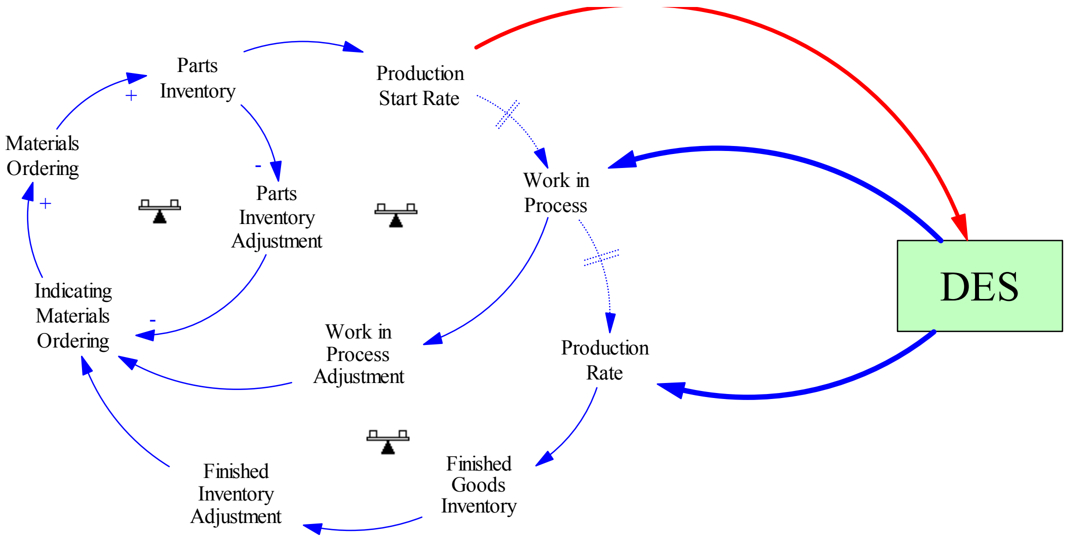


Figure 5.13 A DES module integrated into an SD model

Assume that the input links of the Work in Process and Production Rate are cut to have these two variables receive their values from a separate DES module that models the production processes. The two variables are still used as inputs to some other SD variables. The SD model sends the Production Start Rate as the input to drive the DES module. At each SD computational step, the causal loop diagram of SD reacts to the values of Work in Process and Production Rate by an increase or decrease in Finished Goods Inventory and the appropriate inventory adjustments in addition to updating its Production Start Rate. The reaction is communicated to DES by exporting the new Production Start Rate in expectation of updated Work in process and Production Rate from DES. Unless DES is able to make these values available at the next computational step in SD, the feedback loops will be broken and SD will not be able to adjust itself to maintain equilibrium. Consequently its performance is not easily explained by its structure and is likely to be erroneous and misleading.

The SDDES synchronization mechanism allows exchanging data between SD and DES at each computational step. This, however, may be inefficient if the changes in the DES modules are not as frequent. The choice of the DES segment length should consider the following:

1. It should maintain the integrity of the feedback loops of SD
2. It should maintain the correctness of the SD computations
3. It should capture the changes in the DES modules

Different segment sizes for the different DES modules have the potential of improving the efficiency of the SDDES simulation model. Depending on the system being modeled, different segment lengths can be used. For instance, in a manufacturing system early slow production processes may be modeled by one DES module while the downstream fast assembly processes can be modeled by a different DES module. If the state of the first (slow changing) DES module can be considered fixed for more than one SD computational time step then this module can have a run segment of length $n\Delta t$ where n is a non-negative integer. Meanwhile the other DES module (rapidly changing) may use Δt as its segment length.

5.6 The DES Run Segment Resumption

The SDDES synchronization sequence requires dividing each DES module run into segments. At the end of each segment the state of part of the system modeled by the DES module is saved. And at the start of the following segment the saved state is used to initialize the module, thus the module resumes from where it stopped at the end of the previous segment. Resumption is vital for the correctness of the results obtained from each DES module after its first segment. Resumption ensures the following:

1. Each queue at the start of the segment has the same number of entities it had at the end of the previous segment.
2. Each resource at the start of the segment is in the same state it was at the end of the previous segment.
3. Entities seizing resource units at the end of a segment continue to seize the same resource units at the start of following segment
4. Entities that were in processing at the end of the segment and could not finish processing before the segment ends, continue processing at the start of following using the unused portion of the processing time

Resumption is performed as described below, for each two consecutive DES segments; k and $k+1$.

1. During segment k:

a. When an entity e seizes a resource unit r to start processing, do the following:

   i. Record the entity's identification number

   ii. Record the resource unit's identification number

   iii. Record processing time; pt assigned to the entity at the resource unit

   iv. Record the time of the processing start event; pt_{ps}

b. Purge all recorded values in Step 1-a if entity e releases resource unit r after processing is completed before the end of the segment

c. When the state of a resource unit r that is not seized for processing or is idle, changes to an unavailable state, do the following:

   i. Record the resource unit's identification number

   ii. Record the state of the resource

   iii. Record the time interval; t_{un}, assigned to r for that state

   iv. Record the time of event of entering the state; t_{Sun}

d. Purge all recorded values in Step 1-c if time interval t_{un} has elapsed before the end of the segment

2. At the end of segment k:

   a. For each entity undergoing processing save all recorded values in Step 1-a

   b. For each resource unit in an unavailable state save all recorded values in Step 1-c

   c. For each queue that has a length greater than zero save the number of waiting entities and their attributes

3. At the start of segment $k+1$:
    a. If saved resumption information in Step 2 are not null then do the following in the following order:
        i. Assign each in-processing entity to the appropriate resource unit using the information saved in Step 2-a, and let the processing time equal to $pt-(L-pt_{ps})$ where L is the segment length
        ii. Set each resource unit in an unavailable state into the same state using the information saved in Step 2-b, and let the time interval for that state equal to $t_{un}-(L-t_{Sun})$ where L is the segment length
        iii. Insert entities into the queues they were waiting in at the end of segment k, using the information saved in Step 2-c
    b. Clear all information saved in Step 2
    c. Designate the current segment as segment k and return to Step 1.

Figure 5-14 describes the recording and saving of the resumption data from segment k, and use of that data in segment $k+1$. This is presented for an entity that starts processing in segment k and does not finish processing before the end of k and thus needs to continue processing in segment $k+1$.

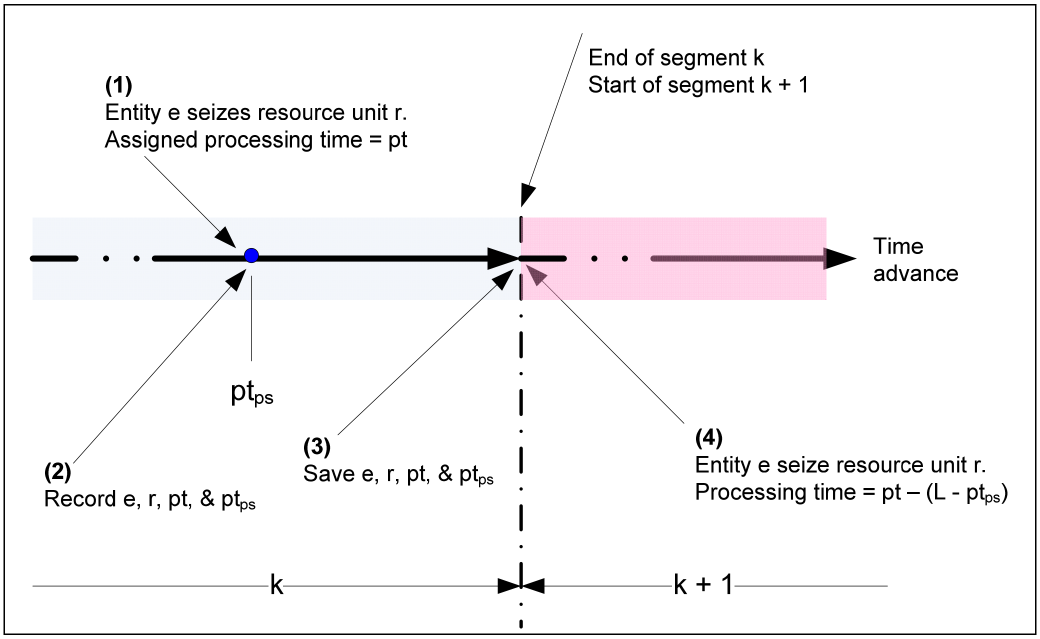

End of segment k
Start of segment k + 1
(1)
Entity e seizes resource unit r.
Assigned processing time = pt
Time
advance
pt_{ps}
(2)
Record e, r, pt, & pt_{ps}
(3)
Save e, r, pt, & pt_{ps}
(4)
Entity e seize resource unit r.
Processing time = pt – (L - pt_{ps})
k
k + 1

Figure 5.14 Resuming processing between two consecutive DES segments

Figure 5-15 describes the resumption in segment $k+1$ of a resource unit state that was in an unavailable state (a failure state) in the previous segment k.

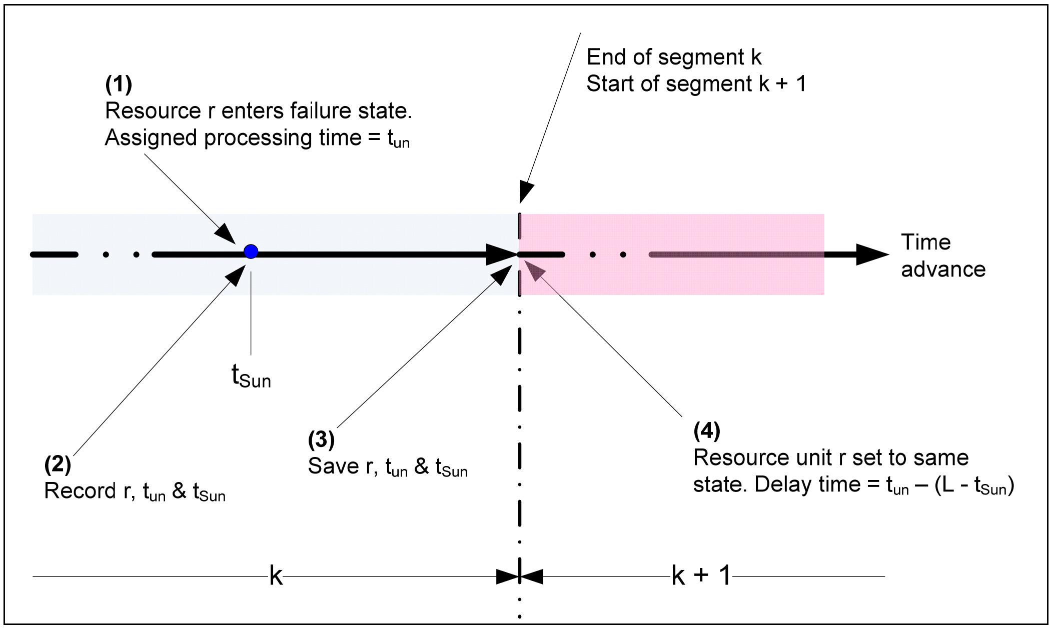

End of segment k
Start of segment k + 1
(1)
Resource r enters failure state.
Assigned processing time = t_un
Time
advance
t_Sun
(2)
Record r, t_un & t_Sun
(3)
Save r, t_un & t_Sun
(4)
Resource unit r set to same state. Delay time = t_un – (L - t_Sun)
k
k + 1

Figure 5.15 Resuming the unavailable state of a resource unit between two consecutive DES segments

Processing resumption can accommodate the following cases in the DES modules:

1. A single entity undergoing processing by a single-unit resource
2. A single entity undergoing processing by one unit of a multiple-unit resource
3. A representative entity (batched entities) undergoing processing by a single-unit resource
4. A representative entity (batched entities) undergoing processing by one unit of a multiple-unit resource

Table 5-1 summarizes these four cases regarding the information to record and save during and at the end of each segment.

Table 5.1 Different cases of processing resumption between consecutive DES run segments

Case	To save at end of segment k	To do at start of segment k+1
Single entity on a single-unit resource	• Entity id number; e • Resource unit id number; r • Processing time; pt • Processing start time; pt_{ps}	• Assign e to r • Processing time = $pt-(L-pt_{ps})$
Single entity on a multiple-unit resource	• For each seized resource unit; i: • Entity id number; e_i • Resource unit id number; r_i • Processing time; $pt_{ei,ri}$ • Processing start time $pt_{ps,ei,ri}$	• For each seized resource unit; i: • Assign e_i to r_i • Processing time = $pt_{ei,ri}-(L-pt_{ps,ei,ri})$
Representative entity on a single-unit resource	• Batch id number; b • Batch size; s_b • For each entity in b, indexed by i: o Entity id number; e_{bi} • Resource unit id number; r • Processing time; pt • Processing start time; pt_{ps}	• Given s_b, assign e_{bi} e$_{\text{bi}}$ to b • Assign b to r • Processing time = $pt-(L-pt_{ps})$
Representative entity on a multiple-unit resource	• For each seized resource unit; i: • Batch id number; b_i • Batch size; s_{bi} • For each entity in b_i, indexed by j: o Entity id number; e_{bij} • Resource unit id number; r_{bi} • Processing time; $pt_{bi,rbi}$ • Processing start time; $pt_{ps,bi,rbi}$	• For each seized resource unit; i: • Given s_{bi}, assign e_{bij} to b_i • Assign b_i to r_{bi} • Processing time = $pt_{bi,rbi}-(L-pt_{ps,bi,rbi})$

Representative entities may represent entities of the same or different attributes. Batched entities are separated before recording their resumption information. Attributes are recorded along with the entities' identification numbers as described in the recoding-saving procedure above.

5.7 Data Exchanged Between SD and DES

DES modules generate two types of data: observational and time-persistent (Henderson and Nelson, 2006; Pegden et al., 1992). Observational data are values of random variables that do not have a life time (e.g. number product units leaving the system). These values are observed at the occurrence of the relevant events then they expire as the associated entities are discarded from the system or moved to another state. They can be counted and averaged using simple arithmetic averaging. A time persistent value is a value of a random variable that is valid from the event time that generated it until the next event that changes it. An example is the number of entities waiting a queue.

SD modules are made of two types of variables: stocks and flows. Stocks are accumulators (e.g. inventory, cash balance) and they continue to exist even when the system brought to a frozen state. Flows are the rates of accumulating in the stocks or the rates at which the stocks are depleted. Flows cannot exist if the system is stopped. Flows represent the activities and policy actions while stocks represent the outcomes of these activities. In SDDES, data from DES are used in SD and data from SD are used in DES as depicted in Figure 5-16 and explained in the following subsections.

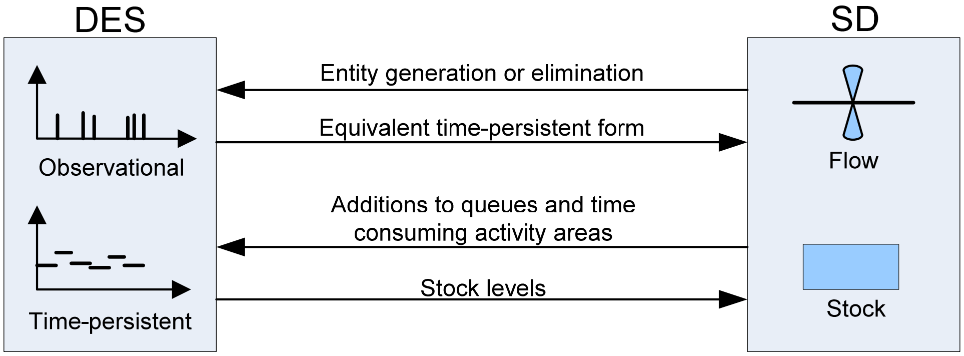

DES
SD
Entity generation or elimination
Equivalent time-persistent form
Observational
Flow
Additions to queues and time consuming activity areas
Stock levels
Stock
Time-persistent

Figure 5.16 Correspondence between SD and DES data in SDDES

<u>5.7.1 Using SD stocks data in DES</u>

SD stocks accumulate units of products, people, orders, etc. Stocks correspond to queues, buffers, storage areas, and where entities can be held for non-zero time intervals in DES. For example, the work in process stock in the SD module corresponds to all unfinished product units in the DES module that are waiting in queues or undergoing processing (delays).

Stocks are not directly measured in time units. They are measured in terms of the units of their contents. They could have dimensional units such as units/week but this means that the system is observed for how many units are present in it during the week (Forrester, 1965) that is, the dimensional units do not represent the flow of the stock contents over a period of time. This may be called the base time unit in the SD module. The dimensional units of all SD variables should be consistent. The contents of a SD stock can be exported to queues and delay objects in the DES modules and they are directly usable in DES.

Figure 5-17 shows a SD module with a single stock of the level of work in process (WIP) and two flow rates (e.g. materials arrival rate and production rate). The figure shows a DES module of two processes and two queues before them. The DES is the details of the process modeled implicitly in WIP in the SD module. The WIP level in the SD module is translated into the number of entities in the DES module: at the queues and in each of the two processes. In the opposite direction, the SD WIP data is collected from DES. The number of units in the queues and the number of units being processed are given to the WIP stock, as shown in Figure 5-18.

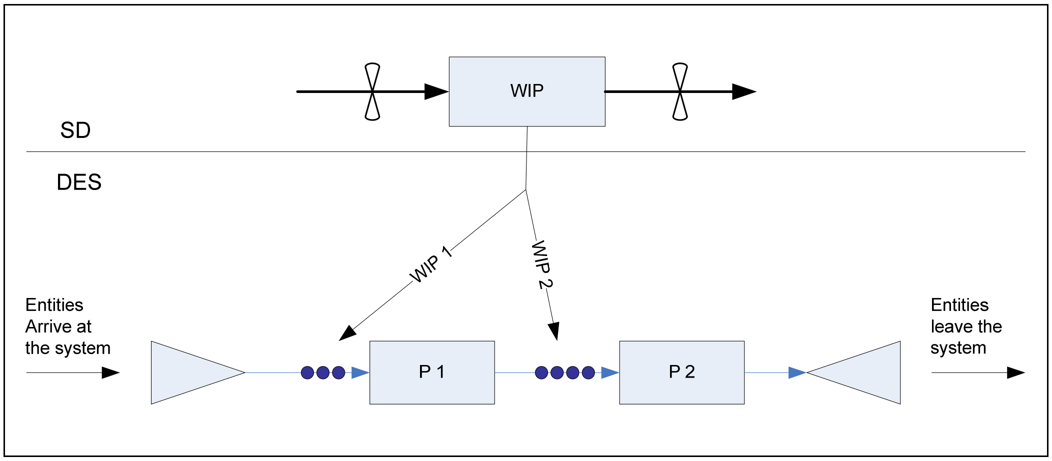


Figure 5.17 Exporting SD stock contents to DES

When implemented in SDDES, the SD stock is disconnected from its flow rates to be a function in the DES data only. The inflow and outflow of WIP are exported and imported from DES. That is the DES module has replaced the WIP stock in the SD module. The SD variables will maintain communications with the other SD variables as to maintain the integrity of the SD feedback loop. Exchanging flow rates data is discussed next.

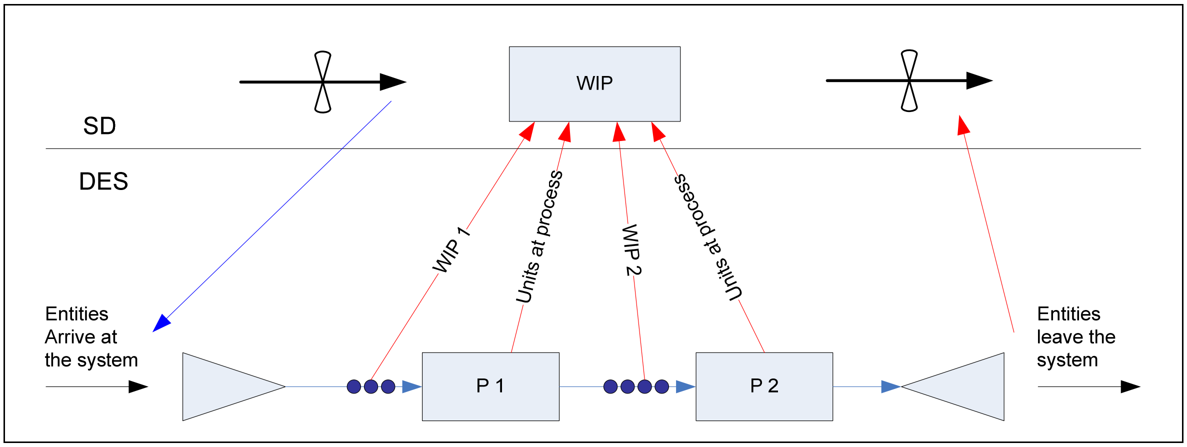


Figure 5.18 Importing SD stock contents from DES

In summary, the SD stock contents can be mapped to DES queues and time-consuming activity areas without particular format changes. The SD estimate of a stock at a certain time step is the present value of the stock at that moment. An estimate from DES provided at the following time step after an input from SD will provide the updated value of the stock. SD will be able to react to the DES value and adjust itself in order to maintain equilibrium.

5.7.2 Using SD flow rate data in DES

SD flow rates describe how stocks change over time. They have dimensional units of units of stock contents per the base unit time. They represent the addition or removal of the stock contents. SD flow rates, hence, can map to the generation or elimination of entities in DES given that the entities in the DES module correspond to the contents of the SD stocks. The value of a flow rate represents the number of units to create in a DES module or eliminate from the module.

In Figure 5-18, the inflow to the WIP stock (materials arrival rate) is directed to the DES module. Materials created at DES based on the inflow rate will be waiting in queues, in processing, or will leave the system when they are finished. As the entities leave the system they are counted and their count over the segment duration will make the DES value for the SD outflow rate. Given the base time unit of SD and the computational time step size, the value of a flow that is to be exported to a DES module at the current point in time t should be scaled to match the DES run segment length such that the value itself without the time dimension can be used. If the run segment length is $TB=n\Delta t$, then a DES equivalent of the SD flow rate variable is calculated by equation 24 where Δt is the SD computational time step.

$$\text{DES equivalent of SD flow rate} = \text{SD flow rate value}\left(\frac{n\Delta t}{SD\_Base\_Time\_Unit}\right) \quad (24)$$

5.7.3 Using DES observational data in SD

Observational data exist in the DES modules only for the duration of the event that created them, which is zero. Observational data can be mapped to flow rates in SD. Mapping to stocks requires time-persistent data. For dimensional correctness in SD, observational data should be transformed into equivalent quantities that can be measured in the same units of the flow rates they map to. Counted over the duration of the run segment, the DES observation data can map to an equivalent SD flow rate using equation 25.

$$\text{SD equivalent of DES counted data} = \text{DES count}\left(\frac{n\Delta t}{SD\_Base\_Time\_Unit}\right) \qquad (25)$$

Let x be the random variable of the number of entities removed from a system modeled by DES. At the event times of removing the entities x may take the values of x_1, x_2, x_3, … etc. at the event times t_1, t_2, t_3, … respectively (Figure 5-19). To estimate a removal rate from DES the number of entities over the in-between events times is divided by the time interval length. The rate estimates are denoted by X_{SD} in Figure 5-19. Assuming the DES model started idle and empty at time zero, then the system needed t_1 time units to deliver x_1 entities. The equivalent rate over t_1, X_{SD1} is estimated as the ratio of x_1 to t_1. Rates over other periods are estimated similarly. When exported to a SD module, the estimated equivalent value over each time interval is used for the appropriate SD flow rate variable.

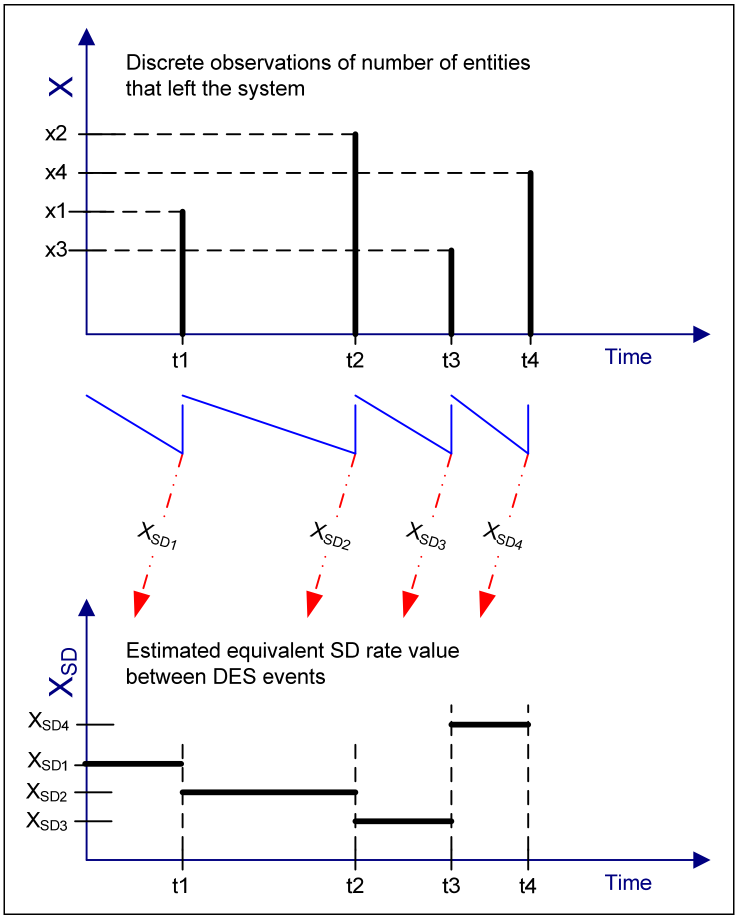

Discrete observations of number of entities that left the system
X
x2
x4
x1
x3
t1
t2
t3
t4
Time
X_{SD1}
X_{SD2}
X_{SD3}
X_{SD4}
Estimated equivalent SD rate value between DES events
X_{SD}
X_{SD4}
X_{SD1}
X_{SD2}
X_{SD3}
t1
t2
t3
t4
Time

Figure 5.19 Mapping observational data from DES (top) to equivalent rate variables in SD (bottom)

5.7.4 Using DES time-persistent data into SD

DES time persistent data are usable in SD as they are generated in DES and they can map to the SD stocks. Both time-persistent data and SD stock contents data represent quantities that stay valid over nonzero time intervals. The time-persistent values are recorded at the times of the events that affect them. More than one event can occur during the DES run segment that affect the time-persistent value. The end-of-run DES value of the time-persistent variable maps to the appropriate SD stock level at the same point in time.

It is also possible to estimate a time-weighted average of the DES time-persistent variable over the DES run and export it to the SD. In this case the average value may not be usable for a stock level. Such a DES value can add more information to the SD module. For instance, if the work in process data is collected from a DES module, the level of work in process at the end of the DES run corresponds to the relevant SD stock. Whereas a weighted average value of the work in process over the DES run can be used to indicate the level of system crowdedness, which can be used to estimate a labor satisfaction measure, or an indicator of the shop floor quality of environment. Assuming a DES segment length of Δt, Figure 5-20 illustrate these two approaches. Some accuracy analysis will be needed since the weighted-average value will correspond to somewhere between the begin and end of the SD computational step. The SD theory calculates the stock level at the end of the time step, which is used in the experimental analysis in the next chapter.

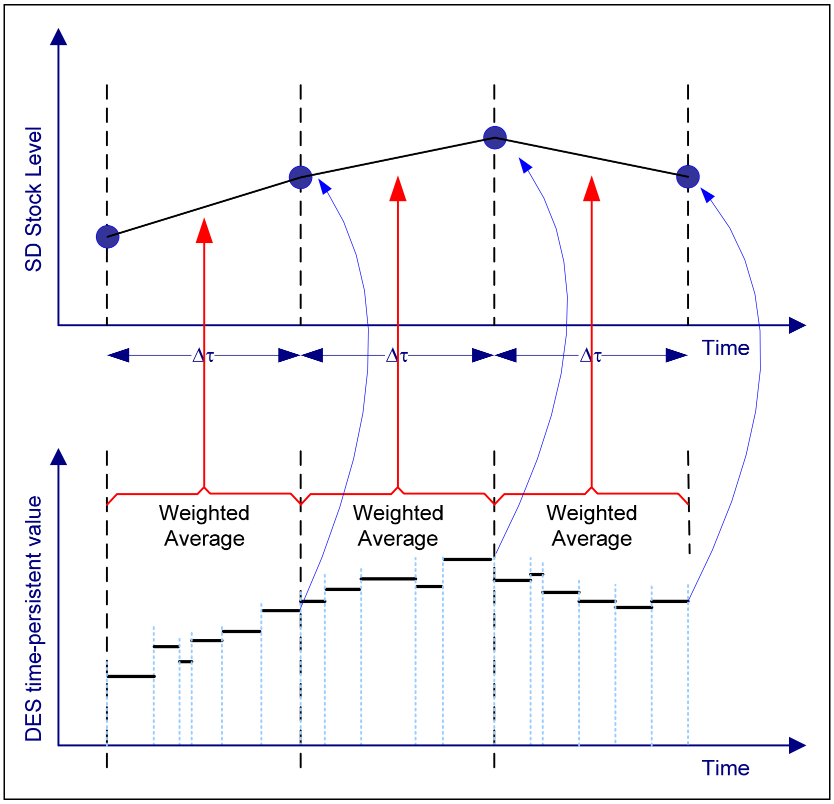


Figure 5.20 Mapping DES time-persistent data to SD stock levels

5.8 The SDDES Controller

SDDES uses the existing SD and DES modeling techniques as they are normally used. The integration of the modules and what it entails are all managed by the SDDES controller. The SDDES controller is the manager of synchronization of the SD and DES simulation modules in the SDDES framework. The controller is a separate unit that interacts with the simulation modules to facilitate the interactions between modules according to the specifications included in the SDDES formalism. The controller also implements the synchronization mechanism and provides the user interface to perform I/O operations and to define/modify/replace the modules or the model or management policy settings.

Figure 5-21 represents the position of the controller between the SD and DES modules and the flow of data from and to the modules through the aggregation/disaggregation functions (symbolized by the up and down triangles). The SDDES controller reads data from all modules and formats the data as described in Section 5.7, before they are sent to the requesting modules. And it keeps track of the simulation time.

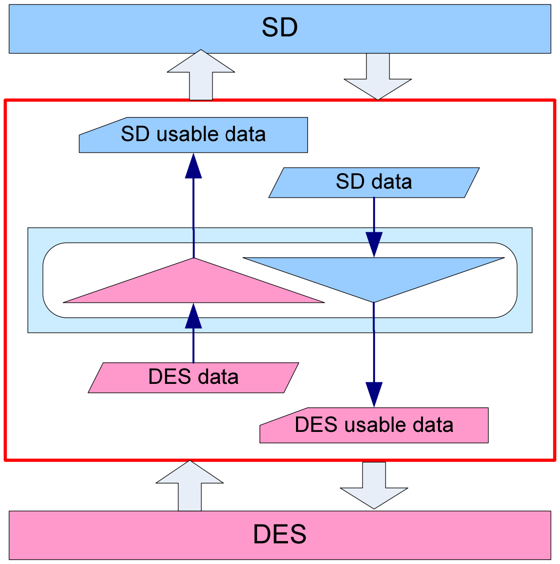


Figure 5.21 The SDDES controller directions of exchanging data

The SDDES controller acts in the following areas:

1. **Data management**: The controller ensures that the information indicated in the definition of the SD and DES modules (in their formalism specifications) are executed

properly regarding formatting and timing. It also allows users to modify the model settings.

2. **Time management**: The controller implements the synchronization mechanism and keeps track of the simulation time. The DES modules do not run for the entire SDDES simulation run length. The controller estimates the time for each with respect to the overall SD modules such that a user can observe the correct simulation time.
3. **Participation management**: The controller offers the functionality needed to add new modules to the SDDES model as well as to modify or replace existing modules. This is achieved through providing and or modifying the module data according to the SDDES formalism.

5.8.1 Functional model of the SDDES controller

To describe how the SDDES controller will perform its functions, we develop an IDEF0 model of it. The functional model describes how the controller manages the SDDES simulation run. The IDEF0 method offers a hierarchal representation of a system that depicts the functions done within the system along with relevant inputs needed to perform the functions, outputs generated upon perfuming the functions, the controls that guide and constrain the functions, and the mechanisms needed in that. The basic model as shown in Figure 5-22 is presented from the point of view of the modeler/user of the SDDES. A single box is used to indicate the function of the controller, namely executing the SDDES model run. The sets of inputs, controls, outputs, and mechanisms (the ICOMs) used in the A-0 model are described in Table 5-2.

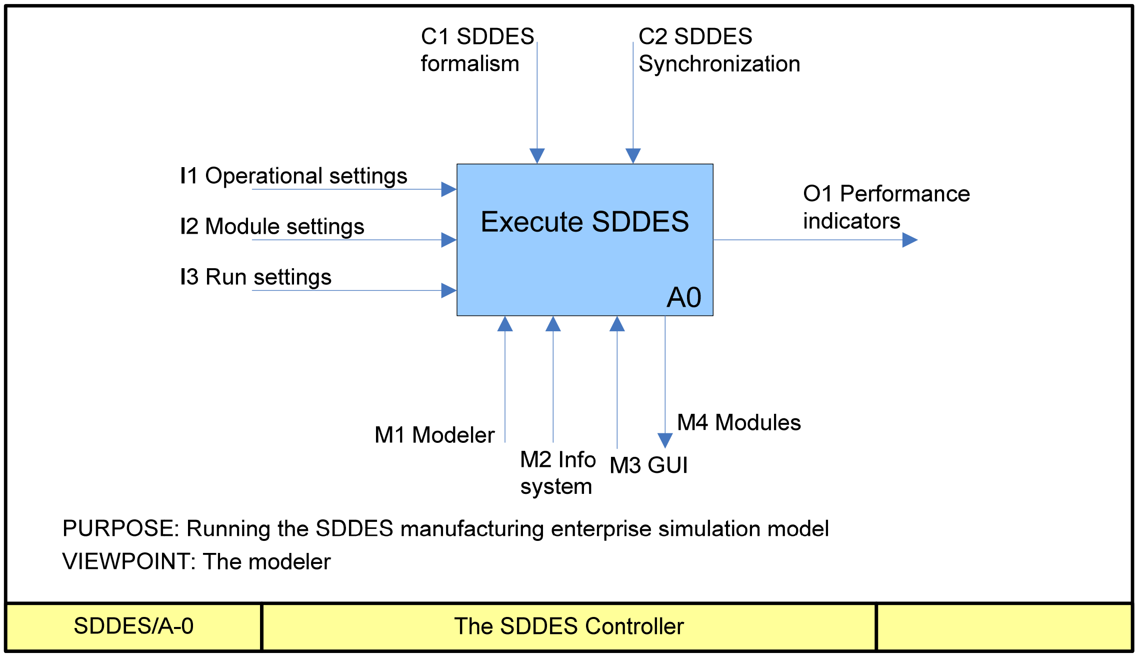


Figure 5.22 A-0 IDEF0 functional model of the SDDES controller

Table 5.2 ICOMs for the A-0 IDEF0 model of the SDDES controller

Inputs	I1	Operational settings	Characteristic information representing the current status of the system. They are elements of the management policies that will be tested and evaluated with the simulation model. The module parameters are assigned values in this action. These values are provided by the modeler or obtained from the active information system (M2).
	I2	Modules settings	The inputting of the data required by the SDDES formalism. Modules can be modified, deleted from, or added to the model.
	I3	Run settings	Specifying the planning horizon, number of replications for the DES modules, as well as the time units and needed parameters that will be monitored. Also the outputs that are of interest are specified here
Controls	C1	SDDES formalism	This guides the addition, modification, or deletion of modules. Also specifies the data needed to set the model and the run.
	C2	SDDES synchronization	This is SDDES synchronization algorithm. It guides the simulation run and the data exchange transactions.
Outputs	O1	Performance indicators	This is the regular outputs of a simulation model
Mechanisms	M1	Modeler	Represents the user of the simulation model in general. The modeler performs all I/O operations
	M2	Info system	This is the existing information system of the company (e.g. ERP or MRP). Module variables are linked to data provided by the information system. Outputs can also be added to the information system.
	M3	GUI	The graphical user interface is an integrated unit of the controller. It offers several user interfaces through which the modeler interacts with the controller and the model.
	M4	Modules	These are the module information saved in their files (e.g. the Arena and Vensim files in the current work). They are called to be used as necessary by the modeler and during the run for sure.

The controller executes the SDDES simulation model using these sets of inputs, controls, outputs, and mechanisms. The modeler uses the appropriate user interface to input module data or the simulation data. The modeler also observes the simulation outputs to assess the need to modify the plans and policies being tested. The inputs provided by the modeler are specified by the two controls; the formalism and the synchronization algorithm. The controller uses a database to store the input data and the ongoing outputs during the run. To set the modules, the controller extracts the parameters of the modules (via calling M4) such that the modeler would assign values to them or link their values to the appropriate data in the information system.

The A-0 diagram is decomposed into more detailed definition of the controller functions. The A0 diagram of the IDEF0 model is the first level of details of the function described in the A-0 model. A0 for the SDDES controller models the three basic functions of the. In the IDEF0 terms these functions are the A1, A2, and A3 in Figure 5-23. Each of these functions is decomposed further as necessary to offer a complete description of the controller role in the SDDES model, prior to its implementation. The A0 model is describe in Figure 5-23 and explained afterward.

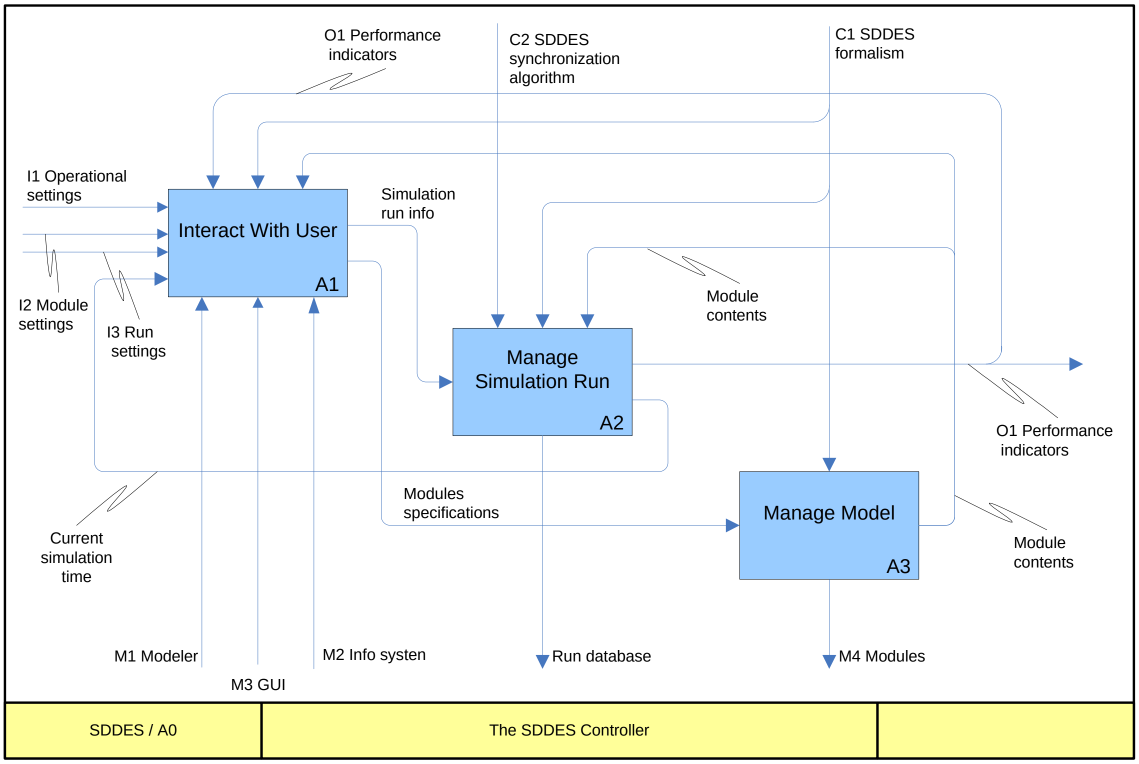


Figure 5.23 The A0 IDEF0 model of the SDDES controller

The Interact With User function (A1) allows the user (the Modeler in the above model) to perform I/O operations as well as defining the modules. The appropriate GUI is initiated for the Modeler to input the necessary settings. These inputs are communicated to A2 and A3 for the models to be defined and the run to be ready to be executed. The GUI is developed to meet all use cases of the system and these use cases are controlled by the SDDES formalism (adding or deleting modules), by the current contents of the saved modules (coming from A3 to modify modules, assign input values to their variables, etc.), and by the performance indicators (coming from A2 for the user to observe outputs and do necessary adjustments when desirable).

The Manage Model function works to accept changes in the existing modules and add new ones to the SDDES model as inputted by the modeler in A1. The modules are saved in their simulation software files and the files are called as necessary (M4). The current contents of the modules are the outputs of A3 that are fed back to A2 so that the controller reads the TB setting for the modules and the defined data exchange transactions that will be executed during the run in the A2 function. The synchronization algorithm (C2) controls A2 along with the relevant information from the formalism (C1). The current module contents from A3 are also fed back into A1 for the Modeler to correctly assign the operational and run settings.

The output of A2 is the output of the simulation run, which is offered as the overall output of SDDES and is fed back to A1 for the modeler to analyze the performance with the appropriate GUI. It is noted that the A2 function is internal; no direct user interactions are needed with it. During the run, the behavior of the system is feedback to A1 for the user to perform any adjustment if desirable.

The output of A1 is the simulation run info representing the settings needed to start the simulation run at A2. These ongoing outputs are saved in the run database and are as appropriate during the run. Of particular importance, the results of the run segments of the DES modules are saved to be used in the following segments as described by the DES resumption algorithm.

A detailed IDEF0 model of the A2 function in Figure 5-24 is given in Figure 5-25. The core of this function is to implement the synchronization algorithm (A2-2), given that the all modules have been formalized and that the resumption specifications have been defined for the DES modules. This data is represented by the simulation run info input to A2-2 module in Figure 5-24. Settings (SD run settings and DES run settings) for each module are forwarded to the modules. The SD module is set to reflect the management strategies and policies using the inputs of market demand, investment and resource allocation related decision and the enterprise financial indicators. Outputs of running the SD module (A2-1) are exported to the DES module via the A2-2 module. They include the decisions regarding the scheduled production, and adjustments for current capacity in addition to desirable performance levels. Upon running the DES modules (A2-3) the outputs (Operational performance measures) are sent to the A2-2 for formatting to be forwarded to A2-1. The overall SDDES model outputs are the system performance measures (O1) as was described earlier in Figure 5-23.

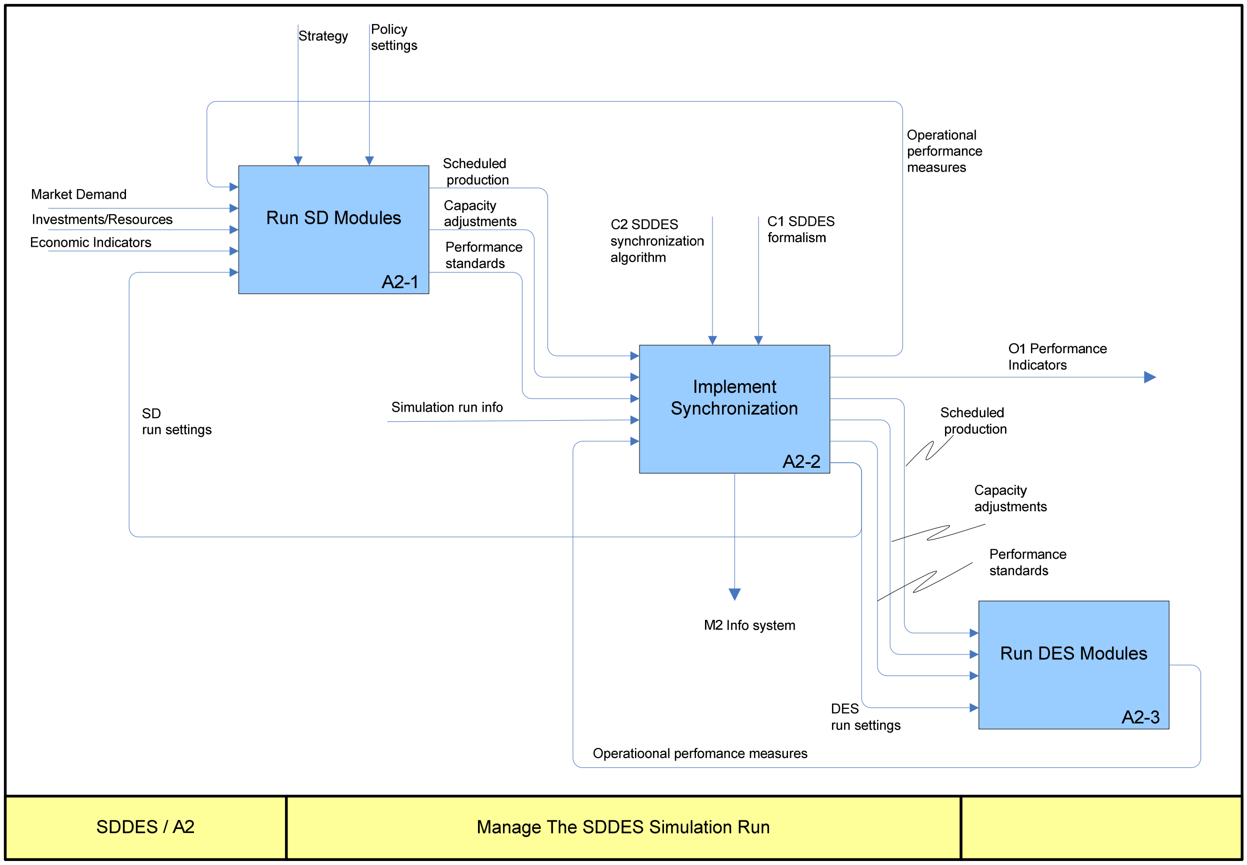


Figure 5.24 IDEF0 model of the SDDES controller function of managing the simulation run

5.9 SDDES Test Bed

This SDDES test bed is an implementation of the SDDES controller and is used for the experimental analysis and testing of the SDDES simulation framework. A Visual Basic (VB) application was built that communicates with the Arena and Vensim software packages. Arena was used to build DES modules for a manufacturing system as described in Chapter 6, while Vensim was used to build the SD modules of the same system. The VB implementation of the

SDDES controller uses the ActiveX Data Object (ADO) technology to connect to the simulation engine in Arena to gain access to and control the simulation modules. The functions and messaging tools of the Vensim's Dynamic Link Library (DLL) are utilized to communicate with the SD modules while establishing a Dynamic Data Exchange (DDE) link to have the software acting as a server/client application for the data exchange operations. To use it as the centralized data repository, the controller uses the ADO of the MS Excel application object to perform the data preparation operations and appropriately authorize the simulation engines to perform data read/write operations. The modeler interacts with the VB application to perform the input/output operations before and while the model run. A schematic diagram of the structure of the test bed implementation of the SDDES controller is shown in Figure 5-25.

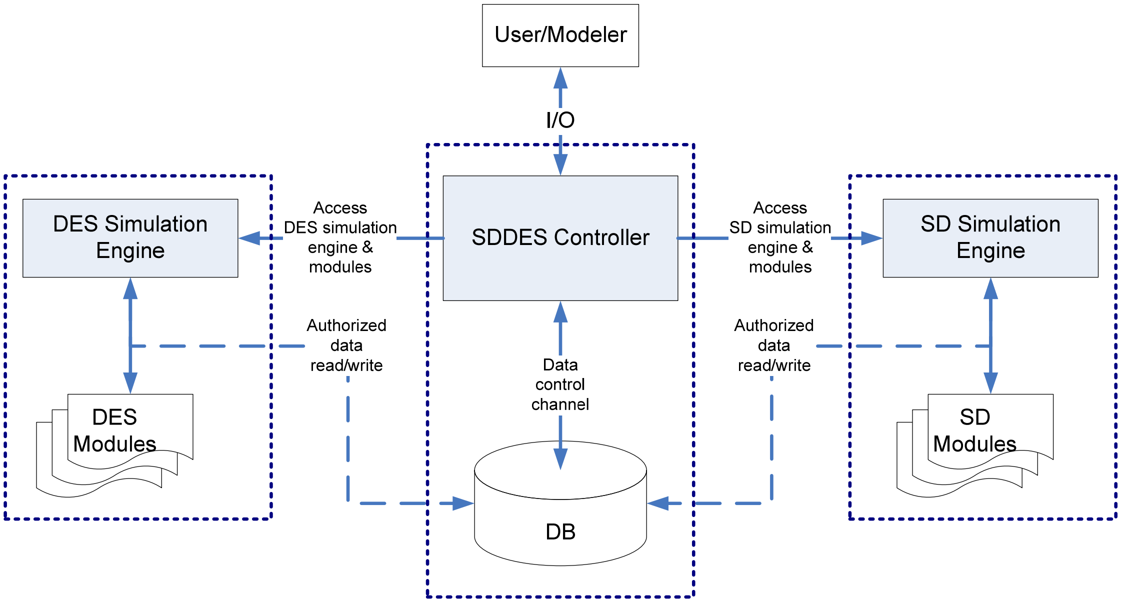

User/Modeler
I/O
DES Simulation Engine
Access DES simulation engine & modules
SDDES Controller
Access SD simulation engine & modules
SD Simulation Engine
Authorized data read/write
Data control channel
Authorized data read/write
DES Modules
DB
SD Modules

Figure 5.25 Schematic diagram of the SDDES controller test bed implementation

The VB code listing of the implementation of this test bed and simulation models described in section 6.1 in the next Chapter are available.

5.10 Chapter Summary

This chapter presented the conceptual design of the SDDES hybrid simulation framework. It presented the overall structure of the SDDES model and its coverage in modeling the manufacturing enterprise system and introduced and explained the concepts and components of the simulation framework. The concepts presented in this chapter are the following:

1. The scope of the manufacturing enterprise system
2. The modular structure of the SDDES simulation framework
3. The SDDES synchronization and controller actions sequence
4. The segmentation of the DES simulation runs
5. The DES run segment resumption algorithm
6. The SD and DES data formatting
7. The functional model of the SDDES controller

CHAPTER 6: EXPERIMENTAL ANALYSIS

This chapter consists of four parts. Part one demonstrates implementing the SDDES hybrid simulation framework to build a simulation model of a local manufacturing company. It is based on using the test bed described in Chapter 5. Part two presents a case of using an SDDES simulation model to analyze the manufacturing value chain. Part three compares SDDES to AnyLogic. Part four discusses the potential of using SDDES in the real time control applications of the manufacturing system.

6.1 Using SDDES to Model The Manufacturing System

This section describes using the SDDES simulation methodology. A case in which an SDDES hybrid simulation model is built for a real manufacturing system is used to describe the implementation and use of the concepts and elements of the SDDES framework. The objective of the case is to demonstrate the validity of the SDDES methodology as described in Chapter 5 and its ability to integrate the SD and DES paradigms and build usable comprehensive hybrid simulation models of the real manufacturing systems.

The implementation of the SDDES methodology will use the test bed described in section 5.9. SD and DES modules will be built to represent the manufacturing system of a local optical product manufacturer (will be referred to as PMOC Inc). The modules will be synchronized using the SDDES controller test bed. The module definition and building, resumption setting, and module formalizing processes will be described.

6.1.1 PMOC Inc.’s lenses manufacturing system

PMOC; a local manufacturing company, engages in the design, development, manufacture, and distribution of optical components and assemblies. The company offers families of precision molded glass aspheric optics – isolators, fiber optics collimators, GRADIUM glass, and other optical materials for laser and light control products. The company offers its products to various markets including industrial, medical, defense, test and measurements, and communications markets. The precision molded optics (PMO) process produces lenses for industrial laser and other optical applications and is the focus of the simulation model. Lenses production is the oldest product line at PMOC. Figure 6-1 shows a high level organizational structure of PMOC.

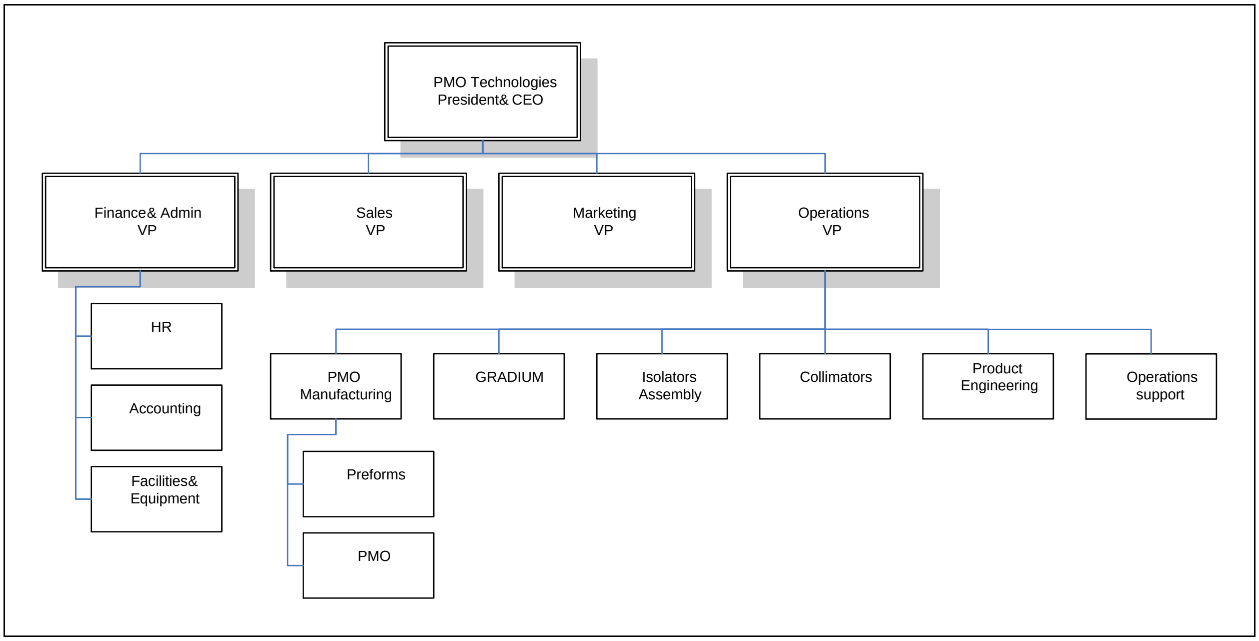


Figure 6.1 PMOC high level organizational structure

PMOC has a stable PMO customer base of about 1700 customers. The company has established long term relationship with its customers by providing customized products. Systems using PMOC's lenses at customers' facilities had been designed to use PMOC's products. With special requirements in lenses in addition to high quality level and support, customers have been willing to pay a premium for PMOC's product. This has helped The Company maintain a stable market share over the past few years despite using an old manufacturing technology with limited capacity.

Rapid technological advances and growth in the optical market (at the industrial and consumer electronics levels) challenged PMOC's strategy of relaying on providing customized products to loyal customers. Customers renovating optical systems are considering switching to competitors who can offer similar variety and quality at cheaper prices. Recognizing the limits of its production capacity and technology and with the expected success and more promising markets for other products, PMOC is planning no investments in its PMO production line and is investigating an outsourcing decision. In this section we describe building an SDDES simulation model of PMOC's PMO operations that can be used to assess the system capabilities and ability to maintain its performance.

6.1.2 Building the SDDES hybrid simulation model

The objective of the model is demonstrating the implementation of the SDDES simulation framework and its potential for modeling the manufacturing system and explaining its behavior and level of performance. SD and DES simulation models were built to be used as modules in the SDDES model. The SD and DES modules were built as regular SD or DES simulation models. We then followed the module definition processes described in Chapter 5 (See Figure 6-2 below) to develop them as modules. Defining a SDDES module is essentially defining its sets of inputs and outputs and then formalizing it. Formalizing the module as described in the SDDES formalism includes the definition of the resumption (for DES modules) and synchronization (data exchange timing and formats) settings for each module.

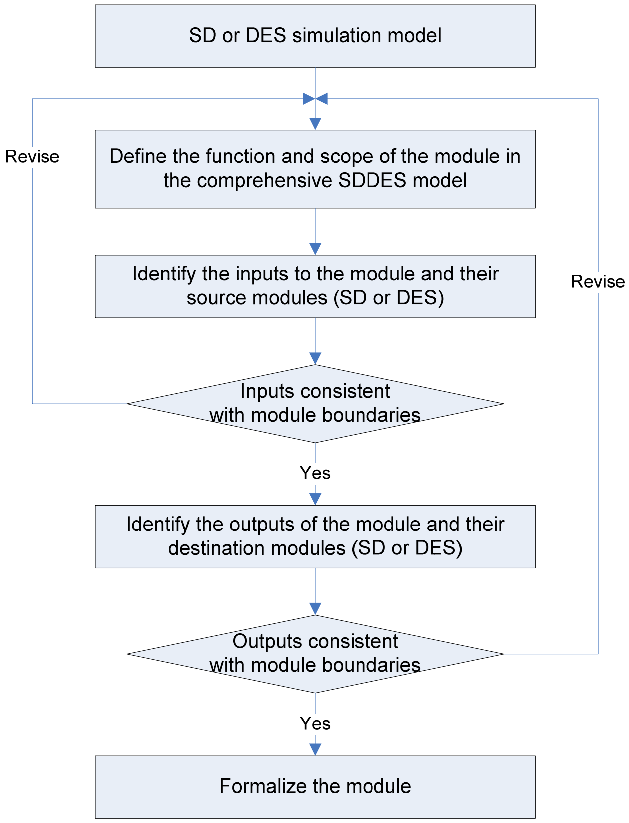

SD or DES simulation model
Revise
Define the function and scope of the module in the comprehensive SDDES model
Identify the inputs to the module and their source modules (SD or DES)
Revise
Inputs consistent with module boundaries
Yes
Identify the outputs of the module and their destination modules (SD or DES)
Outputs consistent with module boundaries
Yes
Formalize the module

Figure 6.2 Defining an SDDES module of an SD or DES model

The following steps were followed to build the SDDES model:

1. Defining the scope and contents of the model
2. Defining the boundaries of each module
3. Building the SD and DES modules
4. Validating the modules
5. Defining the inputs and outputs for each module
6. Defining the DES modules resumption settings
7. Defining the modules synchronization settings

8. Interfacing the modules via the SDDES controller

9. Testing and validation of the SDDES model

The SDDES hybrid simulation model of the PMOC's PMO operations includes the following units (Figure 6-3) to cover the operational level for the PMO process at the shop floor and the aggregate decision making level in addition to the financial and accounting aspects:

1. The shop floor operations at the PreForms and Presses departments
2. The internal supply chain represented by Materials Ordering, Production Planning, Inventory Management, and Shipping
3. Labor Management
4. Finance and accounting

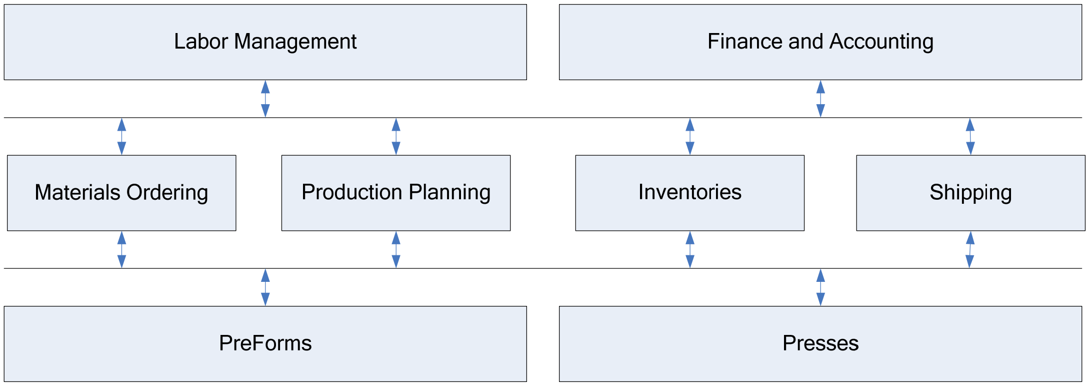


Figure 6.3 Business units included in the SDDES simulation model of PMOC

The PreForms and Presses departments contain all the production equipment. In PreForms, raw materials (glass slabs) are converted into semi-finished products called preforms (glass balls). Raw materials arrive in the form of slabs of 4 by 6 inches and 1 inch thick. Slabs are inspected for physical defects and thermal expansion characteristics and are then sliced into plates of different thicknesses to meet the different sizes of the various types of final product. Plates are formed into glass balls (preforms) of different sizes. Preforms are then annealed, ground, lapped, polished, smoked and baked, and cleaned before they are sent to the Presses department for the finishing operations. In Presses, the preforms are pressed on two types of presses to make usable lenses of different optical characteristics.

The PreForms department uses a relatively old technology. And because of the different types of final product, the processing times and batch sizes at each processing step vary significantly. There is a single annealing oven that can process a batch of 1000 to 1500 units (depending on the size of the raw preforms) per run and it runs for average of 12 hours. There are four grinding, five lapping, and 15 polishing machines that each can process between 100 and 350 units each run where the processing time vary from 25 minutes to more than five hours. The smoke and back and wash operations use heat and chemicals to clean the preforms in batches of up to 100 units and processing times are measured in minutes. There are 13 workers in addition to the production manager in the PreForms department. Workers are grouped for the different processing steps yet they are trained to operate all equipment.

The different lens sizes and necessarily the differences in batch sizes and processing times with the lack of computer control make synchronization critical to ensure the availability of materials to meet the Presses department requirements. Figure 6-4 shows the daily production rate of the PreForms department for a six-month period. This shows all types of lenses pooled together. Preforms are stocked at the department until requested by the Presses department operators.

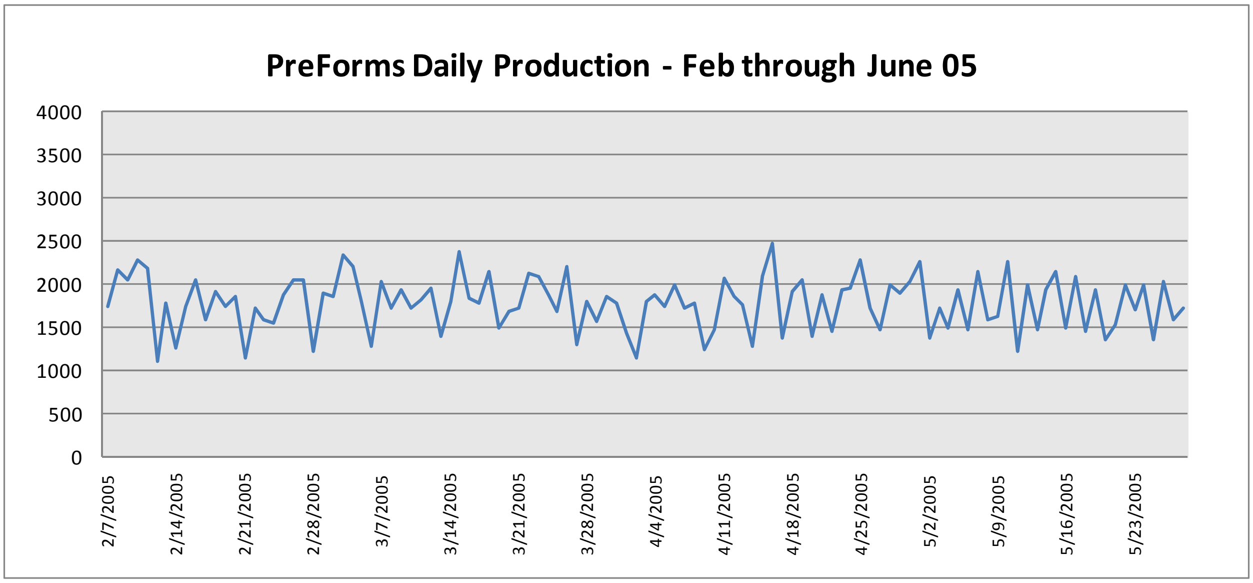


Figure 6.4 Daily raw preforms output from the PreForms department (actual data provided by PMOC)

The Presses department is run as a pull production system that pulls raw preforms from PreForms according to the schedule to meet customer orders. Orders arrive in varying sizes for the different types of lenses. Raw preforms are pressed into final usable lenses at two types of pressing workstations: the air presses and the Nitrogen (Ni) presses. Each air press has seven pressing heads, which can be run separately. Each Ni press has six pressing heads, which are also independent from each other. Air or Ni refers to the technology used in the press where pressing is carried in a vacuum or within the presence of the inert Ni gas. Each type is capable of producing certain set of optical characteristics that overlap such that some types of lenses can be pressed on either type of press. Each press is run by a single operator. There are nine and seven Air and Ni presses respectively. After pressing, the operator inspects the lenses before they are forwarded to the more advanced interferometer testing station where they are accepted or scrapped. Operators retrieve the preforms daily according to the scheduled production of the day. Scrap rate is high at Pressing; ranging between 25% and 35% of attempted pressing operations.

Utilizing the decision criteria presented in Chapter 5, the system units indicated in Figure 6-3 were modeled by SD or DES as indicated in Table 6-1. The production processes at the PreForms and Presses departments are in DES while the rest of the business units are in SD. This is discussed afterward.

Table 6.1 Classifying PMOC's business units in the SDDES model as SD or DES models

Business Units	**Decision Criteria**								**Use SD or DES**
	Perspective		**Resolution**		**Nature**		**State Change**		
	Holistic	Detailed	Homogenized	Individualized	Deterministic	Stochastic	Continually	Discretely	
Production Planning	1	0	1	0	1	0	1	0	SD
Materials Ordering	1	0	1	0	1	0	1	0	SD
Inventories	1	0	1	0	1	0	1	0	SD
Shipping	1	0	1	0	1	0	1	0	SD
Labor Management	1	0	1	0	1	0	1	0	SD
Finance & Accounting	1	0	1	0	1	0	1	0	SD
PreForms	0	1	0	1	0	1	0	1	DES
Presses	0	1	0	1	0	1	0	1	DES

We modeled the PreForms and Presses departments using DES to allow for monitoring each individual unit of equipment and synchronizing their performance to ensure smooth flow of materials in PreFoms and from PreForms to Presses. The high scrap rate can cause occasional loss of materials and accurate estimates of the scrap rate are necessary. Stochastic behavior due to varying processing times and batch sizes in addition to scrapping rate is dominant. DES models can provide good estimates of scrap based on each piece of equipment's performance. DES is effective in modeling materials flow between processing steps. Tracking production, amounts of scrap, and work in process in addition to the equipment failures and the workforce availability and performance are essential in modeling production lines.

The aggregate production management level, represented by the other units indicated in Figure 6-3 were modeled using SD. Materials ordering, production planning, inventories, and shipping represent the internal supply chain of PMCO. Production at the shop floor level is controlled through the interactions with these functional units. They are managed at the aggregate decision making level providing planning responsibilities. Customer orders are received and accordingly needed raw materials, materials usage, and production rates are set. These decisions use shop floor level data for current production yield, available work in process and current work load. Individual production equipment units are not monitored at this planning level. Instead the overall performance of the PreForms and the Presses departments is estimated and used in the materials ordering and inventory management and production scheduling decisions. PMOC partners with a single supplier of raw materials that delivers materials on a monthly basis to cover the monthly demand. Arriving raw materials shipments are always inspected but rejections never occurred. No particular sources of stochasticity are recognizable when making decisions at this level. PMOC serves a fairly stable customer base. The company's strategy is essentially to serve its current customer base. Part of this is due to the limited capacity and the higher prices than competitors that do not attract new customers. It is also noted that PMOC is directing resources to other product lines that are more promising and they maintain PMO production at current stable level without plans for investing in it as outsourcing is being considered.

Labor attrition is at the low rate of less than one worker per month that is compensated for by an equivalent hiring rate with cooperation with a hiring agency that provides basic training. Average employment length is three years. New operators are trained by their coworkers when they join the workforce such that productivity is not negatively affected by them. Finance and accounting units monitor performance in financial measures. These are essentially deterministic business unit given the stable customer base, orders, and market share. This makes these units candidates for modeling in SD models.

6.1.3 Building the SD modules

The SD modules were built using the standard SD methodology in which reference modes of behavior and dynamic hypotheses are developed to describe the perceived historical and projected behavior of the system and the major causal relationships that underlie these modes. These modes and hypotheses reflect the decision makers' mental models and perceptions of the system. They represent the basis for building the stock and flow model, which is then reviewed with them for validity.

We utilized the stock management model (Sterman, 2000) as described in Chapter 2 of this dissertation in building the SD modules. The stock management model (SMM) provides abstract concepts of the causal relationships in terms of the stocks and flows variables. Participants from various departments at PMOC in relation to the PMO manufacturing were interviewed. Company's CEO, VP of operations, finance, marketing, and human resources, in addition to marketing and customer service staff and production managers, were interviewed to develop the dynamic hypotheses of the modules. Financial data, however, were obtained from public data posted on the Internet at www.yahoo.com as the company is a public company.

The main factor that shaped the way they managed PMO was the company's intent to outsource the process. The company purchased the PMO about ten years earlier for market diversity to improve their financial performance. PMOC maintained the level of performance while planning investments in new additional markets and technologies, not including upgrading PMO manufacturing capacities. Rapid technological advances and changes in the market had limited PMO's success. Long term customers continued to partner with PMOC. However, market share and customer base could not be increased with the limited capacity and relatively higher prices given the increasing competition and the evolutionary changes in the market. The company decided to focus on its other markets and not to invest in PMO, which would be a large investment for an already highly competitive market where competitors are technologically ahead. For being in a restructure phase, PMOC is a public company that has been experiencing a decreasing share price (Figure 6-5). This would continue unless the company reorganizes its production lines and direct investments in the more promising markets.

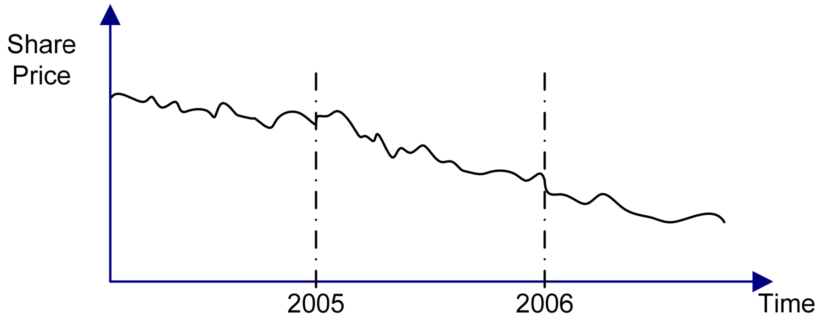


Figure 6.5 Decreasing trend in PMOC market share price - described by PMOC managers and as shown on www.yahoo.com

The objective of the management then was to maintain PMO's performance and minimize operational expenses. The main concern expressed by the participants was the high scrap rate (estimated 25% to 40%). Scrap has been observed to be slightly increasing and as equipment get older; it was projected to be higher (Figure 6-6). Higher scrap is translated into lower yield.

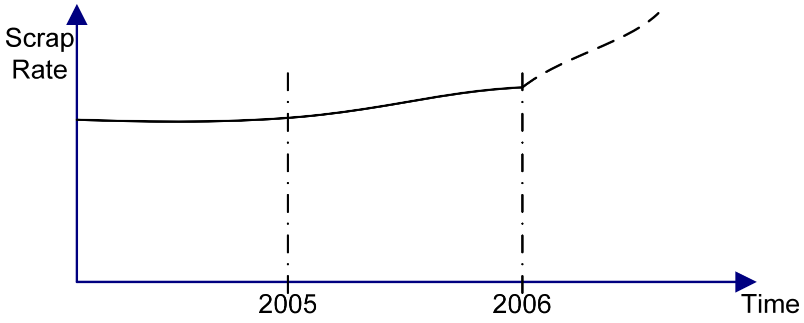


Figure 6.6 increasing trend in scrap rate – described by PMOC managers

Not only scrapping causes the loss of materials (semi finished preforms) but it can also cause longer delivery delays (Figure 6-7 a), the need for emergency materials ordering at higher expenses, and it requires repairing/replacing the metallic pressing head molds which adds to the production expenses (Figure 6-7 b). The company traditionally offered an average of one week delivery delay.

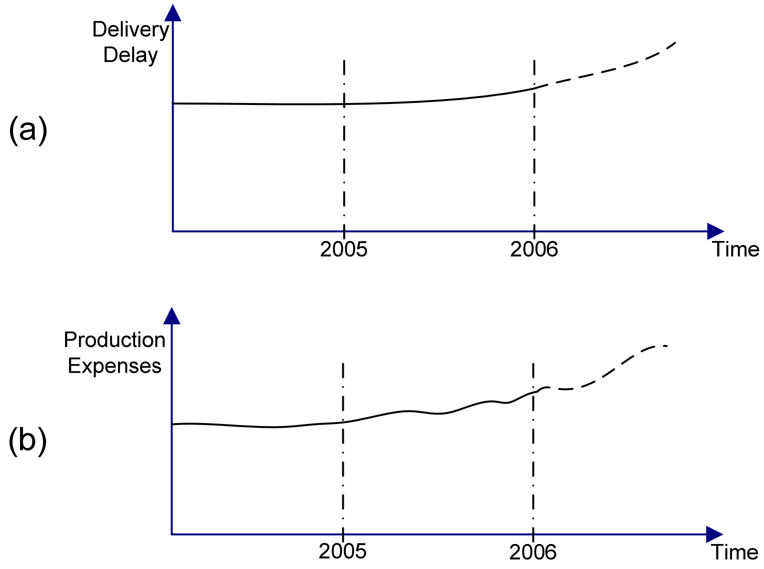


Figure 6.7 Deliver delay expected to increase as well as production expenses – described by PMOC managers

The many types of lenses and the varying order sizes for each type create difficulties for synchronizing the production processes that leads to fluctuating materials and work in process inventories (Figure 6-8 a). Improving scrap rate would require investments in new equipment to replace the technologically old, less reliable equipment. PMOC is planning no such investments.

The reason behind that is the increasing competition. Competitors offer lower prices than PMOC which do not have sufficient capacity to increase productivity in order to lower prices. Besides, the pressing technology is more expensive than the newer ceramic-based presses that competitors use. Customer orders are expected to decrease (Figure 6-8 b) in favor of faster delivery and lower prices. More importantly, current customers upgrading their systems that use PMOC's products are shifting toward using more standardized competitors' products at lower prices. Some Customers have indicated that to PMOC. The company is considering more advertising but higher precise for many types of lenses do not encourage them. PMOC's traditionally market share of about 3% is expected to decrease as its customers start to renovate their equipment.

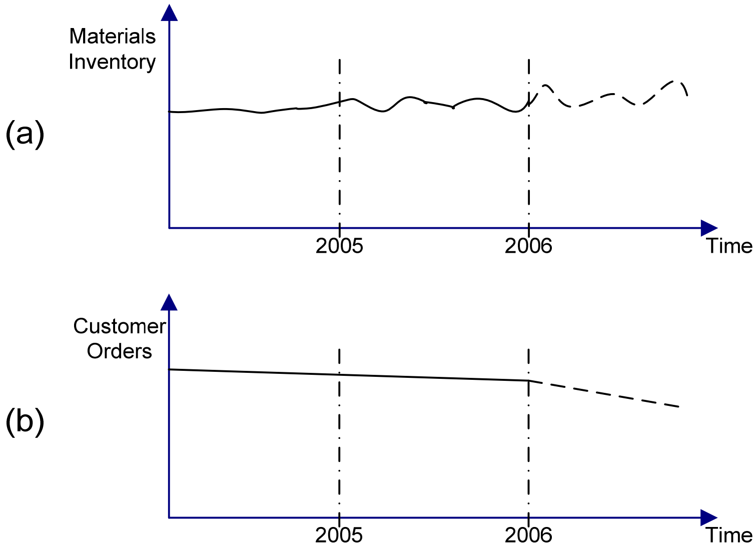


Figure 6.8 Increase in delivery delay contributes to decreasing customer orders – described by PMOC managers

Each of the business units modeled in SD could be modeled using the SMM. The task of the materials ordering and inventory management is regulating the inventory level by maintaining a level of materials on order and estimating the appropriate level of adjustment if inventory is different from its target level. The same regulation task is implemented in the production planning and shipping unit, which also includes the work in process inventory level. Figure 6-9 shows the materials ordering and inventory module and the production planning and work in process module. Together they represent the physical flow of materials from the supplier to the customer. These are two overlapping SMMs. The first is for raw materials inventory and ordering (left part of Figure 6-9) consists of the two stocks of Parts On Order and Parts Inventory, which are regulated by the flow rates of Parts Order Rate, Parts Arrival Rate and Production Start Rate in addition to the auxiliary variables used to estimated the necessary adjustments and the indicated parts order rate. The scheduled production rate from the production planning module (right part of Figure 6-9) is the input that drives the materials ordering section. Materials are ordered to meet the scheduled production and needed inventory adjustment.

The Production Start Rate is the rate at which materials are taken from the raw materials stock (Parts Inventory) to start processing (become work in process). This rate is the link to the production planning and work in process module, which is the second SMM in Figure 6-9 (right part). There are three rather than two stocks in this module. Two work-in-process (WIP) stocks are used to correspond to the PreForms and Presses departments. This production planning and WIP module regulates the WIP at the two departments to ensure smooth production rate and the availability of the final products in the Finished Product Inventory stock for shipping.

As an SMM, the WIP stocks are regulated through estimating the necessary adjustments to bring them to the equilibrium level if they are above or below that level. The Finished Goods Inventory carries the final product prior to shipping to customers. This module is derived by the customer order rate that is used to estimate the scheduled production rate. Scheduled production rate is exported to the materials ordering and inventory module. The level of raw materials inventory (Parts Inventory) is exported to the production planning and WIP module to use it to start processing. Production start rate is a function of the level of parts inventory as well as the available production capacity that is imported from the labor management module.

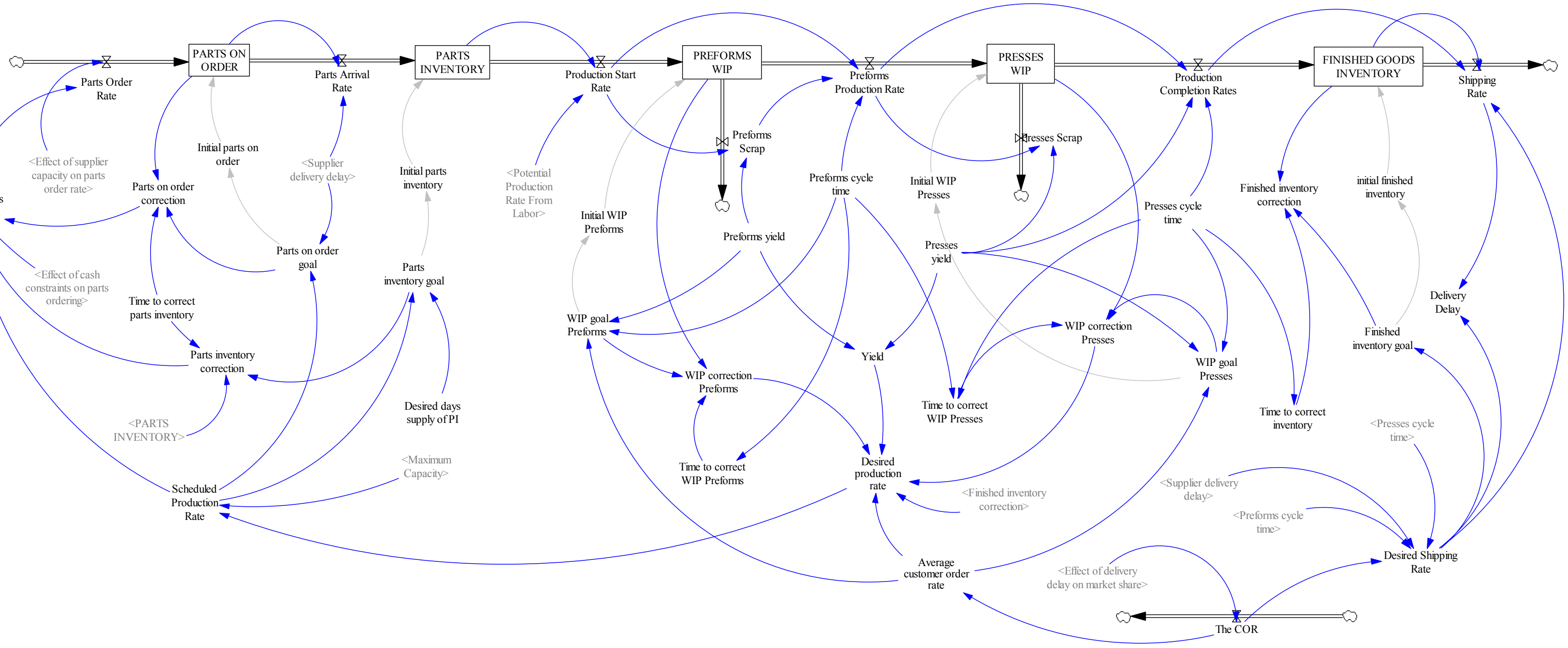


Figure 6.9 SD model of the internal supply chain of PMOC Inc.

This model consists of two overlapping SMM constructs. The first is materials ordering and inventory (PARTS ON ORDER and PARTS INVENTORY stocks). The second is production, work in process, and finished product inventory (PREFORMS WIP, PRESSES WIP, and FINISHED GOODS INVENTORY stocks)

Figure 6-10 shows the labor management module. Two stocks; Labor Being Recruited and Labor are regulated through four flow rates. This module uses the scheduled production rate from the production planning and WIP module to estimate the needed level of capacity including overtime when necessary. The module indicates the need to recruit new worker if scheduled production increase to justify that (and if financial resources support hiring). This is managed by using the needed capacity, available, and scheduled production rate to estimate the corrections to labor and labor being recruited stocks. This indicates the labor recruiting rate. Labor being recruited moves to become labor (get hired) after some hiring delay, according to the labor hiring rate. Labor then bay be fired or they leave voluntarily. The available production capacity form the labor module (regular and overtime capacity) restricts the production start rate at the production planning and WIP module.

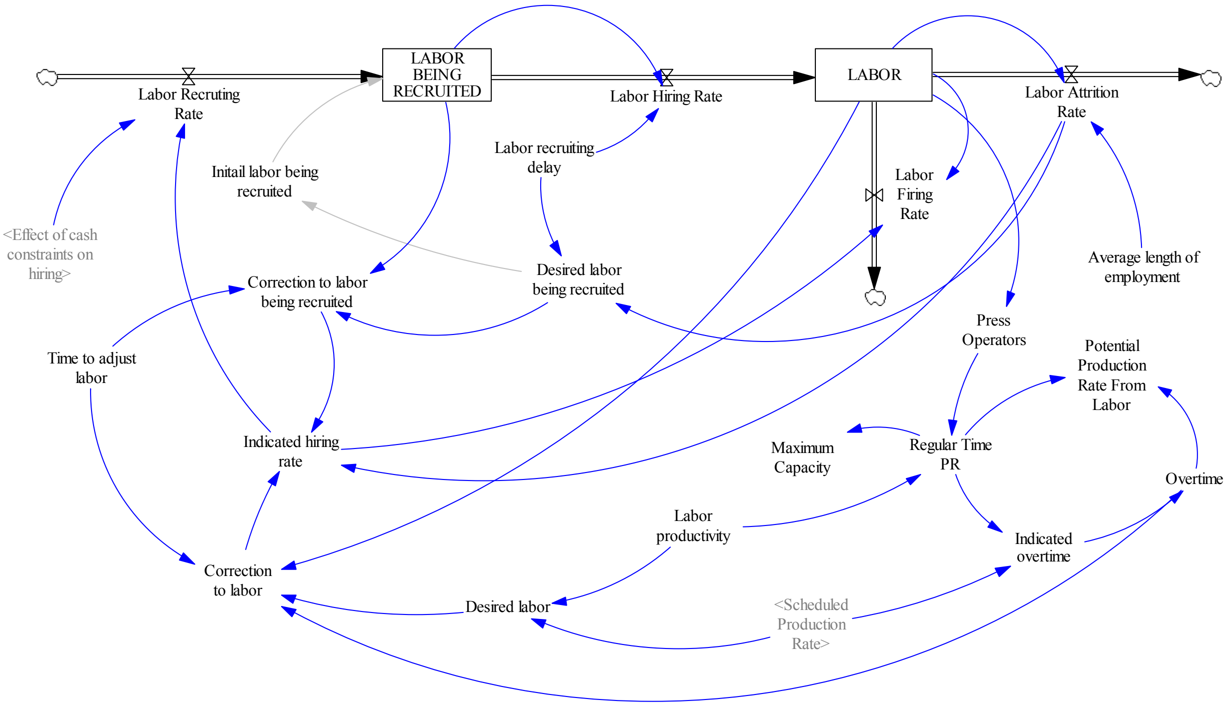
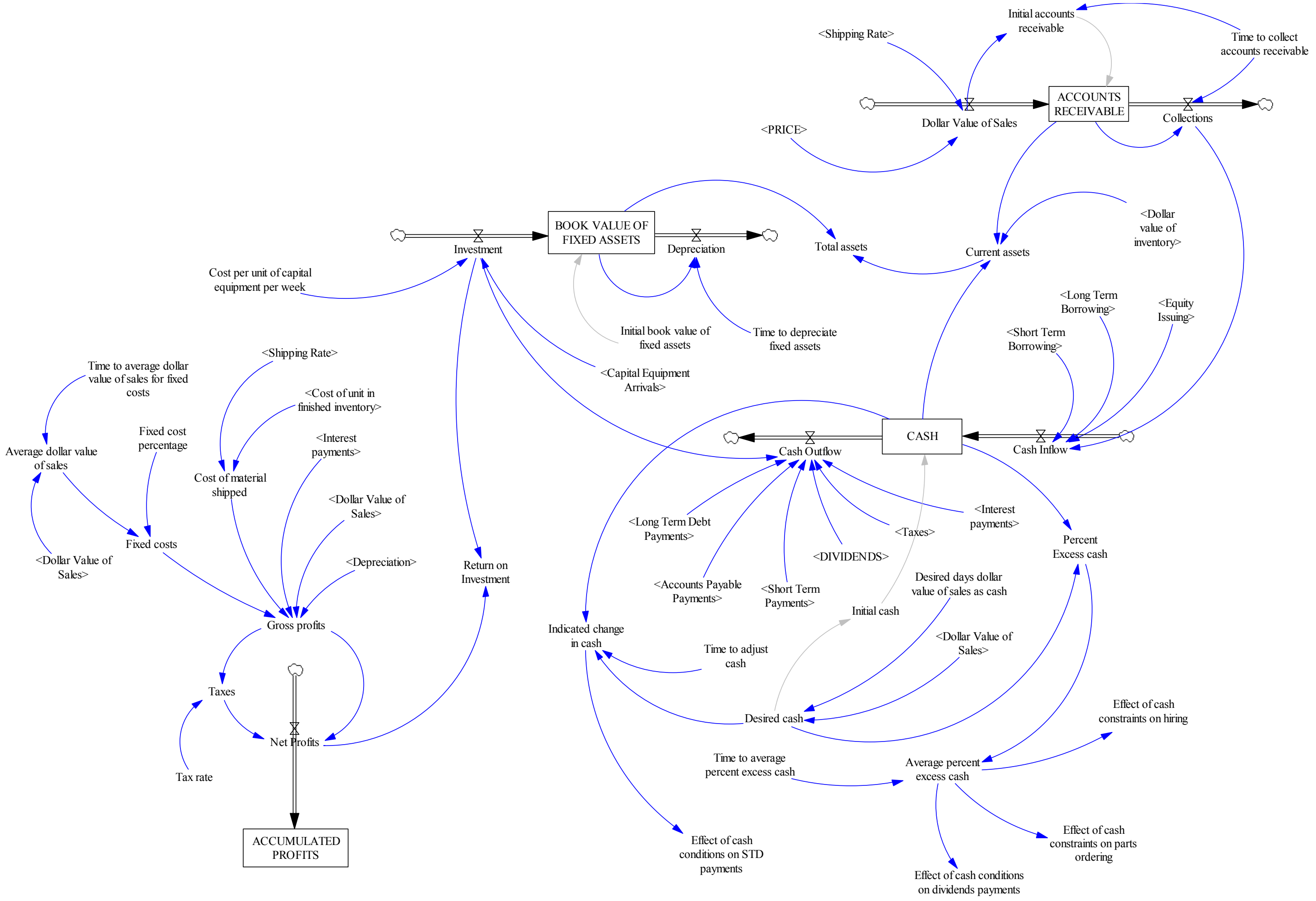


Figure 6.10 SD model of the labor management function of PMOC

The financial units are modeled in three segments: assets, liabilities, and equity (Figures 6-11 through 6-13) for the purpose of modeling process management. Elements of the finance and accounting model include the balance sheet, income statement, and the financial ratios. These are the tools used to monitor the financial performance of the firm and follow the assets and the liabilities. The assets are the accounts receivable, cash, book value of fixed assets, and the dollar value of inventory. Liabilities are the accounts payable, short term debt, long term debt, and equity expenses as well. The equity section includes the dividends, market share and stock price. The financial units were built using generic concepts (Seterman, 2000, Layneis, 1980) that were modified to represent the PMOC's practices and were accepted by PMOC's

CFO at that level. No data was permitted by the company for building these modules. Public reports on www.yahoo.com were visited and assumptions were made as needed. Appendix A includes complete listing of the mathematical formulation of all the SD modules.


Initial accounts receivable
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Dollar Value of Sales
Collections
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Investment
Depreciation
Total assets
Current assets
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Cost per unit of capital equipment per week
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Time to depreciate fixed assets
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Initial cash
Gross profits
Indicated change in cash
Time to adjust cash
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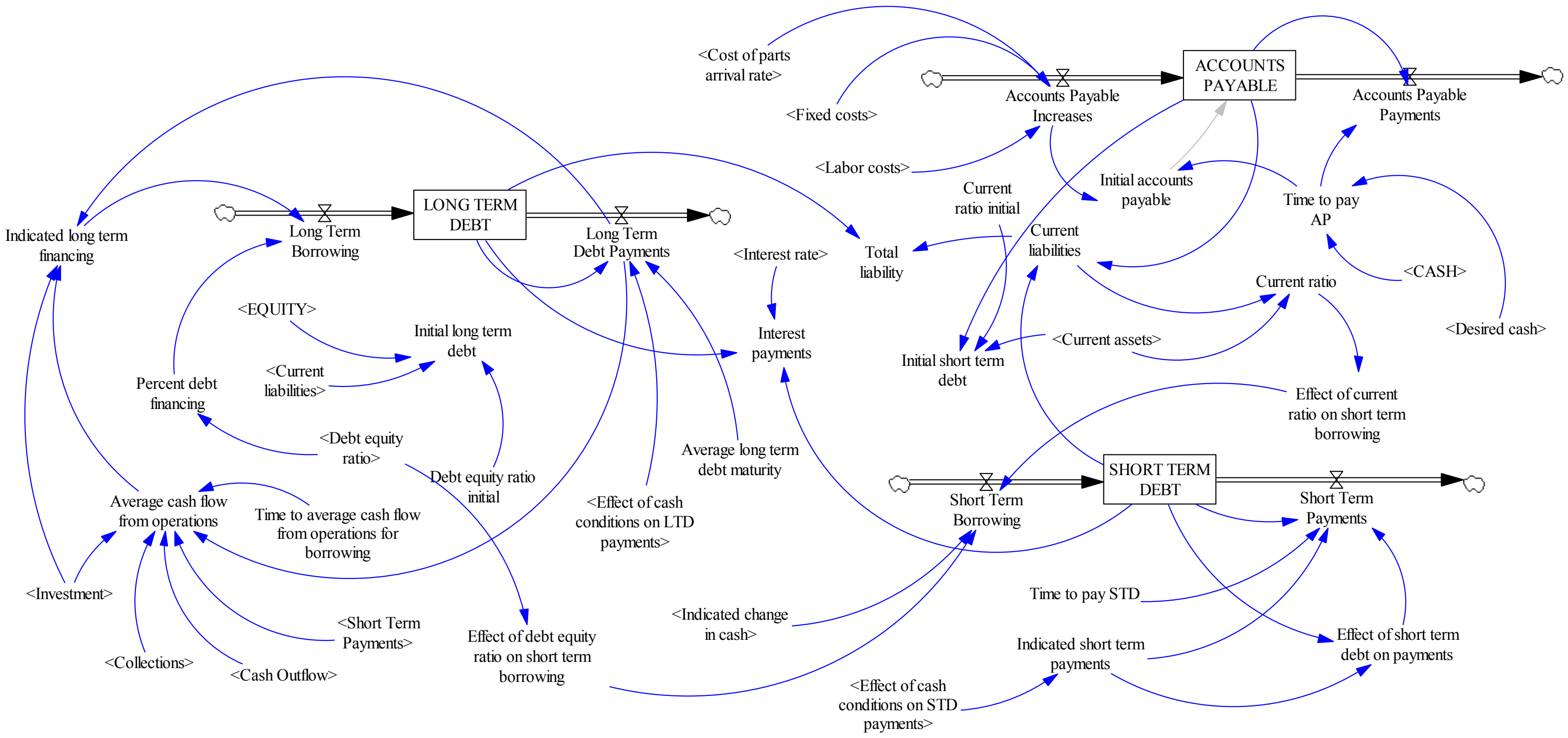
Taxes
Desired cash
Effect of cash constraints on hiring
Net Profits
Tax rate
Time to average percent excess cash
Average percent excess cash
ACCUMULATED PROFITS
Effect of cash conditions on STD payments
Effect of cash constraints on parts ordering
Effect of cash conditions on dividends payments

Figure 6.11 Assets SD module for PMOC

Main assets considered are the accounts receivable, cash, book value of fixed assets, and the dollar value of inventory. Cash is being regulated as the main stock of the SMM (See Appendix A)



<Cost of parts arrival rate>
<Fixed costs>
Accounts Payable Increases
ACCOUNTS PAYABLE
Accounts Payable Payments
<Labor costs>
Current ratio initial
Initial accounts payable
Time to pay AP
Indicated long term financing
Long Term Borrowing
LONG TERM DEBT
Long Term Debt Payments
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Total liability
Current liabilities
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Current ratio
<Desired cash>
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Initial long term debt
Interest payments
Initial short term debt
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<Current liabilities>
Percent debt financing
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Effect of current ratio on short term borrowing
Average long term debt maturity
Debt equity ratio initial
Average cash flow from operations
Time to average cash flow from operations for borrowing
<Effect of cash conditions on LTD payments>
SHORT TERM DEBT
Short Term Borrowing
Short Term Payments
<Investment>
Time to pay STD
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<Indicated change in cash>
Effect of debt equity ratio on short term borrowing
Indicated short term payments
Effect of short term debt on payments
<Collections>
<Cash Outflow>
<Effect of cash conditions on STD payments>

Figure 6.12 Liabilities SD module for PMOC

Short and long term debts and accounts payable are main forms of liabilities considered in the model. No physical flow of materials and standard financial formulations have been utilized in the model (See Appendix A).

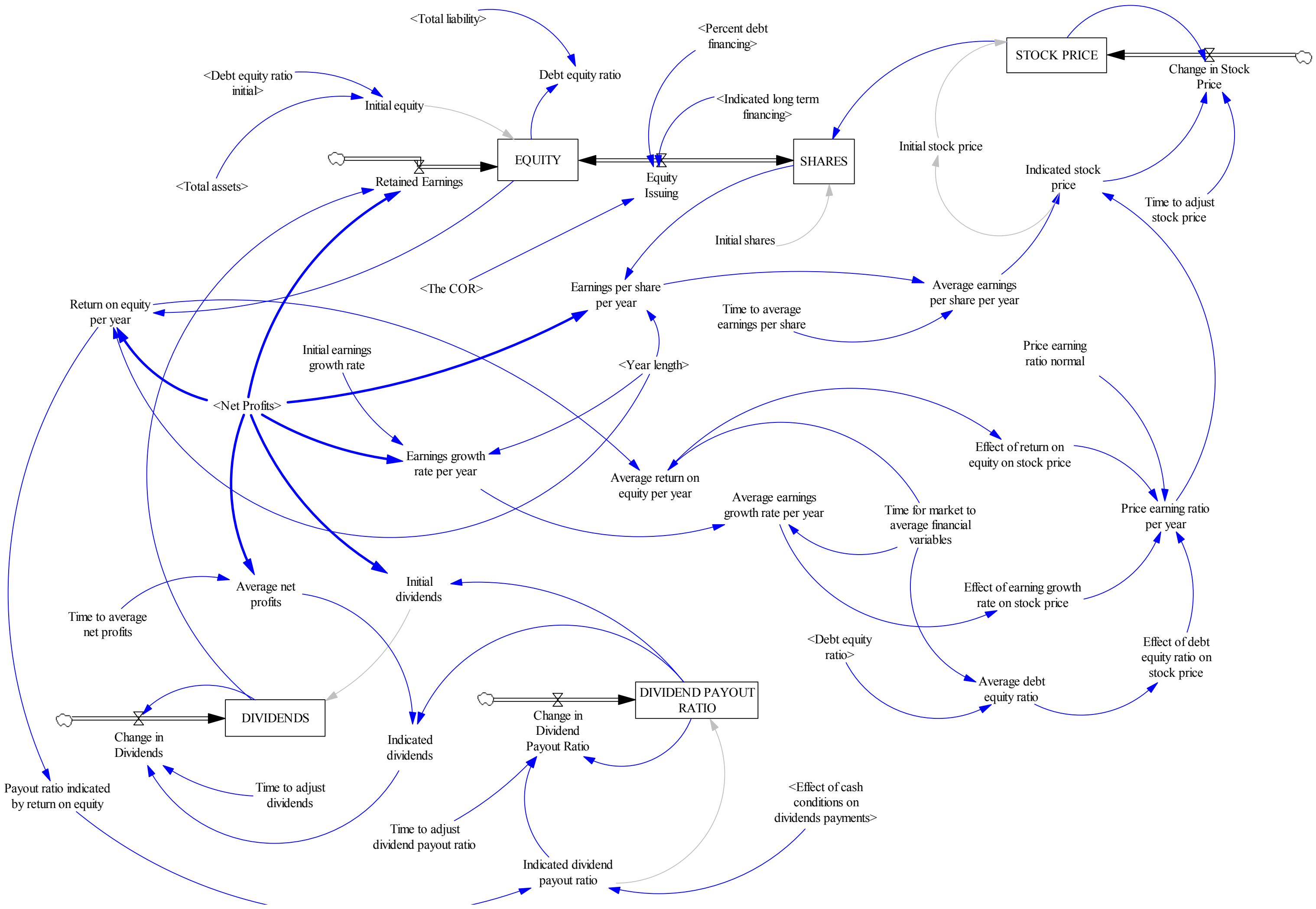

<Total liability>
<Percent debt financing>
STOCK PRICE
Change in Stock Price
<Debt equity ratio initial>
Debt equity ratio
Initial equity
<Indicated long term financing>
EQUITY
SHARES
Initial stock price
Retained Earnings
Equity Issuing
Indicated stock price
<Total assets>
Time to adjust stock price
Initial shares
<The COR>
Earnings per share per year
Average earnings per share per year
Return on equity per year
Time to average earnings per share
Price earning ratio normal
Initial earnings growth rate
<Year length>
<Net Profits>
Effect of return on equity on stock price
Earnings growth rate per year
Average return on equity per year
Average earnings growth rate per year
Time for market to average financial variables
Price earning ratio per year
Average net profits
Initial dividends
Effect of earning growth rate on stock price
Time to average net profits
<Debt equity ratio>
Effect of debt equity ratio on stock price
Average debt equity ratio
DIVIDENDS
DIVIDEND PAYOUT RATIO
Change in Dividends
Indicated dividends
Change in Dividend Payout Ratio
Payout ratio indicated by return on equity
Time to adjust dividends
<Effect of cash conditions on dividends payments>
Time to adjust dividend payout ratio
Indicated dividend payout ratio

Figure 6.13 Equity SD module of PMOC

PMOC is a public company. Standard financial ratios definitions have been utilized in this model (See Appendix A).

6.1.4 Building the DES modules

The PreForms and Presses departments were modeled in two separate DES models. The standard DES modeling approach (Chung, 2004; Law and Kelton, 2000) was followed:

1. Data collection and preparation
2. Model definition and assumptions
3. Model building
4. Verification and validation

Needed data for building the modules were the processing times at each machine, batch size at the PreForms department machines, daily material usage and production and scrap rates, the levels of work in process, workforce configuration and work schedule. At the Presses department, presses and numerically controlled and processing times data were collected based on computer records. Down times were, however, not explicit and were assumed included in the processing times. At the PreForms department, processing times and batch size data were collected by observation and based on inputs from operators and production manager. No track records are available at PreForms. Daily production and scrapped units were based on data recorded by the operators after the completion of each processing step. These were also used to estimate the levels of work in processing.

Customer order rate was considered fixed at the average level of 25,000 per month. It was also assumed that PreForms equipment are reliable and not subject to down time because of failure. Any needed repairs were observed to be negligible compared to processing times. The different types of lenses were pooled and the modules were built to produce a single type. Data was fitted to accommodate this simplifying assumption. Transportation times through the departments were ignored. We also assumed that all air presses are typical in terms in processing times and reliability and the same was assumed for the Ni presses.

Theoretical distributions were fit to the data to be used in the simulations. Goodness of fit tests were acceptable at 95% confidence level. All data and simplification assumptions were reviewed and approved by the production manager at each department and face validity considering the process flow implemented in the modules was achieved. Statistical model validation is discussed later in this chapter.

Figures 6-14 and 6-15 depict the process flow at the PreForms and Presses department as implemented in the simulation modules. Two modules were built as each department has a production manager and its own workforce. No resources (personnel or equipment) are shared between the two departments.

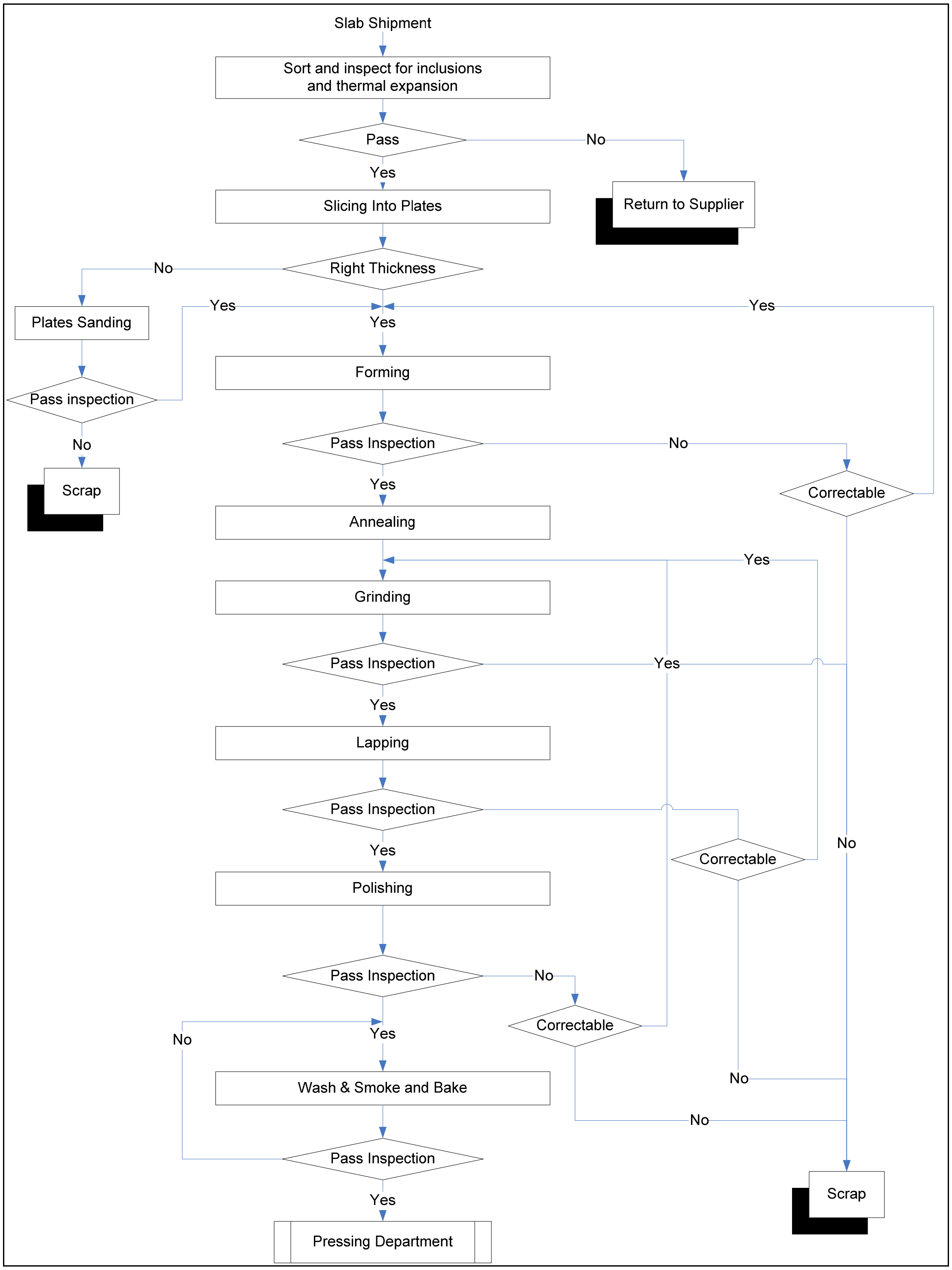


Figure 6.14 PreForms department process flow

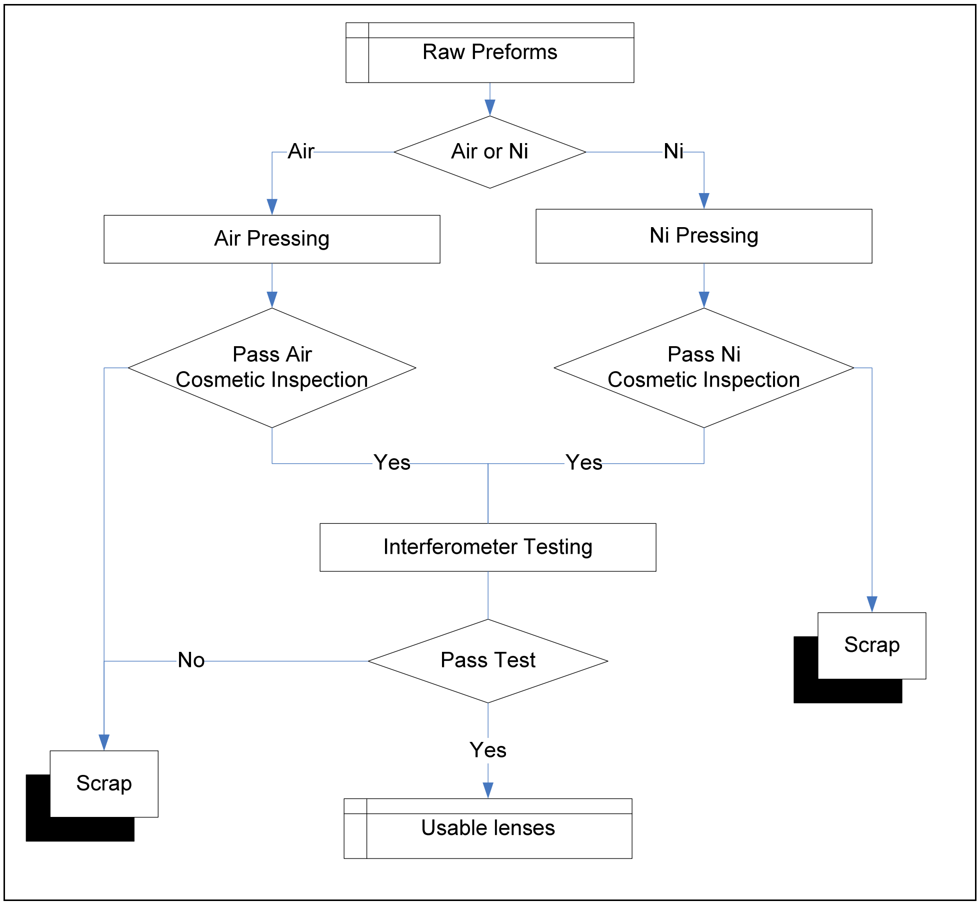


Figure 6.15 Presses department process flow

6.1.5 Defining the SDDES modules

Modularizing starts with defining the sets of inputs and outputs of each module. The synchronization settings are then defined and the modules are expressed in terms of the SDDES formalism. First the SDDES modules are defined and formalized in the following sections. Table 6-2 lists the abbreviations for the variables mentioned in the modularization process in this section. The supplier module is mentioned but not modeled.

Table 6.2 Abbreviations of module titles and variables

Modules:

	Module	Abbreviation	Definition
1	Assets	ASST	The SD assets management module
2	Labor	LAB	The SD labor management module
3	Liabilities	LIAB	The SD liabilities management modules
4	Materials Inventory and Ordering	MIO	The SD raw materials management module
5	PreForms	PREF	The DES Preforms Department module
6	Pressses	PRES	The DES Presses Department module
7	Production Planning and Work in Process	PWS	The SD production planning , work in process, product inventory and shipping module
8	Supplier	SUP	The SD raw materials supplier module

Variables:

	Variable	Abbreviation	Use and Location
1	Annealing Load.Queue	ANLQ	Annealing process queue Preforms department - PREF
2	Assemble For Slicing.Queue	ASLQ	Slicing process queue in Preforms department - PREF
3	Batch For Grinding.Queue	BGRQ	Grinding process queue Preforms department - PREF
4	Batch For Lapping.Queue	BLPQ	Lapping process queue in Preforms department - PREF
5	Batch For Polishing.Queue	BPLQ	Polishing process queue in Preforms department - PREF
6	Batch For Smoke and Bake.Queue	BSBQ	Smoke and bake process in Preforms department - PREF
7	Batch For Washing.Queue	BWSQ	Washing process in Preforms department - PREF
8	Batch To Cool Off.Queue	BCOQ	Cooling off process in Preforms department - PREF
9	Cost of Labor Turnover	LTO	Total cost of labor turnover - LIAB
10	Cost of Parts Arrival Rate	CPAR	Contributes to estimating the dollar value of inventory - ASST
11	Days Supply of Parts Inventory	DSPI	Available supply of materials considering scheduled production rate - MIO
12	Desired Labor	DL	Needed number of workers considering labor productivity and scheduled production - LAB
13	Dollar Value of Inventory	DVI	Total value of all inventories – ASST
14	Dollar Value of Sales	DVS	The inflow rate to the accounts receivable stock – ASST
15	Effect of Cash Constraints on Hiring	ECCH	The financial limit on hiring new labor - ASST
16	Effect of Cash Constraints on Parts Ordering	ECCPO	The financial limits on ordering materials - ASST
17	Effect of Supplier Capacity on Parts Ordering	ESCPO	Constraint of supplier capability on ordering - MIO
18	Finished Goods Inventory	FGI	Level of finished product units – PWS
19	Hold For Air.Queue	HAQ	Air pressing section queue in Presses department - PRES

	Variable	Abbreviation	Use and Location
20	Hold For NI.Queue	HNIQ	Nitrogen pressing section queue in Presses department - PRES
21	Indicated Overtime	IOT	Estimated overtime needed considering scheduling production and current regular capacity - LAB
22	Indicated Parts Order Rate	IPOR	Estimated materials ordering considering inventory adjustments and scheduled production - MIO
23	Initial WIP Preforms	IWIPF	Starting value of the work-in-process at the Preforms processes - PWS
24	Initial WIP Presses	IWIPS	Starting value of the work-in-process at the Presses processes - PWS
25	Interferometer Tests 35.Queue	IT35Q	Interferometer testing unit queue for type 35 product in Presses - PRES
26	Interferometer Tests 37.Queue	IT37Q	Interferometer testing unit queue for type 37 product in Presses - PRES
27	Inspection 35.Queue	35INSQ	Inspection for type 35 product queue – PRES
28	Inspection 37.Queue	37INSQ	Inspection for type 37 product queue – PRES
29	Issued Preforms	IPREF	Output of the Preforms department in the form of semi-finished lenses - PREF
30	Labor	LBR	Labor stock level - LAB
31	Labor Costs	LCT	Total cost of current labor level - LIAB
32	Labor Firing Rate	LFR	Rate of firing of current workers - LAB
33	Labor Hiring Rate	LHR	Rate of joining the current labor - LAB
34	Labor Recruiting Rate	LRR	Rate of opening new labor positions – LAB
35	Maximum Capacity	MXC	Limit of regular plus overtime capacity - LAB
36	Molds For Oven.Queue	MOQ	Prefom oven process queue in Preforms department - PREF
37	Overtime Preforms	OTPF	The required level of overtime at Preforms - LAB
38	Overtime Presses	OTPS	The required level of overtime at Presses - LAB
39	Parts Arrival Rare	PAR	Inflow rate of materials into materials inventory - MIO
40	Parts Inventory	PI	Raw materials inventory stock level – MIO
41	Parts Inventory Goal	PIG	Desirable level of raw materials inventory for smooth production – MIO
42	Parts On Order	POO	Level of raw materials in the supply line – MIO
43	Parts On Order Goal	POOG	Desirable level of raw materials in the supply line considering supply performance and usage rate – MIO
44	Parts Order Rate	POR	Rate of ordering raw materials from the supplier – MIO
45	Potential Production from Labor	PPL	Current capacity considered scheduled overtime - LAB
46			
47	Preforms Overtime	PFOT	Scale factor to set overtime in Preforms - PREF
48	Presses Overtime	PSOT	Scale factor to set overtime in Presses - PREF
49	Shipment Size	SHSZ	Amount of materials released into Preforms – PREF
50	Preforms Production Rate	PFPR	Estimated production rate at the Preforms Department – PREF

	Variable	Abbreviation	Use and Location
51	Preforms Scrap Rate	PFSC	Estimated scrap rate at the Preforms Department - PREF
52	Preforms WIP	PFWIP	Estimated level of work-in-process at the Preforms Department - PREF
53	Presses Production Rate	PSPR	Estimated production rate at the Presses Department – PRES
54	Presses Scrap Rate	PSSC	Estimated scrap rate at the Presses Department – PREF
55	Presses WIP	PSWIP	Estimated level of work-in-process at the Presses Department - PRES
56	Production Completion Rate	PCR	Rate of finalizing end product, map to Presses Production Rate - PWS
57	Production Start Rate	PSR	Rate of starting processing raw materials – PWS
58	Scheduled Production Rate	SPR	Decided production rate considering demand and capacity – PWS
59	Shipment Size	SHSZ	Amount of materials released into Preforms – PREF
60	Shipping Rate	SHR	Rate of shipping products to customers - PWS
61	Supplier Capacity	SC	Capacity of materials supplier to meet orders - SUP
62	Supplier Delivery Delay	SDD	Delay before ordered materials are received - SUP
63	Supplier Demand Rate	SDR	Customer ordering at the supplier end - SUP
64	Value Added in Process	VAP	Average cost share in the product unit - ASST
65	WIP Goal Preforms	WPGF	Estimated desired level of Preforms WIP - PWS
66	WIP Goal Presses	WPGS	Estimated desired level of Presses WIP - PWS
67	WIP Inventory	WIP	Total level of work-in-process inventory – PWS
68	Yield	YLD	Output production as percentage of released materials - PWS
69	Arriving Preformes Shipment	APS	Arriving materials at Presses - PRES

6.1.5.1 The MIO module

The function of the MIO is managing the raw materials inventory and the materials ordering rate. A simplified version of the module is shown in Figure 6-16. The Production Start Rate on the figure is in fact an input from the PWS module. The rate is shown here for clarity. The MIO consists of the Parts Inventory stock, which is the main stock to regulate and the Parts On Order stock, which is the supply line for Parts Inventory. Materials are ordered at the Parts

Order Rate, arrive at the Parts Arrival Rate, and they are used at the Production Start Rate. To maintain the required materials inventory for smooth production, the Indicated Parts Order Rate includes the Parts Inventory and Parts On Order Corrections to keep the stock levels at the desired values. Material ordering is planned based on the Scheduled Production Rate from the PWS module. The Production Start Rate is an input from the PWS module and is determined by the usage of materials in PWS in addition to the needed adjustments to the stocks in that module. Financial constraints should also be considered in ordering materials. Besides, the supplier performance in terms of capacity and delivery delay is necessary to estimate the materials arrival rate and the limit on the order rate.

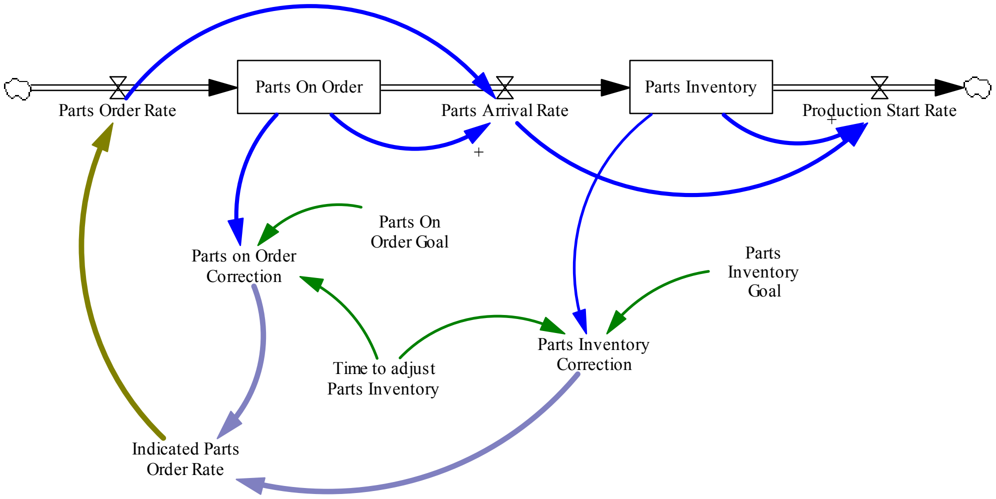


Figure 6.16 Simplified view of the SD MIO module

In the SDDES formalism format, the MIO module is specified as given below.

$$MIO = (SD, X_{MIO}, Y_{MIO}, P_{MIO}, CONT)$$

The sets of inputs and outputs of MIO, referred to X_{MIO} and Y_{MIO} respectively are presented in Table 6-3. MIO interacts with SD modules only and no format or timing requirements necessary.

Table 6.3 Inputs and outputs of the MIO

X_{MIO}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
MIO	SPR	PWS	OP_PWS_01	IP_MIO_01	DSPI	CONT	NONE
					IPOR	CONT	NONE
					PIG	CONT	NONE
					POOG	CONT	NONE
MIO	PSR	PWS	OP_PWS_02	IP_MIO_02	PI	CONT	NONE
MIO	SDD	SUP	OP_SUP_01	IP_MIO_03	PAR	CONT	NONE
					POOG	CONT	NONE
MIO	SC	SUP	OP_SUP_02	IP_MIO_04	ESCPO	CONT	NONE
MIO	ECCPO	ASST	OP_ASST_01	IP_MIO_05	IPOR	CONT	NONE
Y_{MIO}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
MIO	OP_MIO_01	PI	PWS	IP_PWS_01	PSR	CONT	NONE
			ASST	IP_ASST_01	DVI	CONT	NONE
MIO	OP_MIO_02	POR	SUP	IP_SUP_01	SDR	CONT	NONE
MIO	OP_MIO_03	PAR	LIAB	IP_LIAB_01	CPAR	CONT	NONE

6.1.5.2 The PWS module

The PWS module represents the conversion of raw materials into work-in-process (WIP), and work-in-process into finished products. A simplified version of the module is shown in Figure 6-17. There are two work-in-process stocks to correspond to the PreForms and Presses departments at the shop floor level. Customer order is located in this module and is assumed fixed; consistent with PMOC that has fairly fixed customer base and demand. Customer order rate is 25,000 units/month, which is the average monthly demand at PMO Inc. As shown in Figure 6-17, the Scheduled Production Rate accounts for the demand and the corrections to the inventory stocks. Production Start Rate is determined accordingly and based on the available raw materials inventory from MIO and on the available capacity (regular and overtime) from the Labor module.

PWS also interacts with the PreForms and Presses. Preforms provides accurate estimates for the Preforms Production Rate, Preforms work in process (WIP), and Preforms Scrap Rate. Likewise, Production Completion Rate, Presses WIP, and Presses Scrap Rate can be imported from the Presses module. The DES modules need to import the initial level of WIP from the PWS so they start at the steady state and consistent with the SD modules configuration. Several locations in the PreForms and Presses use the initial WIP stock levels form PWS. The DES modules then update The WIP levels as production proceeds. Production rates and scrap rates are also provided by the DES modules.

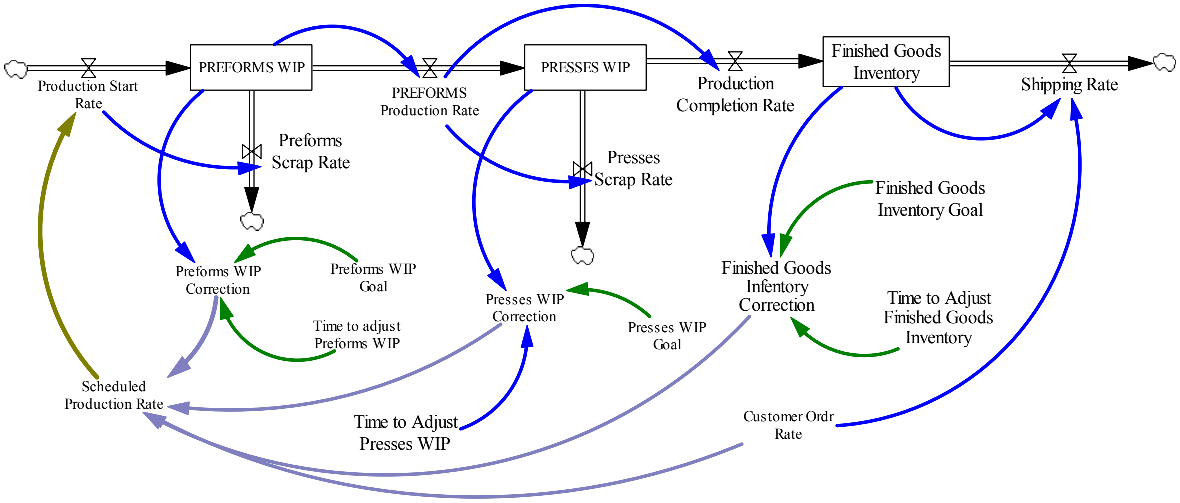


Figure 6.17 Simplified version of the SD PWS module

Based on the above description of the interactions between PWS and the other SD and DES modules, the inputs and outputs of PWS are defined in Table 6-4 in accordance with the SDDES formalism. The SDDES formalism representation of the PWS module is given below.

$$PWS = (SD, X_{PWS}, Y_{PWS}, P_{PWS}, CONT)$$

PWS interacts with SD and two DES modules. Exchanging data between PWS and each of PREF and PRES is carried out at the end of each DES segment. In Table 6-4, it is indicated that data from or to DES and/or SD modules are imported and exported via the SDDES controller at the end of each DES run segment. The TB_END and TB_START values for the data exchange timing indicate that data is needed at the start or end of the run segment. Formatting specifications for the exchanged variables in Table 6-4 are explained below:

Table 6.4 Inputs and outputs of the PWS

X_{PWS}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
PWS	PI	MIO	OP_MIO_01	IP_PWS_01	PSR	CONT	NONE
PWS	PPL	LAB	OP_LAB_01	IP_PWS_02	SPR	CONT	NONE
PWS	MXC	LAB	OP_LAB_02	IP_PWS_03	PSR	CONT	NONE
PWS	PFPR	PREF	OP_PREF_01	IP_PWS_04	PFPR	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PWS	PFSC	PREF	OP_PREF_02	IP_PWS_05	YLD	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PWS	PFWIP	PREF	OP_PREF_03	IP_PWS_06	WIP	TB_END	TIME_PERSIST_DES_TB >> TB_END_READ
PWS	PSPR	PRES	OP_PRES_01	IP_PWS_07	PCR	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PWS	PFSC	PRES	OP_PRES_02	IP_PWS_08	YLD	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PWS	PFWIP	PRES	OP_PRES_03	IP_PWS_09	WIP	TB_END	TIME_PERSIST_DES_TB >> TB_END_READ
Y_{PWS}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
PWS	OP_PWS_01	SPR	MIO	IP_MIO_01	DSPI	CONT	NONE
				IP_MIO_01	IPOR	CONT	NONE
				IP_MIO_01	PIG	CONT	NONE
				IP_MIO_01	POOG	CONT	NONE
			LAB	IP_LAB_01	DL	CONT	NONE
				IP_LAB_01	IOT	CONT	NONE
PWS	OP_PWS_02	PSR	MIO	IP_MIO_02	PI	CONT	NONE
			PREF	IP_PREF_02	SHSZ	TB_START	FLOW_SD >> SCALE_TO_DES_EQUIV_RATE
PWS	OP_PWS_03	IWIPF	PREF	IP_PREF_01	ANLQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PREF_01	ASLQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER

Y_{PWS}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
				IP_PREF_01	BGRQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PREF_01	BLPQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PREF_01	BPLQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PREF_01	BSBQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PREF_01	BWSQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PREF_01	MOQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PREF_01	BCOQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
PWS	OP_PWS_04	IWIPS	PRES	IP_PRES_01	HAQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PRES_01	HNIQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PRES_01	IT35Q	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PRES_01	IT37Q	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PRES_01	35INSQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
				IP_PRES_01	37INSQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
PWS	OP_PWS_05	WIP	ASST	IP_ASST_02	DVI	CONT	NONE
PWS	OP_PWS_06	FGI	ASST	IP_ASST_03	DVI	CONT	NONE
PWS	OP_PWS_07	SR	ASST	IP_ASST_04	DVS	CONT	NONE

- `OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE:` Input is DES observational random variable, collected over TB. Map to SD flow rate given TB
- `TIME_PERSIST_DES_TB >> TB_END_READ:` Input is DES time-persistent random variable. Use at TB end.
- `FLOW_SD >> SCALE_TO_DES_EQUIV_RATE:` Input is SD flow rate. Adjust to TB as entities arrival at Destination.
- `STOCK_SD >> START_UP_READ:` Input is SD stock level. Read at run startup.

6.1.5.3 The LAB Module

The LAB module represents the labor management function. As shown in Figure 6-18, the current level of workforce (Labor stock) is the main stock being regulated. It is increased by the Labor Hiring Rate and decreased by the firing (if used) and voluntary attrition. Management estimates the needed correction to labor level based on the active attrition rates considering the desired labor level, which is decided based on inputs from the production management and financial units. Management seek to hire new labor at the labor recruiting rate. Labor in the process of training and completing paper work are represented by the Labor being Recruited stock. Corrections to the Labor and Labor Being Recruited provide the estimates for the indicated hiring rate, which is also restricted by the financial constraints. At this module also and based on the scheduled production, the level of overtime is estimated to meet the schedule. Available capacity (regular and overtime) is the limit over the production rate at the PWS module.

The LAB module interacts with the PWS and Liabilities modules. It uses the scheduled production rate from PWS to estimate the needed overtime and desired labor level and sets the limits over the feasible production rate at the PWS. Hiring and attrition are restricted by the financial constraints. The current labor level is an input to the liabilities module to estimate the cost of labor turn over and production expenses. Table 6-5 presents the sets of inputs and outputs for the LAB module along with the rest of its formalism information.

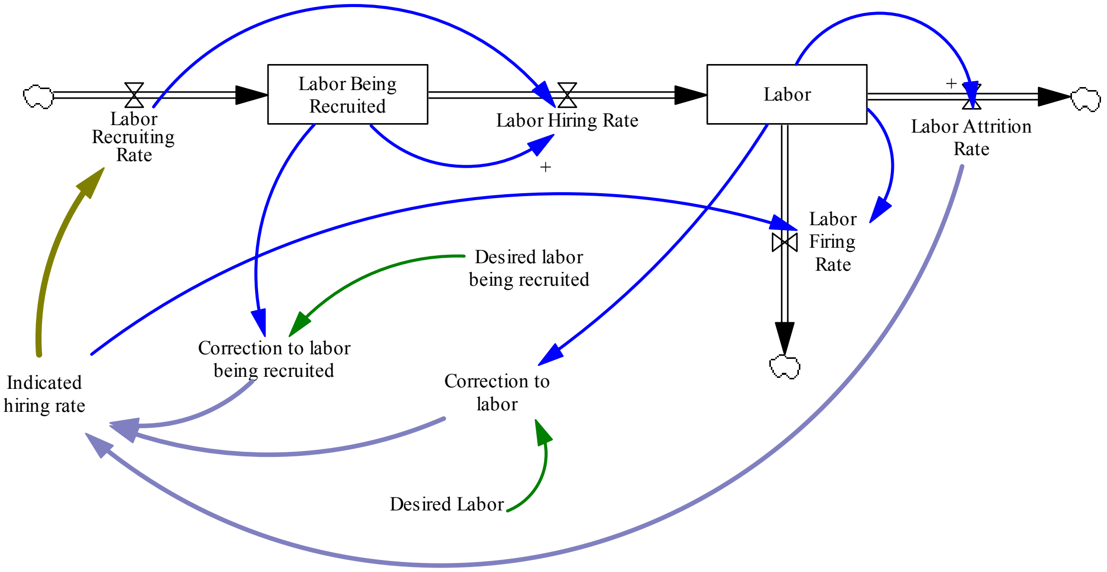


Figure 6.18 Simplified version of the SD LAB module

The LAB model is expressed in terms of the SDDES formalism as follows.

$$LAB = (SD, X_{LAB}, Y_{LAB}, P_{LAB}, CONT)$$

Table 6.5 Inputs and outputs of the SD LAB module

X_{MIO}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
LAB	SPR	PWS	OP_PWS_01	IP_LAB_01	DL	CONT	NONE
					IOT	CONT	NONE
LAB	ECCH	ASST	OP_ASST_01	IP_LAB_02	LRR	CONT	NONE
Y_{MIO}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
LAB	OP_LAB_01	PPL	PWS	IP_PWS_02	SPR	CONT	NONE
LAB	OP_LAB_02	MXC	PWS	IP_PWS_03	PSR	CONT	NONE
LAB	OP_LAB_03	LBR	LIAB	IP_LIAB_02	LCT	CONT	NONE
					VAP	CONT	NONE
LAB	OP_LAB_04	LHR	LIAB	IP_LIAB_03	CLT	CONT	NONE
LAB	OP_LAB_05	LFR	LIAB	IP_LIAB_04	CLT	CONT	NONE
LAB	OP_LAB_06	OTPF	PREF	IP_PREF_03	PFOT	TB_START	NONE
LAB	OP_LAB_07	OTPS	PRES	IP_PRES_03	PSOT	TB_START	NONE

6.1.5.4 The PREF module

The PREF module interacts with the PWS module and the PRES module. PREF is driven by the production start rate from PWS. Production start rate (is the estimated rate at which raw materials start processing. It represents the implementation of the scheduled production. PREF also receives the level of overtime from the Labor module, should overtime be needed. The feedback from PREF is its production rate, its scrap rate, level of work in process, and process cycle time. This feedback information from PREF is collected at the end of the run segment. Updated values of production start rate and overtime are calculated by PWS based on that. The production start rate is converted into arrival rate of materials at PREF. Overtime needs no formatting. Production rate and scrap rate from PREF are observational data (number of units that finished processing and number of units that were scrapped during the run segment) and they are converted into equivalent rate quantities over the run segment duration and then scaled to the SD base time unit before they can be used in PWS.

PREF module is the source of materials for PRES. Semi finished lenses (the preforms) from PREF are the materials for PRES. Preforms, observation data in PREF, are issued daily to PRES. No formatting is needed to use the PREF production in PRES. PREF module is expressed as a SDDES module as follows:

$$PREF = (DES, X_{PREF}, Y_{PREF}, P_{PREF}, TB)$$

The sets of inputs and outputs of PREF are given in Table 16-5. The TB_END and TB_START values for the data exchange timing indicate data needed at start or end of the run segment. Formatting specifications are explained below.

- `STOCK_SD >> SCALE_TO_DES_USER:` Input variable is based on an SD stock variable and should be scaled to initialize the DES user variable.
- `FLOW_SD >> SCALE_TO_DES_EQUIV_RATE:` Input variable is based on an SD flow rate variable and should be scaled to TB as DES entities creation rate.
- `OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE:` Input variable is based on observational data from DES module that was collected over the TB duration. This data should be converted into a rate variable over TB to be usable in the SD module.
- `TIME_PERSIST_DES_TB >> TB_END_READ:` Input variable is based on time-persistent data from DES module. The TB-end value is usable in the SD module.

Table 6.6 Inputs and outputs for the PREF module

X_{PREF}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
PREF	IWIPF	PWS	OP_PWS_03	IP_PREF_01	ANLQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					ASLQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					BGRQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					BLPQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					BPLQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					BSBQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					BWSQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					MOQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					BCOQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
PERF	PSR	PWS	OP_PWS_02	IP_PREF_02	SHSZ	TB_START	FLOW_SD >> SCALE_TO_DES_EQUIV_RATE
PREF	OTPF	LAB	OP_LAB_01	IP_PREF_03	PFOT	TB_START	NONE

Y_{PREF}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
PREF	OP_PREF_01	PFPR	PWS	IP_PWS_04	PFPR	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PREF	OP_PREF_02	PFSC	PWS	IP_PWS_05	YLD	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PREF	OP_PREF_03	PFWIP	PWS	IP_PWS_06	WIP	TB_END	TIME_PERSIST_DES_TB >> TB_END_READ
PREF	OP_PREF_04	IPREF	PRES	IP_PRES_02	APS	TB_START	NONE

6.1.5.5 The PRES module

The PREF interacts with the PREF module to get raw materials. It also needs to be initialized at the start of the SDDES simulation run. Initialization involves initial work in process level from the PWS module. It also uses the overtime information from the LAB module. Its outputs are its production rate, scrap rate, level of work in process, cycle time. These outputs are exported to the PWS module. The PRES module is described in SDDES formalism format as given below.

$$PRES = (DES, X_{PRES}, Y_{PRES}, P_{PRES}, TB)$$

The sets of inputs and outputs are listed in Table 6-6. The TB_END and TB_START values for the data exchange timing indicate that data is needed at start or end of the run segment. Formatting specifications are explained below.

- `STOCK_SD >> SCALE_TO_DES_USER:` Input variable is based on an SD stock variable and should be scaled to initialize the DES user variable.
- `OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE:` Input variable is based on observational data from DES module that was collected over the TB duration. This data should be converted into a rate variable over TB to be usable in the SD module.
- `TIME_PERSIST_DES_TB >> TB_END_READ:` Input variable is based on time-persistent data from DES module. The TB-end value is usable in the SD module.

Table 6.7 Inputs and outputs for the PRES module

X_{PRES}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
PRES	IWIPS	PWS	OP_PWS_04	IP_PRES_01	HAQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					HNIQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					IT35Q	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					IT37Q	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					35INSQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
					37INSQ	STARTUP	STOCK_SD >> SCALE_TO_DES_USER
PRES	IPREF	PREF	OP_PREF_04	IP_PRES_02	APS	TB_START	NONE
PRES	OTPS	LAB	OP_LAB_01	IP_PRES_03	PSOT	TB_START	NONE

Y_{PRES}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
PRES	OP_PRES_01	PSPR	PWS	IP_PWS_07	PCR	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PRES	OP_PRES_02	PFSC	PWS	IP_PWS_08	YLD	TB_END	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
PRES	OP_PRES_03	PFWIP	PWS	IP_PWS_09	WIP	TB_END	TIME_PERSIST_DES_TB >> TB_END_READ

6.1.6 DES modules run segmentation and resumption

The implementation of the resumption algorithm provided very good approximation to maintain the state of the DES modules between the segments. Production rate at the Presses department at PMOC is scheduled weekly for the daily production size. Press operators retrieve materials from the PreForms department at the beginning of each work day for the stated production of the day. Schedule is revised based on the performance. The PREF and PRES modules were thus configured to run for one-day segments to represent the actual work practices. Each one-day segment is a complete DES run. The output from each PRES segment at day k is the input to the PRES segment at day k+1.

We tested the segmented DES modules in comparison to the original non-segment modules for both PREF and PRES. The PREF module was run for a period of two months without segmentation and was then run after implementing the resumption algorithm and segmenting its run into one-day segments. In both cases the module received fixed production start rate value from PWS to create the raw materials. Daily production rate, scrap, and WIP were observed in the two cases. The two data samples (large sample size of 50) generated by the two module versions were tested for the difference between the means. The null hypothesis was that the two sample means are equal. Variances were not assumed equal. The test results showed no sufficient evidences (at 95% confidence level) to suggest that the observed measures were different when using segmented DES module from their values when using the original non-segmented DES model. Similar statistical testes were done for the PRES modules. Appendix B presents the test results for the two modules.

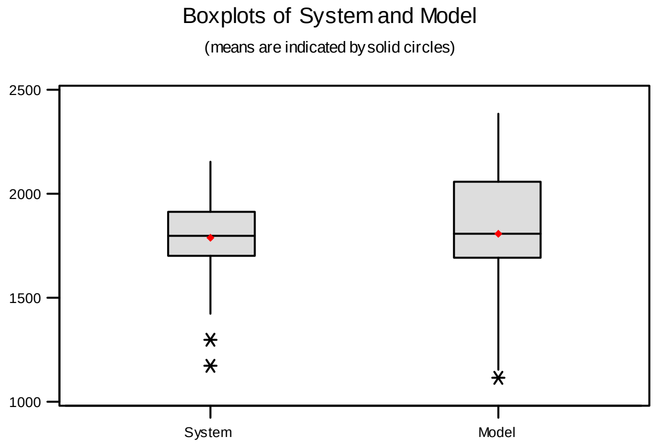
6.1.7 SDDES model validation

The SDDES model was validated at the face validity and data validity levels. The SD and DES modules were tested for face validity in a cyclic model review process with the production managers of the PreForms and Presses departments and with the senior managers who participated in the development of the SD modules. The DES modules were also reviewed with the operators at the two departments as some data assumptions (processing times, batch sizes, loading/unloading times, and rejection rates at the PreForms department in particular) were made based on their inputs. The objective of the face validity process was to confirm that the modules satisfactorily captured the system structure for the units they modeled and represent their actual behaviors. Face validity establishes the starting level of confidence in the SDDES model and points out the areas needing enhancement or corrections. Yet face validity is not sufficient to consider the model valid. The model validity decision is made based on data validation by comparing its output data to the actual system data using statistical techniques.

Data validation was performed at the module level and at the whole SDDES model level. It involved statistical comparisons of the model-generated data and the system data. The primary measures of performance were the production and scrap rates and the level of work-in-process. Data generated by the SDDES model were used for testing. Using a large sample size (50) and making no assumption about the variances of the SDDES model or system data, the two sample t-test of the difference between means was utilized. Table 6-7 and 6-8 show the test results for the difference between mean production rates for the PreForms and Presses departments respectively. Table 6-9 and 6-10 show the test results for the scrap rates of the system and model at the two departments. The test results show no sufficient evidences to suggest that the model generated data is different from the actual system data. Based on the statistical tests, the SDDES was considered valid. The interfaced DES and SD modules could model and reflect the actual system behavior of PMOC as approved by the system experts and according to the statistical tests.

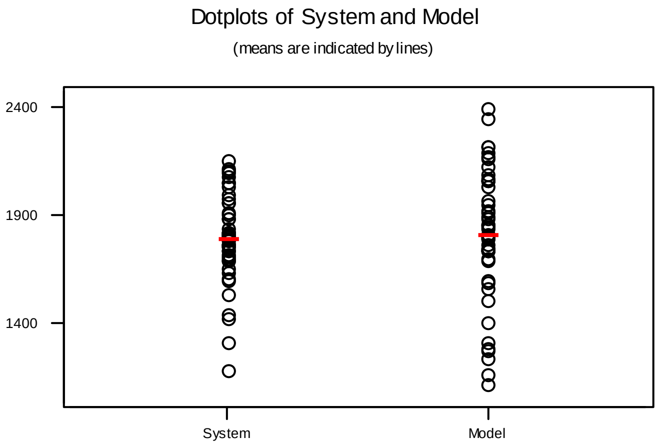
Table 6.8 Testing the difference between the preforms mean production rates – system data vs. SDDES model data

```
Two-sample T for System vs Model

         N      Mean     StDev   SE Mean
System  50      1791       201        28
Model   50      1806       301        43

Difference = mu System - mu Model
Estimate for difference:  -15.7
95% CI for difference: (-117.6, 86.2)
T-Test of difference = 0 (vs not =): T-Value = -0.31  P-Value = 0.760  DF = 85
```



Boxplots of System and Model

(means are indicated by solid circles)

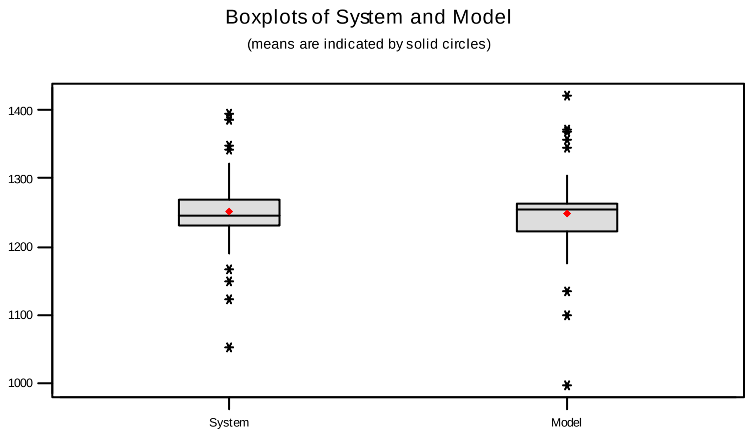


Dotplots of System and Model

(means are indicated by lines)

Table 6.9 Testing the difference between presses mean production rates – system data vs. SDDES model data

```
Two-sample T for System vs Model

         N      Mean     StDev   SE Mean
System  50    1251.5      61.7       8.7
Model   50    1247.9      67.4       9.5

Difference = mu System - mu Model
Estimate for difference:  3.6
95% CI for difference: (-22.0, 29.3)
T-Test of difference = 0 (vs not =): T-Value = 0.28  P-Value = 0.779  DF = 97
```



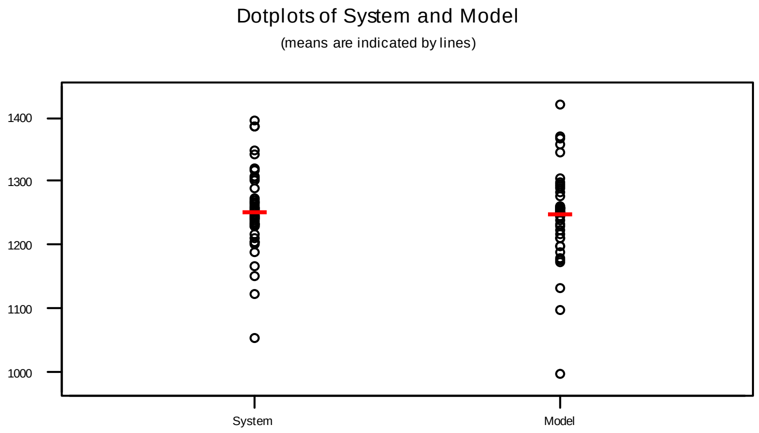
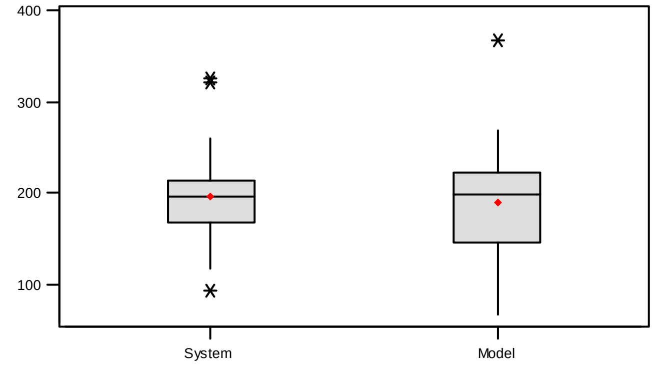


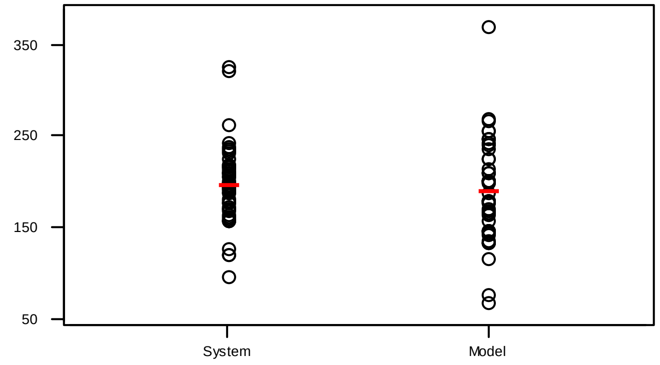
Table 6.10 Testing the difference between PreForms mean scrap rates – system data vs. SDDES model data

```
Two-sample T for System vs Model

         N      Mean     StDev   SE Mean
System  51     195.7      41.8       5.9
Model   51     190.3      52.2       7.3

Difference = mu System - mu Model
Estimate for difference:  5.43
95% CI for difference: (-13.17, 24.03)
T-Test of difference = 0 (vs not =): T-Value = 0.58  P-Value = 0.563  DF = 95
```



Boxplots of System and Model

(means are indicated by solid circles)

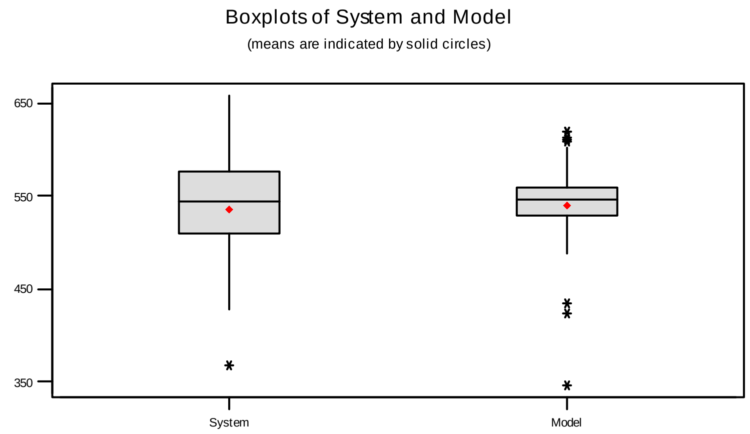


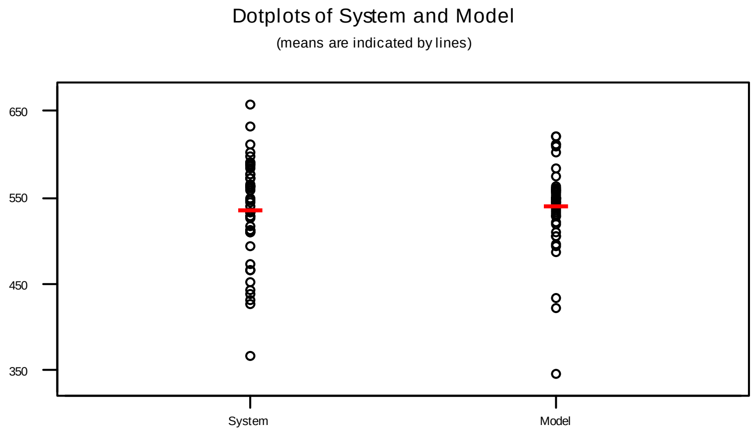
Dotplots of System and Model

(means are indicated by lines)

Table 6.11 Testing the difference between Presses mean scrap rates – system data vs. SDDES model data

```
-sample T for System vs Model

         N      Mean      StDev   SE Mean
System  51     535.1       57.7       8.1
Model   51     540.7       47.2       6.6

Difference = mu System - mu Model
Estimate for difference:  -5.6
95% CI for difference: (-26.3, 15.1)
T-Test of difference = 0 (vs not =): T-Value = -0.53  P-Value = 0.595  DF = 96
```





6.1.8 Synchronizing the SD and DES

The SDDES controller implements the synchronization mechanism (Section 5.5) to interface the simulation modules as specified by the formalism in Section 6.1.4. In the current experiment the PWS, LAB, MIO, PREF, and PRES are interfaced. The interactions between the SD and DES occur between PWS and PREF and PRES. Figure 6-19 represents the overlap between these three modules. PREF is the left ellipse covering while PRES is the right eclipse. The two DES modules also interact between themselves and with the LAB module for updated capacity and overtime usage information. This overlap between these modules is the core of the experiment conducted in this work as explained later.

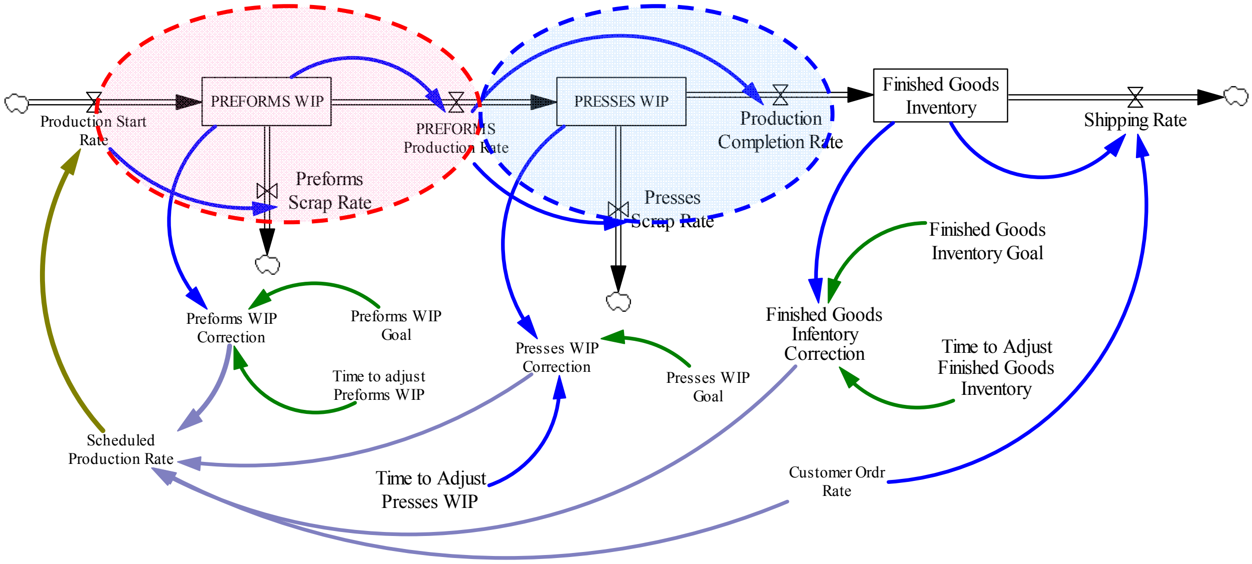


Figure 6.19 Overlap between SD and DES in the internal supply chain functions

Figure 6-20 depicts the variables exchanged between the PREF, PRES modules at the DES side and the internal supply chain SD modules, as defined by the formalized modules. The current experiment is focused on demonstrating the interfacing of these modules. These interactions are implemented by the controller as shown by the synchronization diagram in Figure 6-21.

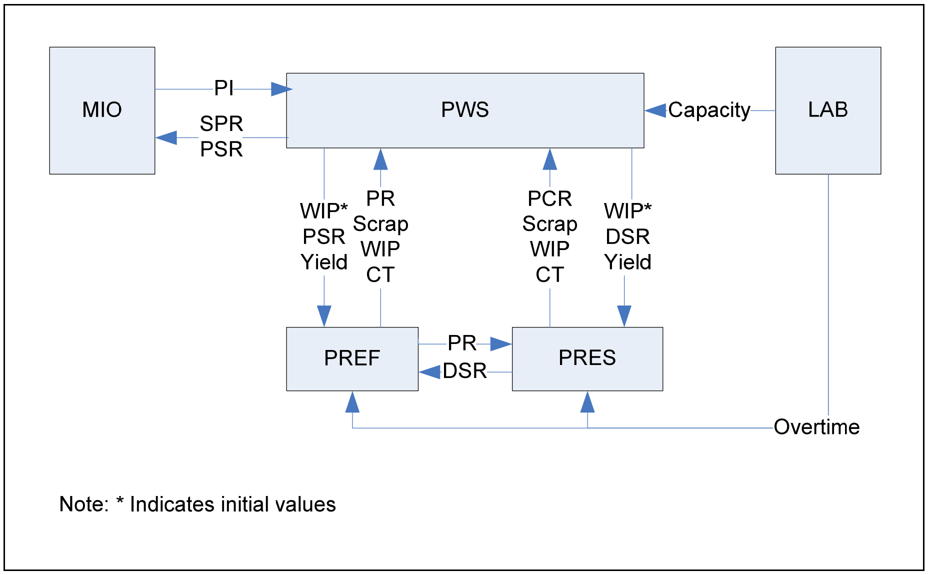


Figure 6.20 The exchanged variables between the SD and DES in the current experiment

In Figure 6-21 the SD modules are combined together as SD for clarity whereas the two DES modules are indicated explicitly. The segment length for the DES modules is set equal to the SD computational time step for simplicity. The sequence of interactions is executed as follows:

1. At the simulation model start up (time 0):

    a. The SDDES controller imports the initialization data from the SD modules <arrow 1>. This includes the initial work in process (WIP), overtime (OT) for PREF and PRES use, the initial production start rate (PSR) for PREF use, and the initial PREF production rate (PR), desired shipping rate (DSR) and yield for PRES use. The initial values are exported after satisfying any formatting requirements to PREF and PRES <arrows 2 and 3>.
    b. PREF and PRES are signaled to run the first segment <arrows 4 and 5>.
2. At the end of the first segment (time Δt):
    a. The SDDES controller collects the WIP, PR and scrap level from PREF and the WIP, production completion rate (PCR), and scrap level from PRES <arrows 6 and 7>. These feedback data is exported to the SD modules (PWS) after satisfying all required formatting <arrow 8>.
    b. SD is signaled to advance its time to Δt and perform its first segment calculations using the DES feedback <arrow 9>.
    c. The controller imports the updated PSR, DSR, OT, yield from PWS and LAB <arrow 10>. The updates inputs are exported to the appropriate DES module in addition to exporting the PR from PREF to PRES as the raw materials for the pressing operations <arrows 11 and 12>.
    d. The DES modules are signaled to run the second segment to advance to time 2Δt.
3. At the end of the second segment (time 2Δt) and each segment afterward, the

transactions a through d in (for arrows 4 through 12) Step 2 above are repeated using the updated data created by the modules at time $n\Delta t$, where n is the number of the segment just completed by the DES modules.

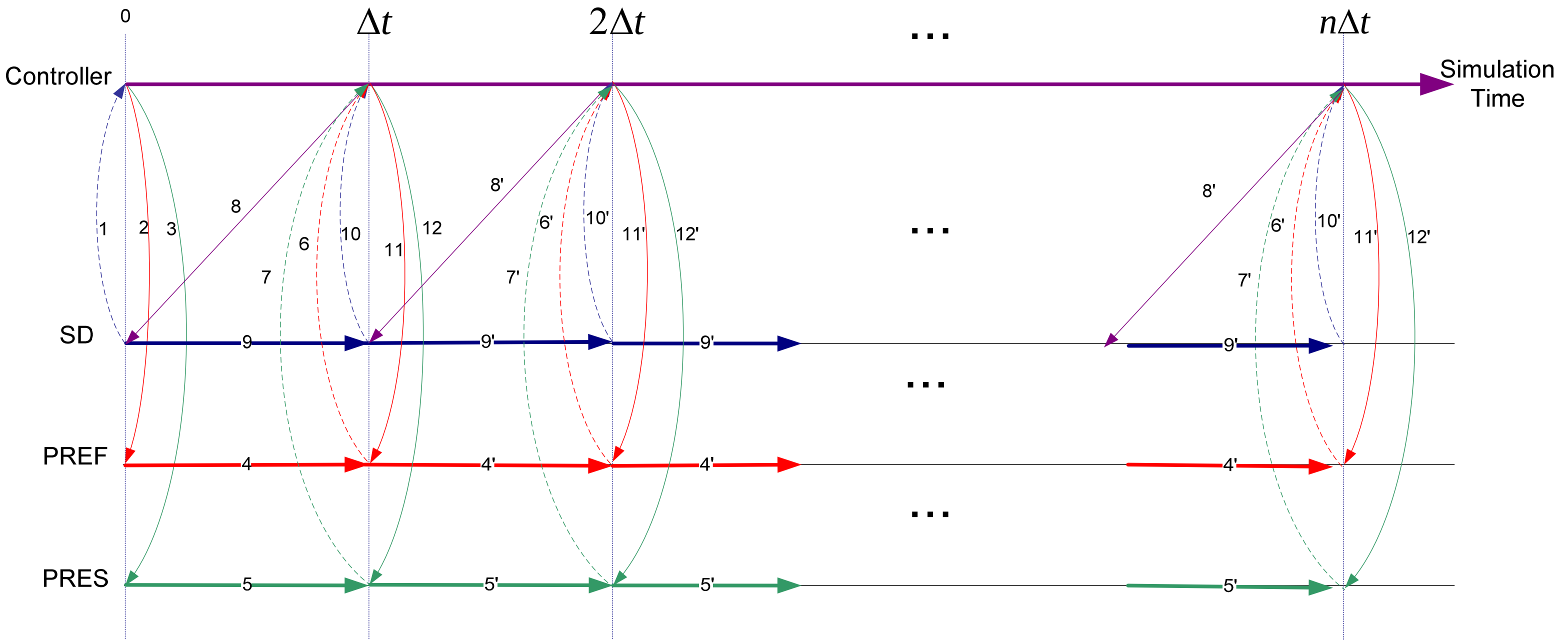


Figure 6.21 Synchronization sequence in executing PMOC's SDDES model

6.1.9 Results and Discussion

The objective of the current experiment is demonstrating the potential of SDDES to model the manufacturing system. The modules were synchronized as described in the previous section to exchange the inputs and outputs specified in the SDDES formalism at the specified format and timing. We ran the model for a period of three months without external stimulation. The current customer order rate was kept fixed to allow observing the effect of exchanging the data between the DES and SD modules. Starting at equilibrium at time zero, the desired production rate of the final product; represented by the desired shipping rate is estimated at the PWS module based on the known customer order rate. PWS also estimates the appropriate material usage rate (production start rate) given the available raw materials inventory level and production capacity. Desired shipping and production start rate are exported to the PRES and PREF modules respectively. The PREF module uses the production start rate to produce raw preforms which the PRES module uses to meet the desired shipping rate. The outputs of PREF and PRES are exported to the PWS so it can update its estimates of the desired shipping and usage rates.

Figure 6-22 and 6-23 show the production rates at the PREF and PRES respectively. It is observed that the two modules perform at a horizontal trend as the customer order rate is fixed. As can be seen the productivity at PRES follows the productivity at PREF. the output of PREF is the input to PRES. A drop in PREF's production before the end of week 1, at week 5, and after week 10 causes corresponding drops in PRES' productivity at the following work days.

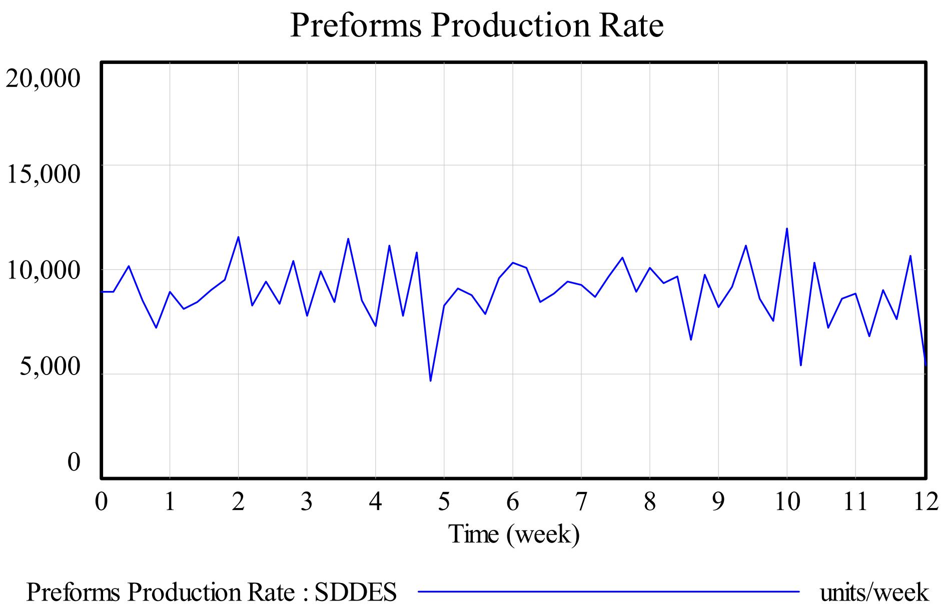


Figure 6.22 PreForms production rate by SDDES

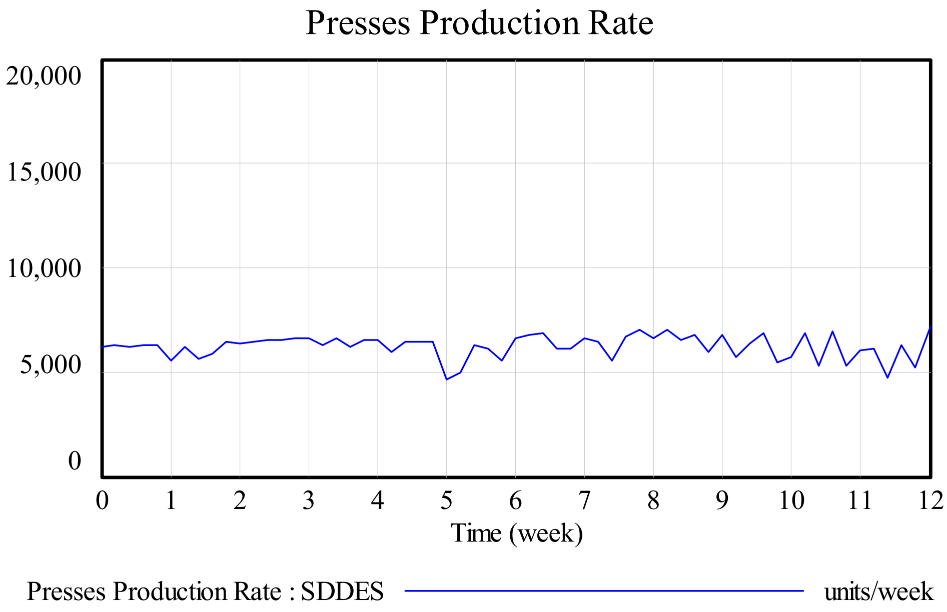


Figure 6.23 Presses production rate by SDDES

Since PRES is controlled by the desired shipping rate from PWS, its productivity tends to show less variability compared to PREF. PRES uses the necessary amount of raw preforms from PREF to match the desired shipping rate while PREF is managed to use all raw materials available to it given that raw materials have been ordered to meet the customer order rate.

PREF and PRES productivity is exported to PWS along with their scrap and WIP performances (Figure 6-24 through 6-27). When made available at PWS, the module updates its estimates of the production start rate, desired shipping rate, and the scheduled production rate. The SD module also updates the finished goods inventory level and ships to meet the current customer orders. If production from PRES is below expected level, the unmet customer orders are added to the desired shipping rate so that PRES is instructed by PWS fulfill them at the following work days. Raw materials to meet the unmet orders are ordered based on the deviation in the finished goods inventory level from its desired level.

It should be noted that any value generated by a module being; a DES or an SD is in fact an SDDES-generated value. In SDDES the interfaced modules are not independent of each other. They are all components of the same simulation model acting as parts of a set of overlapping feedback loops. Although the PREF production rate, for instance, is generated by PREF it is exported to PRES and PWS. New estimates from PWS are made based on it to be the inputs to PREF. Thus the following production rate from PREF is actually a function of PREF current configuration and the inputs obtained from PWS that are in turn functions of the PRES data and the other SD modules as well.

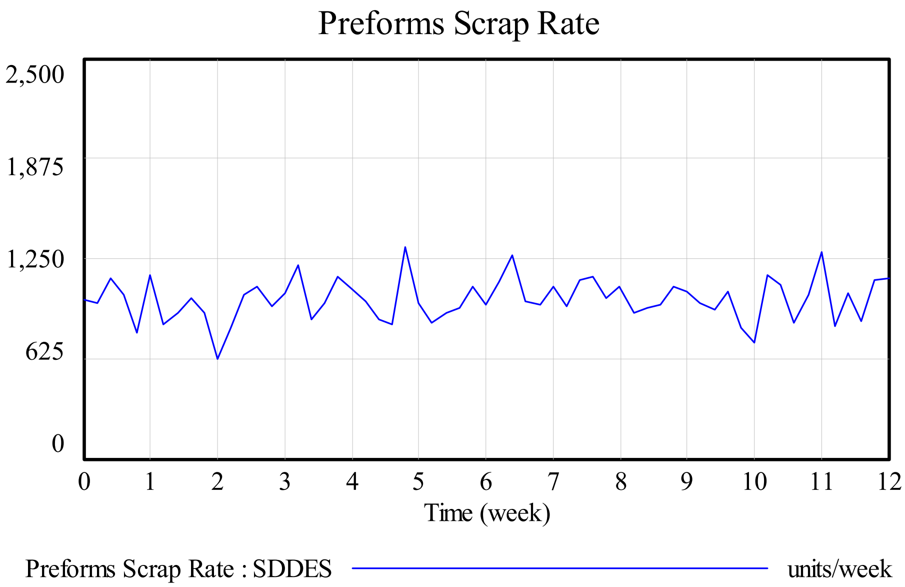


Figure 6.24 PreForms scrap rate by SDDES

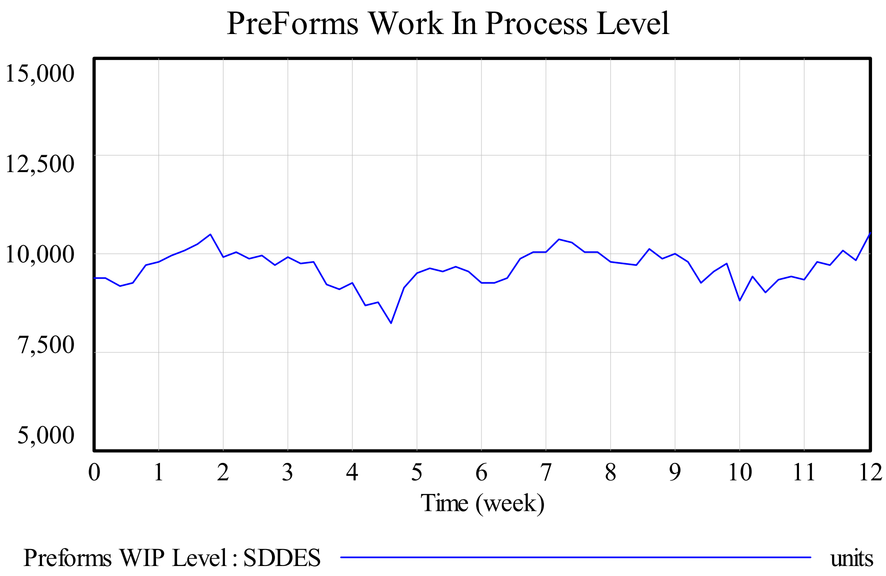


Figure 6.25 PreForms work in process level by SDDES

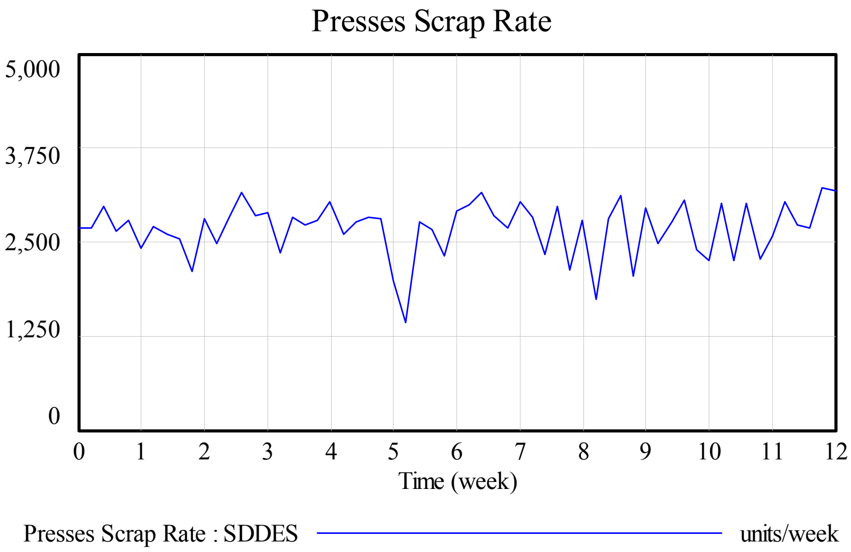


Figure 6.26 Presses scrap rate by SDDES

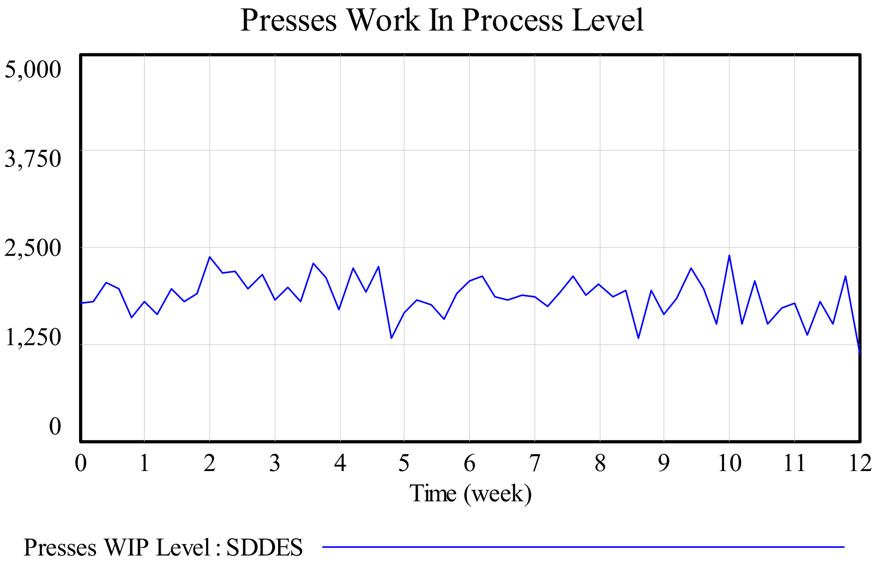


Figure 6.27 Presses work in process level by SDDES

Given the PRES production rate, PWS monitors the finished goods inventory level and consequently the unshipped demand, which is the demand that could not be met so far due to unexpected drops in PRES productivity. Figure 6-28 shows the finished goods inventory level at PWS. Comparing this inventory level to PRES production rate (Figure 6-24) shows that the drop in production at PRES at weeks 1 and 5 and after week 10 corresponds to the starting of finished inventory level to decrease.

The drop in finished goods inventory below the current customer order rate increases the unshipped demand as shown in Figure 6-28. PWS estimates the unshipped and updates the desired shipping rate to account for the unshipped quantities. At equilibrium, the desired shipping rate (Figure 6-28) should equal the customer order rate but it increases as the unshipped increases, following the level of the finished product inventory. The updated desired shipping rate is exported to PRES such that it pulls more raw preforms (if available) from PREF to produce to meet both current customer order rate and the delayed demand (the unshipped).

Experiencing delayed customer order rate leads to the occasional increase in the delivery delay. The normal delivery delay quoted by the company is one week. Delayed orders are shipped as soon as they are available. Due to unavailable production, occasional delays of an extra one day may occur as shown in Figure 6-28; some orders are shipped the following day after their due dates.

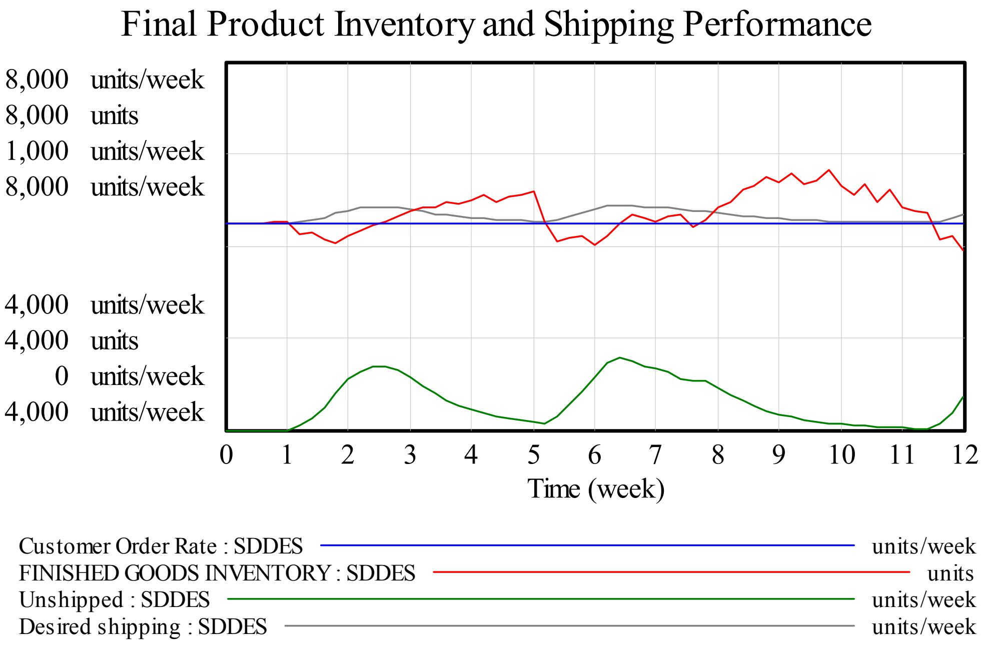


Figure 6.28 Finished goods inventory level and shipping performance by SDDES

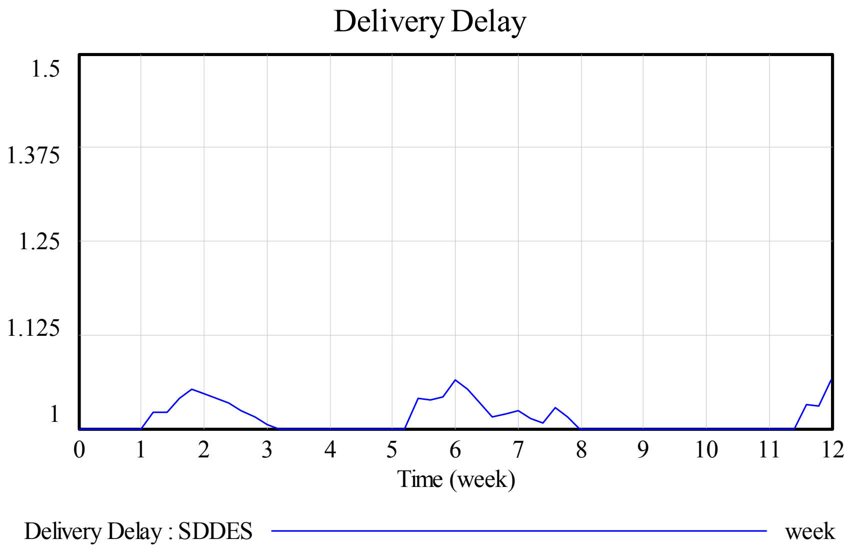


Figure 6.29 Delivery delay performance by SDDES

The raw materials inventory (Parts Inventory) is estimated by the MIO module based on the scheduled production rate from PWS that is calculated to accommodate the PREF and PRES productivity and the shipping performance. Based on the scheduled production rate, MIO orders the needed raw materials. The production start rate of PWS is a function in the availability of the raw materials in the Parts Inventory stock and the available production capacity from the LAB module. The oscillating behavior of the Parts Inventory level (Figure 6.30) is the result of the behavior of the work-in-process in PREF (Figure 6-25), the work-in-process in PRES (Figure 6-27), the finished goods inventory level (Figure 6.29), and the changes in the shipping rate (Figure 6-29). The combined behaviors of these variables contribute to the estimating of the scheduled production rate (Figure 6.30) at PWS that drives the materials ordering and the parts inventory level in MIO. The time lag between the scheduled production rate and the parts inventory level is supplier delivery delay period.

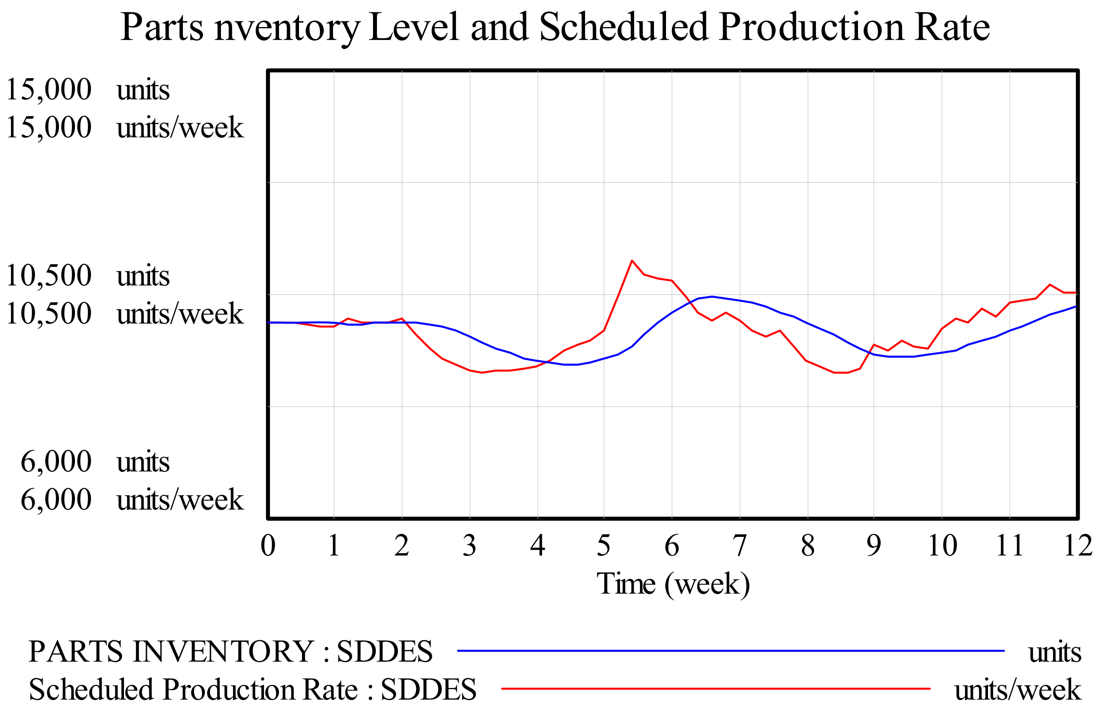


Figure 6.30 Scheduled production rate and raw materials inventory behaviors by SDDES

<u>6.1.10 Reviewing the SDDES model results with PMOC</u>

It was shown that the SD and DES modules in the PMOC SDDES model are interacting appropriately and the model could be used to explain the behavior of the system at the shop floor and planning level. It is concluded that the variation in production rate, particularly at the PreForms department and at the Presses department are the root cause of the oscillating behavior (although around a horizontal trend) observed for some of the system variables (inventory levels) and shipping performance. Even with a stable level of demand and no special occurrences at the shop floor, the system occasionally fell short of meeting demand and the inventory levels oscillated.

We reviewed the model results with the PreForms department's production manager and with the manager of operations of the company. With the fixed customer order rate they have recognized the behavior generated by the model as familiar adding that the variability in the daily production is due to the large number of product types with relatively small order sizes for each type. Their commitment to meet loyal customer orders led to the need to manage the production line in that manner. Synchronization between PreForms and Presses was continuously in focus but used to be tedious to achieve. The high scrap rate in the Presses would negatively affect the scheduling and synchronization efforts. Attracting larger order sizes and minimizing the number of variants of the product types was not an easy decision because of using pressing technology that was not economically competitive. The metallic molds for the pressing heads at the Presses department become defective when a pressing attempt fails. Molds would require to be sent for machining or they would be scrapped as well. Japanese and Korean and other competitors use ceramic-based pressing heads that had longer service lives and were cheaper. In addition the company was committed to its long-term customer needs and its higher prices could not attract more demand. Unwilling to invest in renovating the production facilities at PMO, the company eventually outsourced the PMO operations in favor of directing their financial resources to the GRADUIM alloys production and other markets.

As for using the SDDES model, it was perceived as useful tool to improve the communications between the shop floor managers at the level and the operations manager (VP level). The lack of timely communications and updated data between the operational and aggregate levels is a real concern. The estimates of the system capacity used to differ from the production manager and the operations manager (as expressed by the production manager). The operations manager level uses data from the company's central database (Spreadsheet based application) and from other units including engineering, materials, etc. As described by the PreForms production manager:

- More often than otherwise, the VP team over estimates the system performance; the reason being the use of data from the centralized database as well as their most recent knowledge of the system capabilities. The production manager would request permits for using overtime or extra materials ordering (which are the VP decisions) to match the expectations.
- Due to significant differences in estimating the system yield (lower yield expected by VP than what the production manager knew about her production line capabilities !), they launched a project to evaluate each individual equipment unit's performance to update the central database. Need for that was caused by changes at the shop floor made by the production manager as she started her job that. The data available at the VP level and in the data base was compiled under a previous production manager and could not be updated on a timely way.
- The production manager expressed an interest in having a tool that she could manipulate to reflect the current status (as it frequently changes) so she can be able to

communicate accurately to the VP and CEO and avoid the “frustration of convincing them” of the actual situation in the meetings.

The operations VP considered SDDES valuable to experiment and evaluate the performance of the system and the impact of the resource allocation (materials, and manpower) decision on the shipping performance. The causal relationships captured in SDDES can save the time analyzing and summarizing the collected data at the central database. And he suggested including the database as an integer component of SDDES to benefit from SDDES in analyzing the system data.

6.2 Modeling the Manufacturing Value Chain[2]

The value chain describes the activities performed by organizations and how they lead a competitive advantage (Porter 1985). The value chain of the manufacturing enterprise can be viewed as extending the scope of the production/assembly supply chain to include the marketing and sales and service activities in addition to the supporting activities (Figure 6-31), all when managed properly at the most cost-effective way improve the generation and sustenance of growth and lead to a higher competitive position. The value chain partners perform and coordinate all design, engineering, production, and information flow necessary to manufacture

[2] Rabelo et al, (2007). Value chain analysis using hybrid simulation and AHP. Intl J of Production Economics, (105) 536-547

products and provide services that meet customers' needs at the lowest costs. Yet the system becomes more complex for modeling and analysis.

In the manufacturing value chain where the majority of resources and costs are allocated to manufacturing and service operations, organizations should concentrate on these areas in order to maximize savings and consequently the profit margin. This should be approached while maintain a high degree of vertical integration with the system. From a modeling perspective hybrid, comprehensive simulation models with the systemic coordinated macro and micro views are necessary to analyze and manage such complex systems in consistence with strategic business objectives. This is of particular importance in the global economy of today, where companies operate across countries' borders giving significance to the decentralized organizational structures and the modularization of the business processes.

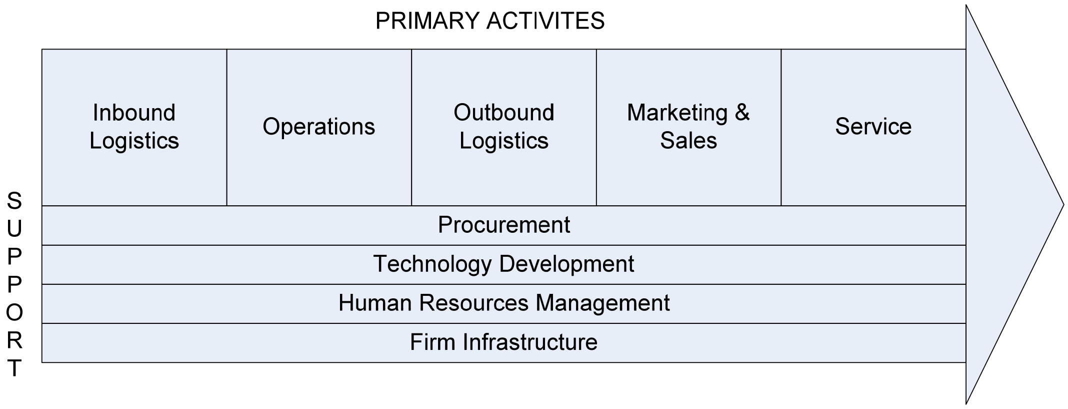


Figure 6.31 The value chain system

SD with its system view offers an effective framework to model the scope of the value chain at the aggregate strategic level over long range analysis horizons. Meanwhile, DES models are mainly flow models that track the flow of entities through a system making them appropriate and effective in building detailed models of the operational level activities (See Table 2-4 in Chapter 2 for comparing SD and DES). The SDDES hybrid simulation framework can support the simulation modeling of the value chain of the manufacturing enterprise.

In this section, SDDES is used to build a hybrid simulation model of the value chain system of a construction equipment manufacturer. Two strategic business units are at the focus of the analysis: the manufacturing facility (SBU1) and the service providing facility (SBU2). The analysis of the value chain system helps achieving a competitive advantage in two ways: by developing a cost advantage through a better understanding of the costs associated with the value-adding processes and working to minimize them and by differentiation where the focus is given to enhancing current competencies and capabilities to outperform competitors. In their effort to achieve a competitive advantage through minimizing costs while maintain quality and high level of customer satisfaction, the construction equipment manufacturer is considering outsourcing some, or all of the manufacturing activities. Outsourcing the value chain activities should be considered if there are the possibilities of getting the activity performed at a lower cost by a supplier. This also considers the opportunities for improvements in performance (e.g. lead times, and responsiveness). However, companies should also estimate the risk associated with outsourcing a value chain activity, which could be considered a core competency, as well as the risk associated with keeping the activity in-house on the overall system performance. An analysis of the outsourcing alternatives should be approached from an integrative perspective. The value chain activities are not isolated from each other. They affect each other in terms of costs and performance.

In the SDDES model of this manufacturing value chain, SD is used to model the entire value chain system and the strategic decision making processes at the extended enterprise system while DES is used to provide detailed models of the service and manufacturing sub-systems that interact directly with the customers. SD provides a comprehensive view of the system allowing decision makers to analyze the impact of the outsourcing decision on the system as a whole. And as the main driver to consider outsourcing is cost-effectiveness, accurate estimates of costs associated with each outsourcing alternative are necessary. In addition the estimate of the customer satisfaction level will be made based on detailed estimates of the level of responsiveness and lead times related to delivering products and services. These lend themselves to the modeling in DES models of the manufacturing and service business units.

The SDDES model is used to assess an outsourcing decision based on the projected performance over the period of five future years for each outsourcing alternative. The model works by having SD estimate the demand for the products and the services, the quality of each, customer reactions to quality of provided service and product, the investment decisions, overhead costs, and the new product and service development functions. This data are exported to the DES models of the manufacturing and service units separately to assess the performance of the manufacturing and service facilities and provide estimates the associated costs. Costs and number of units produced and services provided are fed back to SD to re-evaluate the overall performance of the entire system. Figure 6-32 depicts the interactions among the SD and the DES modules where product and service quality are functions of investments and new products and service designs developed based on the SD model.

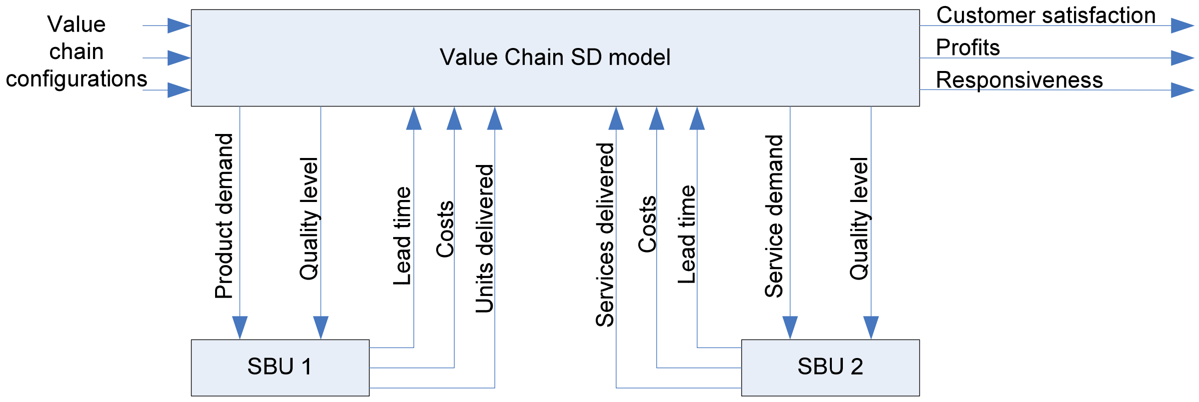


Figure 6.32 Data exchanged between SD and DES in the value chain model

The company is evaluating the following three alternatives for outsourcing the manufacturing facilities:

A. Keep the manufacturing facility (SBU1) and the service facility (SBU2) under the enterprise and in continental USA

B. Outsource the majority of SBU1 to South East Asia (but to keep the core competencies of design and new product and service development in house) and keep SBU 2 in the continental USA

C. Outsource the majority of SBU1 to East Asia (but to keep final manufacturing performance testing in the continental USA and the core competencies of design, and new product and service development in house) and keep SBU2 under the organization.

The management wants to base the evaluation of the three alternatives on four factors (1) profitability, (2) customer satisfaction, (3) responsiveness, and (4) political stability. Profitability is measured as the net total profits after all costs. In a profitable year, 30% of profits are paid as taxes, one third after taxes is paid as dividends, and the rest is reinvested to improve performance. These with the considerations for new product and service development costs and general administration costs are modeled in SD. The DES models estimate the manufacturing and service delivery costs. Customer satisfaction (in SD) is measured in several dimensions based on returns, requests for proposals, service levels, and retention of customers. Responsiveness is measured as the total replenishment (lead) time needed to satisfy any order placed. This factor is very important as it significantly contributes to being able to adapt to variations in the market demand at the customers' end.

The political stability factor was not part of the simulation models. Decision makers had to assess it themselves. East Asia is relatively stable and strongly emerging in the international economy, which offers a trustable business environment. Meanwhile other parts in Southeast Asia are experiencing a few instabilities due to some military and violent actions, in addition to relatively less stable governments. In addition, the economic crises that hit Southeast Asia during the past decade are still in memory. The assessment of relative weight of the four factors was made using the analytical hierarchy process (AHP) based on the inputs from the SDDES simulation model for each model.

6.2.1 The SD and DES value chain system simulations

The SD model for the value chain model, shown in Figure 6-33, consists of three main units to represent SBU 1 for the manufacturing facilities and its performance measures, the SBU 2 for the service facilities and its performance measures, the customer management sections for the customer request for proposals, acquisition, loss, and recovery for demand and customer retention and satisfaction. Further, the SD model includes the financial environment representing profits estimates and the investment decisions, productivity and manpower requirements, for each of the SBU1 and SBU 2. Having a good ratio of service staff to customer means better customer satisfaction and increased number of customers. Investments in the service organization imply more investments in staff development and higher service rate. It is important to invest in service staff but it is critical to keep the balance as good service and higher satisfaction are dependent on good products. The SD model was validated in Rabelo et al. (2004). To capture the details of the manufacturing and service facilities, DES models were built SBU 1 and SBU 2. Generic flow diagram of the DES models is shown in Figure 6-34. The DES models provide accurate estimates of productivity, associated expenses, and lead times.

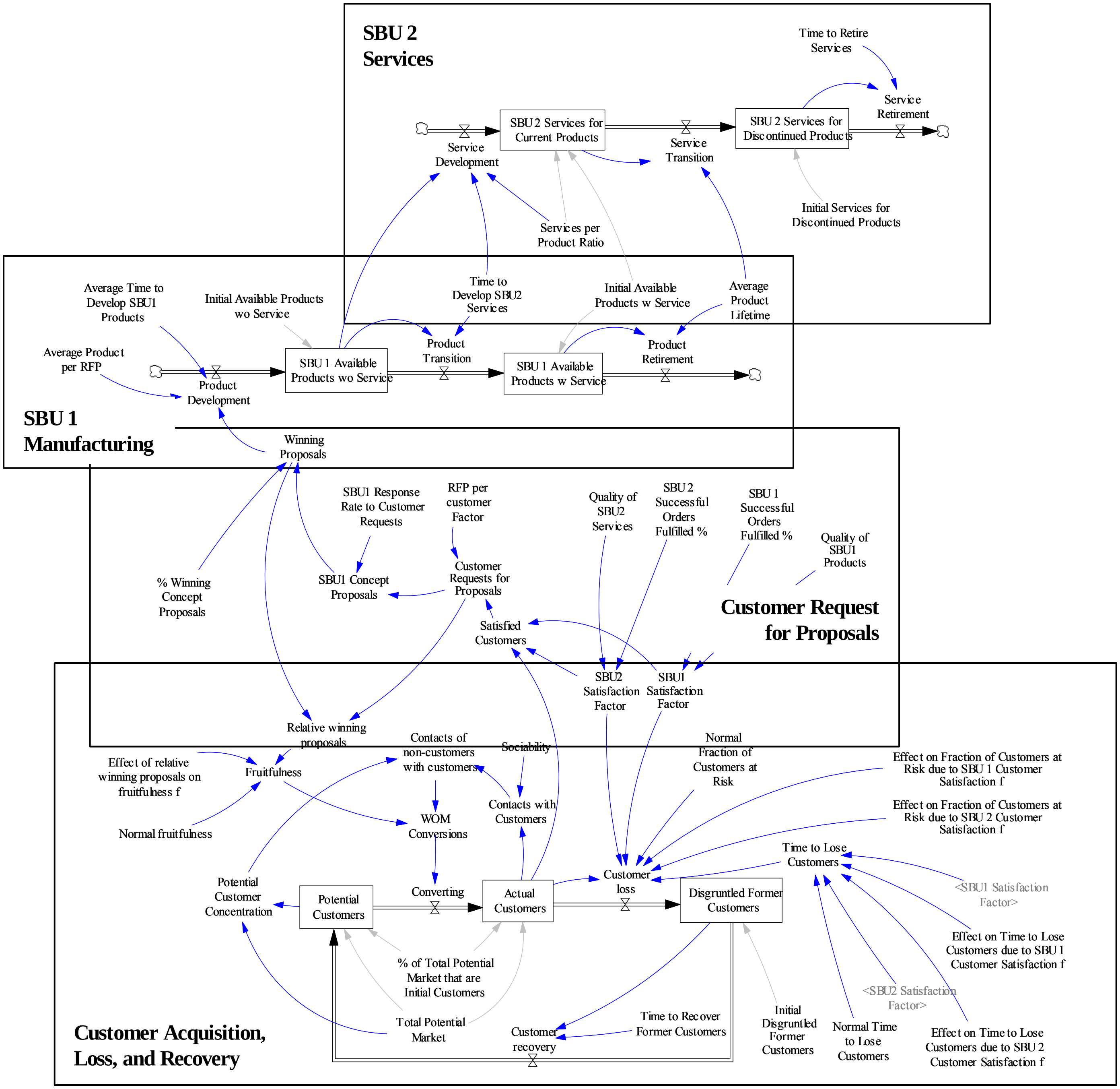

SBU 2
Services
Time to Retire Services
Service Retirement
SBU2 Services for Current Products
SBU 2 Services for Discontinued Products
Service Development
Service Transition
Services per Product Ratio
Initial Services for Discontinued Products
Average Time to Develop SBU1 Products
Initial Available Products wo Service
Time to Develop SBU2 Services
Initial Available Products w Service
Average Product Lifetime
Average Product per RFP
Product Development
SBU 1 Available Products wo Service
Product Transition
SBU 1 Available Products w Service
Product Retirement
SBU 1
Manufacturing
Winning Proposals
SBU1 Response Rate to Customer Requests
RFP per customer Factor
Quality of SBU2 Services
SBU 2 Successful Orders Fulfilled %
SBU 1 Successful Orders Fulfilled %
Quality of SBU1 Products
% Winning Concept Proposals
SBU1 Concept Proposals
Customer Requests for Proposals
Customer Request for Proposals
Satisfied Customers
SBU2 Satisfaction Factor
SBU1 Satisfaction Factor
Relative winning proposals
Contacts of non-customers with customers
Sociability
Normal Fraction of Customers at Risk
Effect on Fraction of Customers at Risk due to SBU 1 Customer Satisfaction f
Effect of relative winning proposals on fruitfulness f
Fruitfulness
Contacts with Customers
Effect on Fraction of Customers at Risk due to SBU 2 Customer Satisfaction f
Normal fruitfulness
WOM Conversions
Time to Lose Customers
Potential Customer Concentration
Potential Customers
Converting
Actual Customers
Customer loss
Disgruntled Former Customers
<SBU1 Satisfaction Factor>
Effect on Time to Lose Customers due to SBU 1 Customer Satisfaction f
% of Total Potential Market that are Initial Customers
<SBU2 Satisfaction Factor>
Initial Disgruntled Former Customers
Total Potential Market
Time to Recover Former Customers
Customer recovery
Normal Time to Lose Customers
Effect on Time to Lose Customers due to SBU 2 Customer Satisfaction f
Customer Acquisition,
Loss, and Recovery

Figure 6.33 SD core model of the value chain system

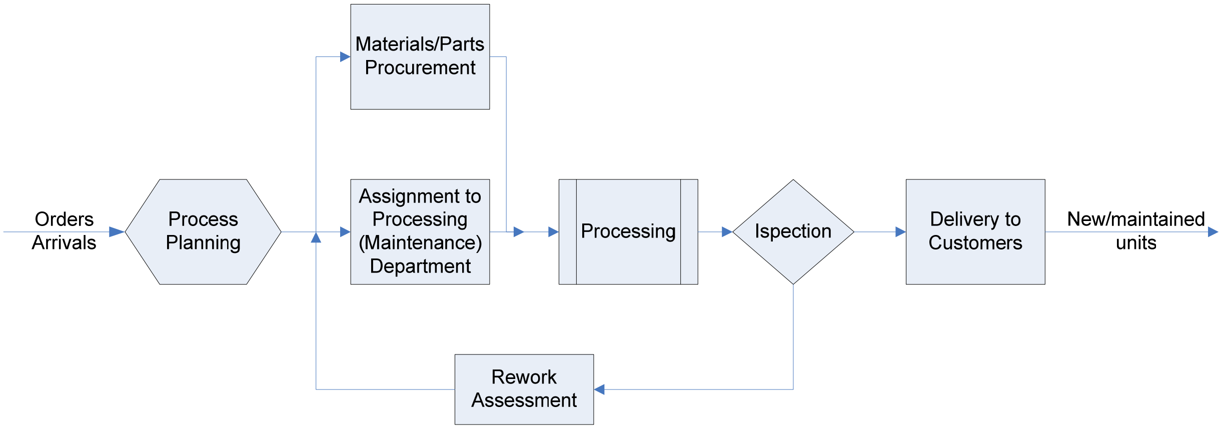


Figure 6.34 Generic work flow in the manufacturing and service DES models

The DES models are conceptually embedded into the SD model; to provide cost and productivity data. The goal of the company is to minimize costs and improve responsiveness to customer needs, which necessitates the higher resolution analysis of the manufacturing and service capabilities particularly when considering outsourcing options. Figures 6-35 and 6-36 show the inputs (arrows to the left) from SD to the DES modules of the SBU1 and SBU2, and the feedback from each SBU to the SD module. The DES modules for manufacturing and services include estimating the resource usage expenses and the average lead time for providing a service or delivering a product. Lead time as well as the level of rejection by customers is used in the SD model to estimate customer satisfaction and eventually the demand and profits. DES outputs-based performance of each location considering for the manufacturing facilities and its impact of the performance of the service capabilities was used in SD to evaluate the long range desirability of the location, estimated over a period of five future years.

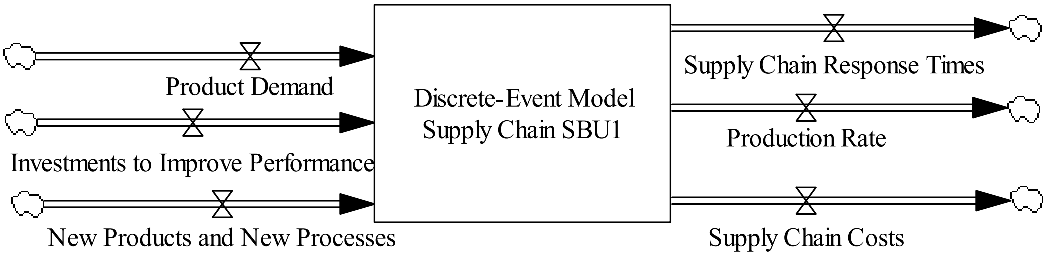

Product Demand
Investments to Improve Performance
New Products and New Processes
Discrete-Event Model
Supply Chain SBU1
Supply Chain Response Times
Production Rate
Supply Chain Costs

Figure 6.35 SD-embedded SBU1 DES model and inputs and outputs

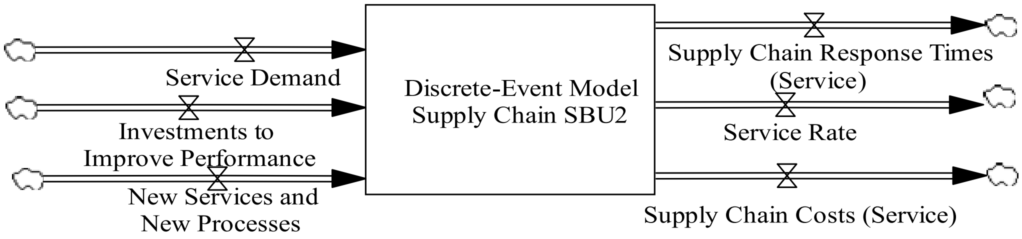


Figure 6.36 SD-embedded SBU2 DES model and inputs and outputs

The SD module, named SDVC is described in the SDDES formalism format as follows. Table 6-12 lists the sets of inputs and outputs for SDVC.

$$SDVC = (SD, X_{SDVC}, Y_{SDVC}, P_{SDVC}, CONT)$$

SDVC receives the product and service delivery lead times from SBU1 and SBU2 along with the number of product units delivered and services provided and costs incurred. It uses this information to forecast for future sales and to estimate the profits from each SBU, the total profits, and predict the product and service quality based on the allocated investments.

Table 6.12 Inputs and outputs of the SDVC module

X_{MIO}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
SDVC	LEAD_TIME1	SBU1	OP_SBU1_01	IP_SDVC_01	PROFITS1	TB_END	NONE
SDVC	LEAD_TIME2	SBU2	OP_SBU2_01	IP_SDVC_02	PROFITS2	TB_END	NONE
SDVC	PRODUCTS	SBU1	OP_SBU1_02	IP_SDVC_03	SALES1	TB_END	NONE
SDVC	SERVICES	SBU2	OP_SBU2_02	IP_SDVC_04	SALES2	TB_END	NONE
SDVC	TOTAL_COST1	SBU1	OP_SBU1_03	IP_SDVC_05	PROFITS1	TB_END	NONE
SDVC	TOTAL_COST2	SBU2	OP_SBU2_03	IP_SDVC_06	PROFITS2	TB_END	NONE
Y_{MIO}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
SDVC	OP_SDVC_01	PRODUCT_DEMAND	SBU1	IP_SBU1_01	PRODUCT_AR	TB_START	MISC_SD >> TB_BASED_RATE
SDVC	OP_SDVC_02	SERVICE_DEMAND	SBU2	IP_SBU2_01	SERVICE_AR	TB_START	MISC_SD >> TB_BASED_RATE
SDVC	OP_SDVC_03	PRODUCT_QUALITY	SBU1	IP_SBU1_02	REWORK_RATE	TB_START	NONE
SDVC	OP_SDVC_04	SERVICE_QUALITY	SBU2	IP_SBU2_02	REJECT_RATE	TB_START	NONE

PRODUCTS: Number of product units delivered
SERVICES: Number of services provided
PRODUCT_DEMAND: Predicted order for product
SERVICE_DEMAND: Predicted demand for service
PRODUCT_AR: At USB1 to denote the order arrival rate at the module based on the SDVC input
SERVICE_AR: At USB2 to denote the demand for service rate at the model based on the SDVC input
REWORK_RATE: At USB1 to indicate the rejection rate of the product based on the current quality level
REJECT_RATE: At USB2 to indicate the rate of failure to provide the service to the desirable standard, based on the current quality level
MISC_SD >> TB_BASED_RATE: the SD input variable is a simple value and should be converted into the arrival rate of entities at the DES module for the TB length

The inputs from the DES modules are calculated by the modules in monetary values and they are used without formatting at the SD module. The SBU1 module is described in the SDDES formalism format as follows. Table 6-13 lists the sets of inputs and outputs for the module.

$$USB1 = (DES, X_{USB1}, Y_{USB1}, P_{USB1}, TB)$$

The SBU2 module is described in the SDDES formalism format as follows. Table 6-14 lists the sets of inputs and outputs for the module.

$$USB2 = (DES, X_{USB2}, Y_{USB2}, P_{USB2}, TB)$$

Table 6.13 Inputs and outputs of the SBU1 module

X_{MIO}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
SBU1	PRODUCT_DEMAND	SDVC	OP_SDVC_01	IP_SBU1_01	PRODUCT_AR	TB_START	MISC_SD >> TB_BASED_RATE
SBU1	PRODUCT_QUALITY	SDVC	OP_SDVC_03	IP_SBU1_02	REWORK_RATE	TB_START	NONE
Y_{MIO}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
SBU1	OP_SBU1_01	LEAD_TIME1	SDVC	IP_SDVC_01	PROFITS1	TB_END	NONE
SBU1	OP_SBU1_02	PRODUCTS	SDVC	IP_SDVC_03	SALES1	TB_END	NONE
SBU1	OP_SBU1_03	TOTAL_COST1	SDVC	IP_SDVC_05	PROFITS1	TB_END	NONE

Table 6.14 Inputs and outputs of the SBU2 module

X_{MIO}							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
SBU2	SERVICE_DEMAND	SDVC	OP_SDVC_02	IP_SBU2_01	SERVICE_AR	TB_START	MISC_SD >> TB_BASED_RATE
SBU2	SERVICE_QUALITY	SDVC	OP_SDVC_04	IP_SBU2_02	REJECT_RATE	TB_START	NONE
Y_{MIO}							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
SBU2	OP_SBU2_01	LEAD_TIME2	SDVC	IP_SDVC_02	PROFITS2	TB_END	NONE
SBU2	OP_SBU2_02	PRODUCTS	SDVC	IP_SDVC_04	SALES2	TB_END	NONE
SBU2	OP_SBU2_03	TOTAL_COST2	SDVC	IP_SDVC_06	PROFITS2	TB_END	NONE

Molding the DES modules contents was guided by the supply chain operations reference (SCOR) model (Bolstorff and Reosenbaum, 2004). SCOR describes the business activities, operations, and tasks in all steps of satisfying supply chain's internal and external customer demand. The three decision alternatives are described in the wider scope Figures 6-37 through 6-39. It is noted that in all three alternatives, service units are kept in the continental USA since consumers are located mainly in the continental USA.

Alternative A – SBU 1 under the organization (no outsourcing): As shown in Figure 6-37, the manufacturing facility handles the sourcing of stocked raw materials (*S1*) from stocked raw material suppliers (*D1*) and processes the make-to-order manufacturing (*M2*), the deliver-to-order finished products (*D2*), the sourcing of returned defective products (*SR1*), the sourcing of maintenance required operations (MRO) for sold products (*SR2*) from all local warehouses, and the delivery of MROs back to warehouses (*DR2*). Moreover, the warehouse handles the sourcing of make-to-order products from SBU 1 *(S2),* the delivery of the make-to-order products to end customers *(D2),* the sourcing of returned defective products (*SR1*), the sourcing of MROs for sold products (*SR2*) from customers, and the delivery of MROs back to customers (*DR2*).

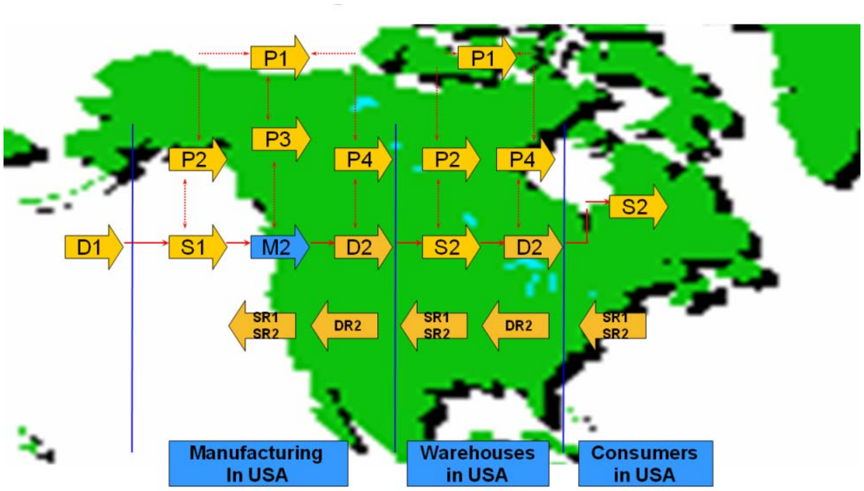


Figure 6.37 SCOR representation of alternative A (no outsourcing)

Alternative B – Outsourcing SBU1 in South East Asia: As shown in Figure 6-38 all process categories are similar to Alternative A, except that the manufacturing facility does not handle MROs *(SR2 & DR2)* and product returns *(SR1),* as they are all handled locally at the warehouses and service facilities. On the other hand, delivery of make-to-order products from SBU 1 to local warehouses *(D2)* consumes a relatively longer duration due to maritime transport and customs operations in California.

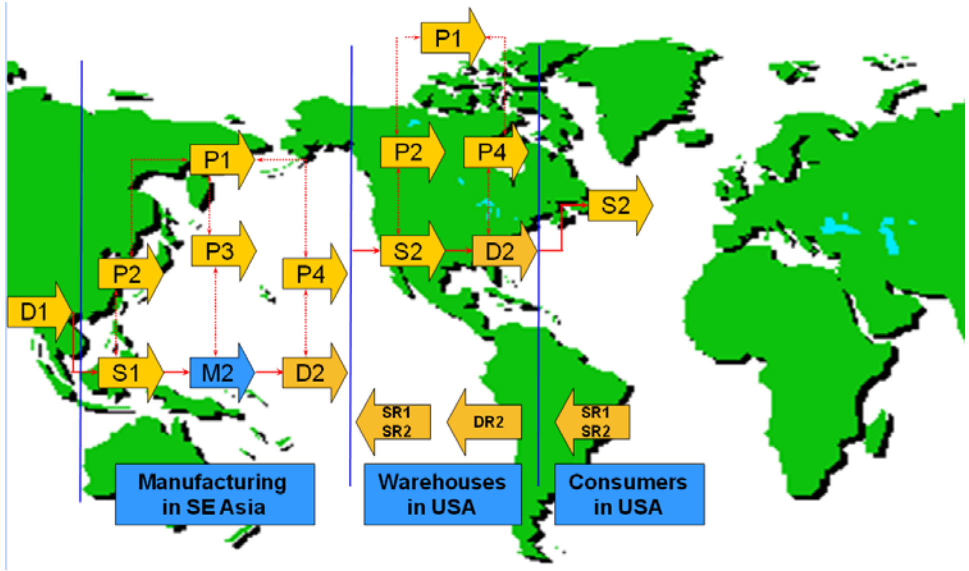


Figure 6.38 SCOR representation of alternative B

Alternative C – Outsourcing SBU1 to East Asia: As shown in Figure 6-39, all process categories are similar to Alternative B, except that delivery of make-to-order products from SBU 1 to local warehouses *(D2)* consumes the longest duration in comparison to alternatives A and B. Moreover, the local warehouse handles an extra QC inspection for the incoming products prior to delivering to customers *(D2).*

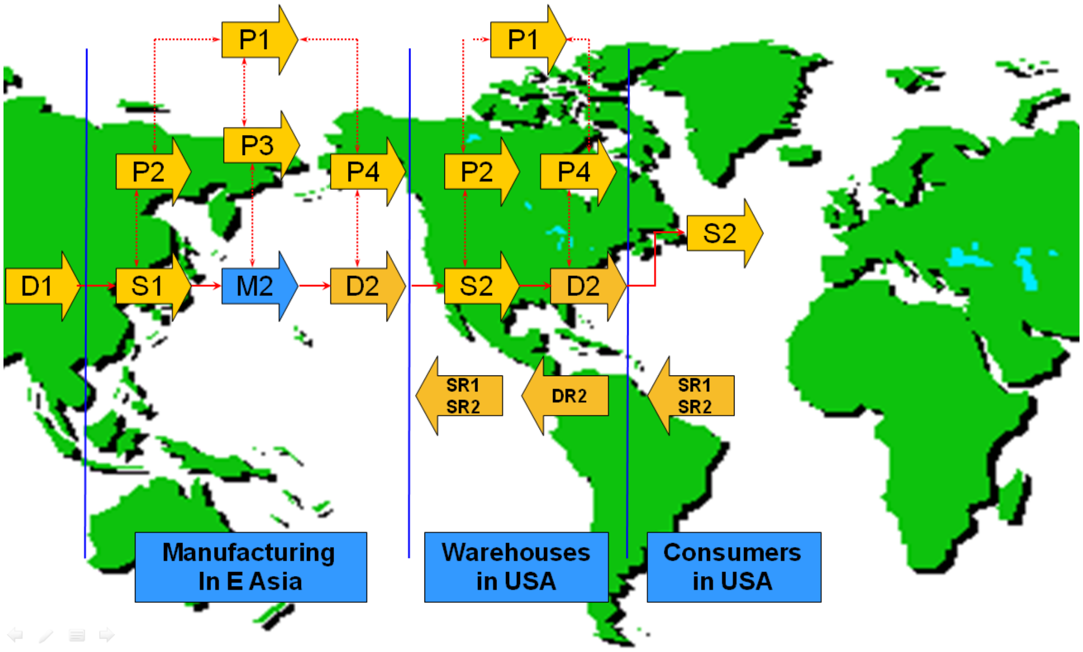


Figure 6.39 SCOR representation of alternative C

The SDDES approach of embedding of the DES simulation model into the SD value chain model provides a good frame work for simulating the SCOR representation of the supply chain system.

6.2.2 Running the SD DES model

The SD and DES models were run while interacting and exchanging data as depicted in Figure 6-40. The segment run length (TB) for both SBU1 and SBU2 was set to one month to accommodate the long manufacturing and shipping cycle times as well as allow a closer review of the performance. The SD computational time step (Δt) was set to one week, where each month is four weeks long. When a DES input value is not updated yet the most recent available value is used in the SD calculations. The SDDES controller actions sequence to synchronize the modules is indicated by the numbers on the arrows in Figure 6-40.

At the beginning of the simulation run SD exports the estimates of product and service demand for the coming period and the affordable quality levels to the DES modules. Upon completing each run segment, the DES model provides estimates of the costs associated with meeting the orders for products or services and the number of units delivered with the lead time and rejection levels for the current quality standards. SD uses the DES inputs to updates its estimates of the system performance, profits from each business unit and the total profits, and the level of customer satisfaction. Based on the profits realized investments in production equipment and service staff and capabilities are decided and the expected level of quality can be predicted. The analysis is conducted for a five year period, for each of the outsourcing alternatives. The overall performances from the three alternatives are compared with respect to profits realized, responsiveness, and the customer satisfaction.

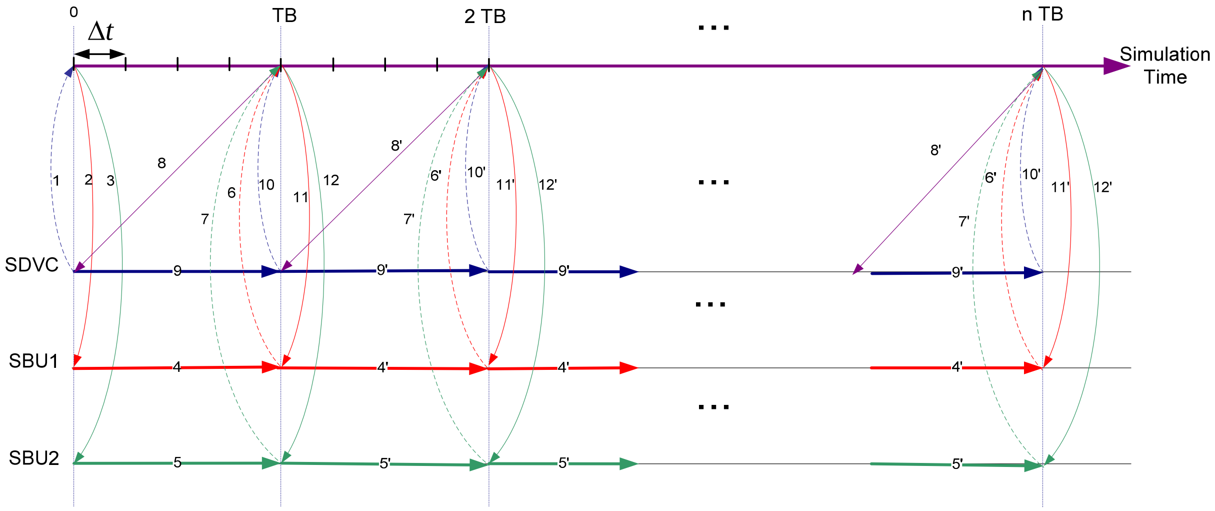


Figure 6.40 sequence of synchronizing the SD and DES modules

6.2.3 Simulation results and analysis

The five-year analysis period showed that keeping both the manufacturing and service facilities in the continental USA leads to the best level of responsiveness. However, due to high overhead, profits are not expected before the third year and during that period the customer satisfaction will fall significantly. Meanwhile the two outsourcing options can lead to higher levels of profits and good stable customer satisfaction rates despite the low performance in terms of responsiveness. Figures 6-41 through 6-43 compare the three alternatives with respect these measures of performance.

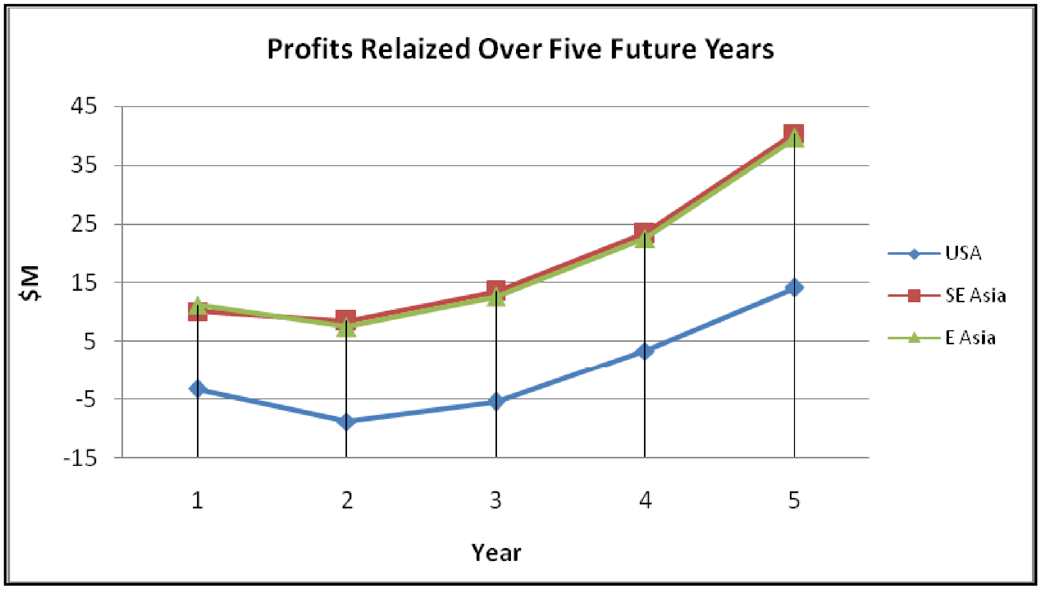


Figure 6.41 Comparing outsourcing alternatives with respect to profits

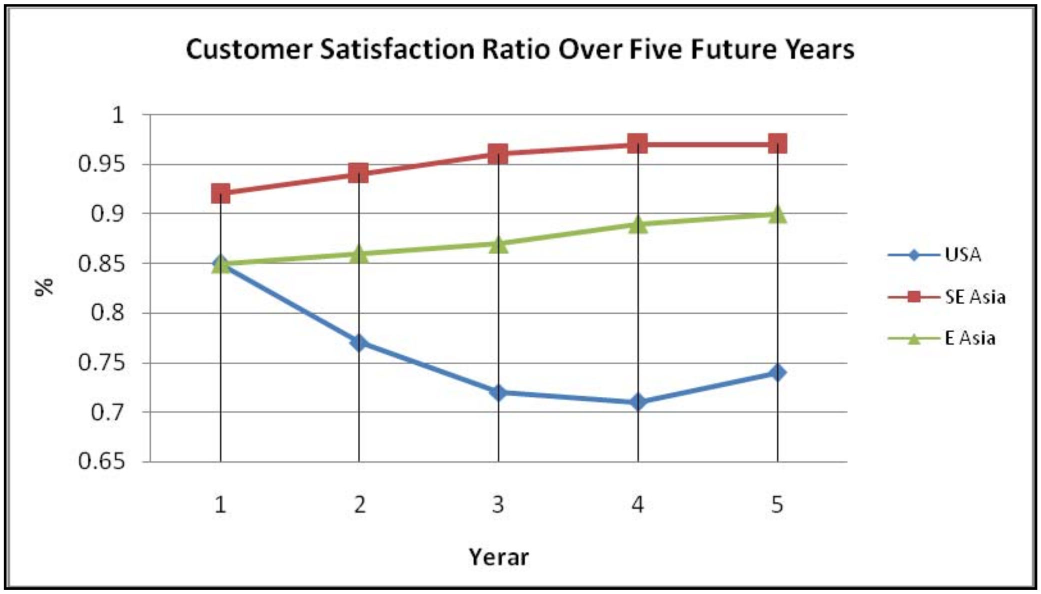


Figure 6.42 Comparing outsourcing alternatives with respect to customer satisfaction rate

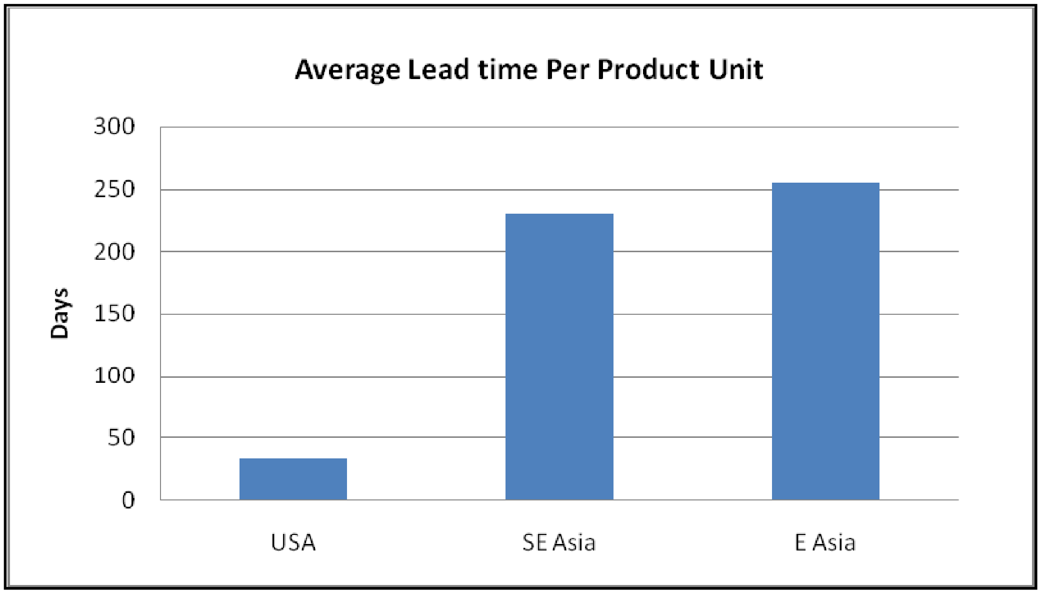


Figure 6.43 Comparing alternative with respect to manufacturing lead time

The simulation results provided insights on the expected performance of the system under the outsourcing alternative in considerations. The results provided the decision makers with inputs to make the decision. Yet to further support the decision makers and incorporate their experiences of the global economy, a stochastic AHP framework (Rabelo et al., 2007; Eskandary and Rabelo, 2006) was used. With AHP utilizing the simulation model outputs, decision makers can build on their experiences and consider relevant tradeoffs (political, social, technical, etc) in making the final decision. This also increases the decision makers' confidence in the expected outcomes.

For the value chain system, three decision makers – Chief Financial Officer, Chief Operations Officer, and Vice-President of Sales/Marketing – engage in the strategic decision making process by expressing their preferences. The weighted geometric mean method (Aull-

Hyde et al., 2006, Forman and Peniwati, 1998) is employed to estimate global weight of participant preferences while minimizing inconsistencies. All participants are weighted equally and the stochastic AHP approach is applied to the aggregated group estimates rather than individual estimates. Investigating the 95% confidence intervals of the global weights gained by the stochastic AHP methodology (Figure 6-44), it is noticed that there is considerable overlap between alternatives A and C.

The apparent ranking of the alternatives is B, A, then C. But the overlap between A and C indicates that they are tied and that further investigation is needed. Using the simulation of the stochastic AHP methodology, the summary of output results of 10,000 replications is given in Table 6-15. We can see that alternative B occupied the first place 99.99%. Alternative B does dominate A and C. However, the summary shows that alternative A and C ranked second 77.5% and 22.5% of the time, respectively, indicating that the null assumptions that alternative A is probabilistically superior to alternative C is rejected.

Using the stochastic AHP analysis with the hybrid simulation outputs could confirm the decision that outsourcing the manufacturing facility as in Alternative B in the best choice for the current value chain system over the planning horizon.

Table 6.15 Simulation results of the stochastic AHP for ranking the outsourcing alternatives

	Rank			**Rank**		
Alternative	**1**	**2**	**3**	**1**	**2**	**3**
A	1	7747	2252	≈0.0%	≈77.5%	≈22.5%
B	9999	1	0	≈100%	≈0.0%	0.0%
C	0	2253	7747	0.0%	≈22.5%	≈77.5%
Totals	**10000**	**10000**	**10000**	**100%**	**100%**	**100%**

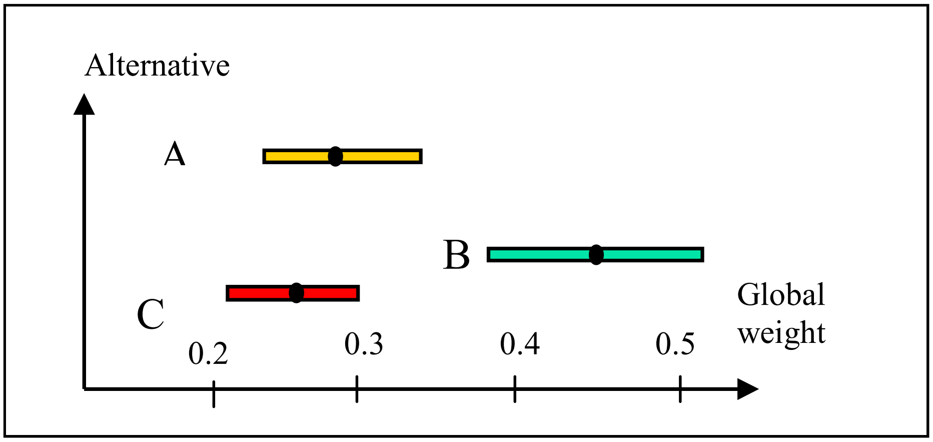


Figure 6.44 Global weights of the outsourcing alternative based on the stochastic AHP analysis

6.3 Comparing SDDES and AnyLogic

This section presents the results of comparing a hybrid simulation model of SD and DES units built using AnyLogic with the same model built using the SDDES framework. AnyLogic is being marketed as the only commercial simulation package that combines comprehensive DES and SD simulation building tools in the same interface with the ability to combine them. The objective of the comparison is benchmarking SDDES with AnyLogic as well as providing insights about how AnyLogic implements the interactions between SD and DES.

As discussed in Chapter 2, AnyLogic implemented the hybrid state machine process (Maler et al, 1992, Harel, 1987) to provide tools to build hybrid discrete and continuous simulations. Objects for traditional DES simulation and dynamic variables for SD modeling are accessible from within the same user interface. Yet AnyLogic users need to be Java programmers. Technically, AnyLogic is a Java programming interface that offers pre-designed classes of objects for simulation purposes.

In conducting this study we contacted representatives of XJ Technologies; the vendors of AnyLogic and requested them to demonstrate interfacing SD and DES models in AnyLogic. They recommended using the dynamic event object (See Chapter 2) and provided an AnyLogic model that used the dynamic event to interface a SD and a DES objects. This model is based on the classical pass diffusion model with added DES objects. Although this AnyLogic model included a stochastic DES part, it used AnyLogic's default simulation experiment, which allows for a single simulation run replication only. For statistical validity we also requested them to demonstrate replicating the DES unit. But since the default simulation experiment in AnyLogic does not allow replication, they recommended writing Java code to replicate the stochastic DES model part. A Java repetition construct (e.g. FOR or WHILE-DO structure) can be used to control the simulation experiment and replicate the DES part of the hybrid SD-DES model. Using Java required separating the SD and DES parts into separate objects.

AnyLogic does not provide any particular support to synchronizing a deterministic SD model and a replicated stochastic DES model. But as a programming language interface and since many objects can be included in the model, modelers can resort to their programming skills to design any special simulation run scenarios.

The AnyLogic model was modified to use a For-loop statement for replicating the DES object as will be described later. We then built an equivalent SDDES model and compared the results generated by it to the results generated by the AnyLogic model.

The DES models can be built in AnyLogic using the enterprise library (a collection of objects representing the common elements used in the traditional flowchart-based DES simulation modeling). SD models can be built using the stocks and flow rate variables (called dynamic variables). In its current version 6.0, AnyLogic allows two approaches to interface the SD variables and the DES objects:

1. Using the statechart object: state charts are defined within an object to control its behavior. The transition from a state to a state is a timeless discrete event that can be triggered by changes in the state of the system (the occurrence of other events) or based on the advance of the simulation time. To incorporate the continuous behavior, Java code that references one or more continuous variables can be linked to a transition or a state (See Chapter 2) to trigger an event to take the transition or update the system state based on the values of the continuous variables.
2. Using the dynamic event object: this special type of event was added in AnyLogic 6 as a simplified form of using the statechart. The dynamic event object can be scheduled to occur as a reaction to a condition that has just been met, or to act at specified points in time, in such case it is used as a timer. The action to be taken is defined in the event using java.

Further, since the SD variables in AnyLogic are treated as variable not objects, these variables can be directly referenced in the mathematical formulas or within the code used in any other object in the simulation model as indicated.

AnyLogic models are run by the execution of an instance of the object class Experiment.

The default simulation experiment does not allow replications in the simulation run. The parameter variation experiment can be added to the model to execute several single model runs while varying one or more root object parameters within specified ranges, for comparative and sensitivity analysis purposes. The optimization experiment can be used to perform performance and design optimization analysis. Using Java, users can also define custom experiments, which is the case in the current comparative discussion.

Thus, AnyLogic provides no support to develop hybrid SD-DES simulation as described in the SDDES framework except by using Java. In the following subsections, we compare the AnyLogic model to an equivalent SDDES model. The purpose of the comparison is to demonstrate the potential of SDDES to synchronize the separate SD and DES modules and simplify the model building process.

6.3.1 The AnyLogic model

As shown in Figure 6-45, AL represents a hypothetical supply and demand situation, where the demand for a certain product is modeled in SD while the supply is modeled in DES; forming a closed feedback loop. The variables in the SD section of the model are defined below:

- PotentialAdopters: the total population who under the effect of advertisement generate demand for the product.
- Demand: the current unmet demand for the product
- AdEffectivness: the level of effectiveness of advertisement; convincing

PotentialAdopters to demand the product

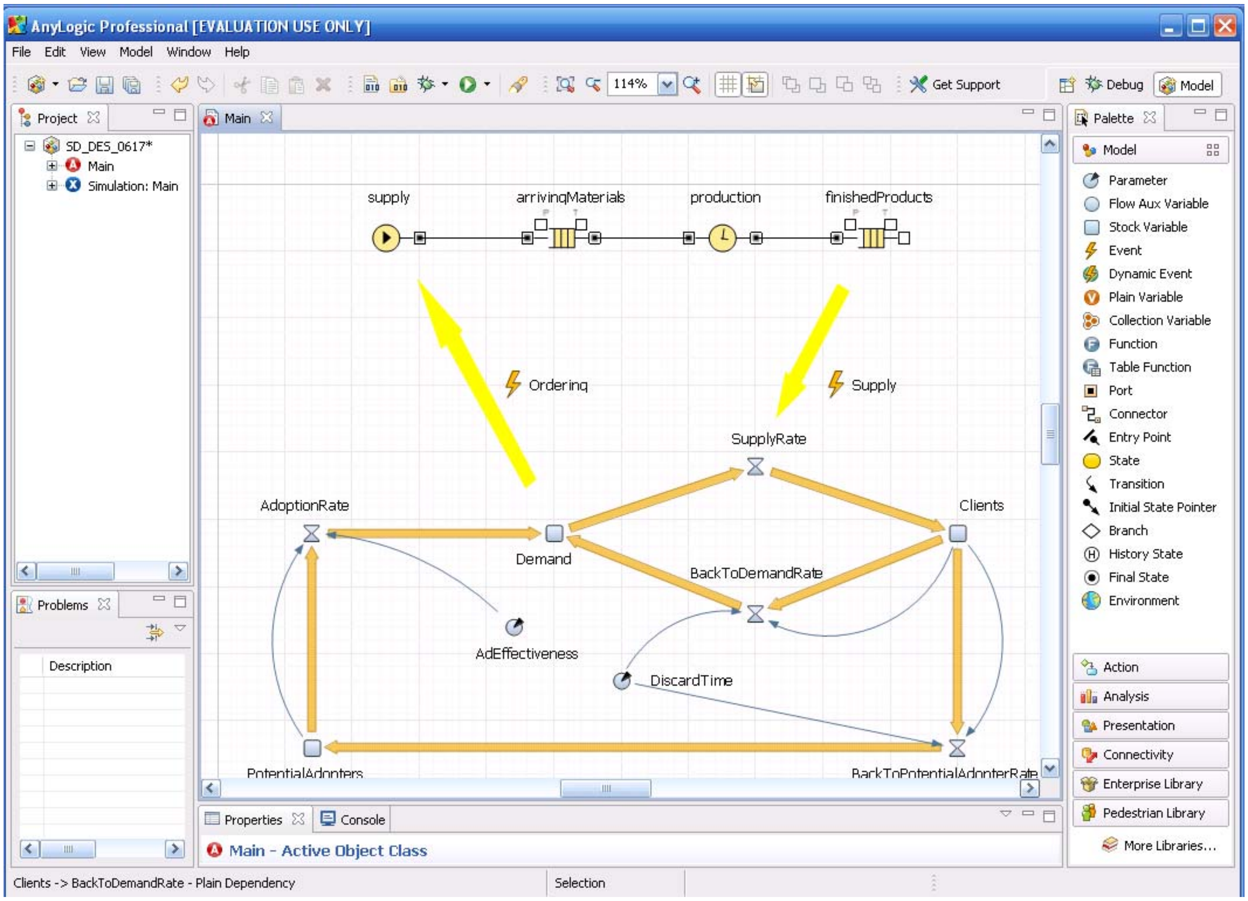


Figure 6.45 The AnyLogic model: SD variables (lower part) and DES objects (upper part)

- AdoptionRate: the rate at which PotentialAdopters create demand
- Clients: the product adopters level
- DiscardTime: the product service life, after which Clients discard the product and return to be PotentialAdopters or to demand new product units
- BackToDemandRate: rate at which Clients discard the product and demand new units
- BackToPotentialAdoptersRate: rate at which Clients discard the product and return to

the general population.

- SupplyRate: rate at which adopters move from Demand to Clients.

The SupplyRate represents the rate of decrease of the Demand and the rate of increase of the Clients. It is input from the DES section of the model which in turn receives the Demand level as the input.

The objects in the DES section are defined below:

- supply: a source object that cause the creation of the entities (raw materials units) in at the production line. It is driven by the Demand level provided by the SD section.
- arrivingMaterials: a queue object where new arriving materials can wait until the availability of the production resources.
- production: a delay object to model the processing delay of the material units. Materials are delayed for the specified processing time before they can proceed
- finishedProducts: a queue object where final product units may wait until pulled to the SupplyRate in the SD section.

The interactions between the SD and DES are implemented using the two dynamic event objects: Ordering and Supply shown in Figure 6-45. The ordering event communicates the Demand level to the production facility (DES) at the beginning and middle of each workday. The Demand level becomes the number of arriving material units at the supply object. The Sales event communicates the number of final product units at the production facility to the SupplyRate variable at the SD section. This is done at the middle and end of each workday.

Thus the model works by following the three overlapping negative causal loops shown in Figure 6-46. This causal loop diagram also applies to the SDDES model.

1. Loop 1: Higher level of potential adopters creates a higher level of demand which increases ordering at the production facility. Production and consequently the clients level will increase. The increase in clients decreases the potential adopters' level.
2. Loop 2: Higher level of demand increases ordering at the production facility to increase production and consequently increases the clients level. The increase in clients decreases the demand level.
3. Loop 3: the higher the demand the higher the clients level but as the clients level increases the demand level will decrease.

Since this AnyLogic model can only run for a single replication it does not give statistically valid results. If the model is run for a number of times using different streams of random numbers each time, an independent set of data samples can be generated to perform useful statistical analyses. This forces the deterministic objects in the model to be replicated as well. More statistical analysis and programming efforts will be needed to collect the output and perform the output analysis of the results.

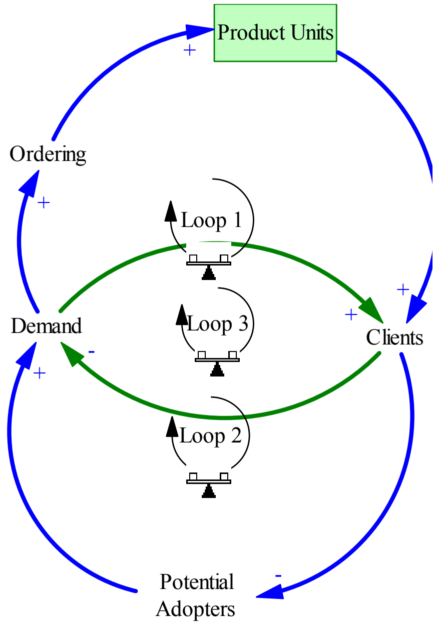


Figure 6.46 Overlapping causal loops in the AnyLogic model. The shaded box; Product Units indicate the DES section of the model

6.3.2 Replicated DES object in the AnyLogic model

We asked the XJ Technologies representatives to demonstrate running their AnyLogic model such that only the DES section is replicated. They used the Java for-loop programming structure for that purpose. In order to replicate DES, it has to be isolated in a separate object in the simulation model. The DES and SD parts in Figure 6-45 were separated in two objects. The SD object was designated as the main root object for the simulation run experiment. While SD is running, a dynamic event object executes the for-loop code to instantiate the DES object, instantiate the simulation engine object, run the DES instance, and then destroy all object instances in each loop. Meanwhile the object is collecting the discrete data. Each loop thus represents a replication. The pseudo code implementing the looping structure to run the DES object for a number of replication from within the run of the SD object is listed below. This pseudo code uses AnyLogic's Java methods and functions. It can be used in the action section of a dynamic event, which should be added to the SD object. The replication counter is i while *reps* is used to denote the number of replications. Engine is the AnyLogic simulation engine object class and *engine* is an instance. DES is the discrete simulation object and *des* is an instance. The runFast()method is a Java method applies to the Engine object and causes the DES object instance to run in the virtual time.

```
for ( int i=0; i<reps; i++ )
{
    // create a new engine instance
    Engine engine = new Engine();

    // create a new DES model instance to run
    DES des = new DES( engine, null, null );

    // actions before running model instance
    ....
    ....
    ....

    // start and running the DES instant
    engine.start( des );
    engine.runFast();

    // actions before end of run # i
    ....
    ....
    ....

    // end run # i and destroy model instant
    engine.stop();
 }

// actions for all replications (collecting model outputs)
    ....
    ....
    ....
```

6.3.3 The hybrid SDDES model

The equivalent SDDES model made use of the SDDES controller testbed described in Chapter 5. Figures 6-47 and 6-48 show the SD and the DES modules respectively (Using Vensim and Arena respectively). The SDDES model matches AL as described in Table 6.16

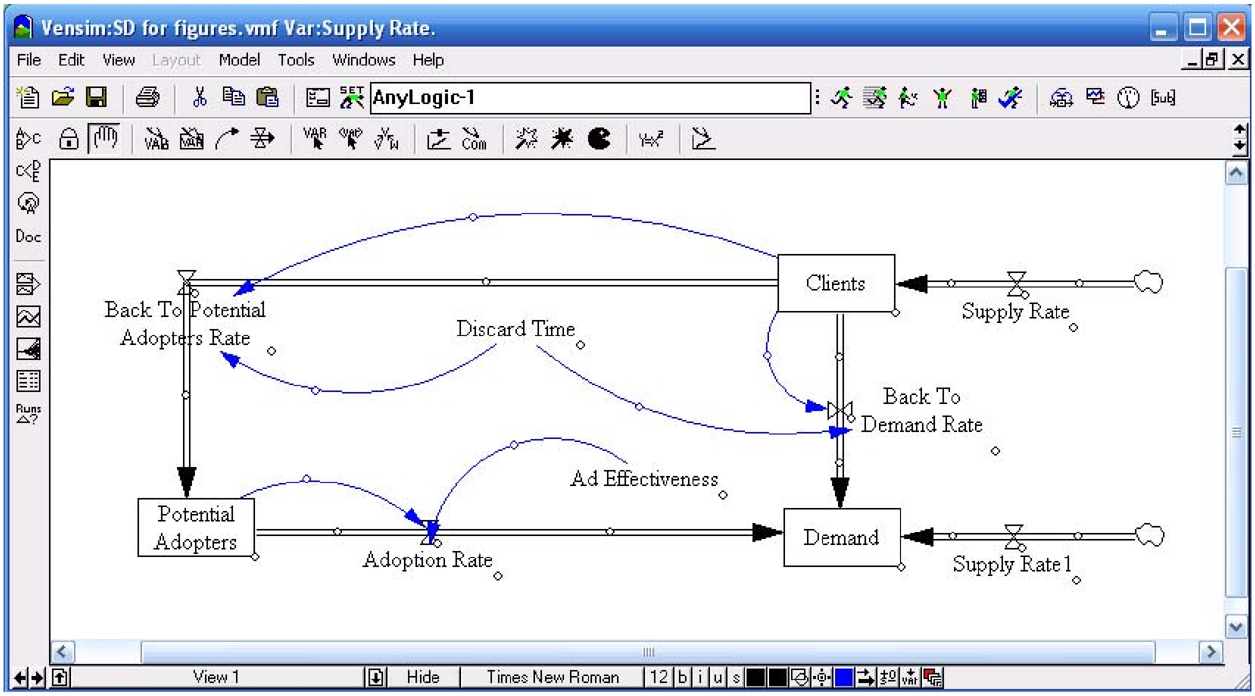


Figure 6.47 The SD module of the SDDES model

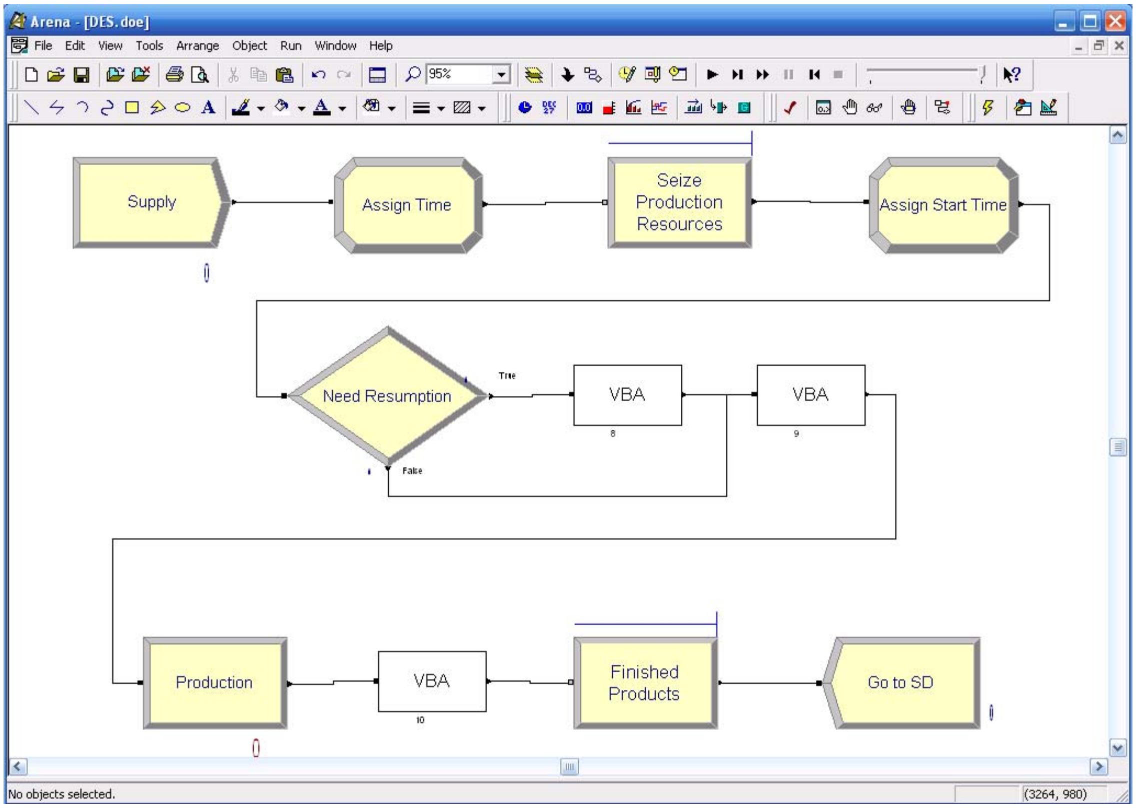


Figure 6.48 The DES module of the SDDES model

Table 6.16 Corresponenence between the AnyLogic and the equivalent SDDES models

Model Element	AnyLogic	SDDES
SD		
Potential Adopters	Stock variable changing by the net effect of the inflow BackToPotentialAdoptersRate and outflow AdoptionRate flow rates. Units: Person	Stock variable changing by the net effect of the inflow Back To Potential Adopters Rate and outflow Adoption Rate flow rates. Units: Person
Advertising effectiveness	Parameter AdEffectiveness = 0.01 Dimensionless	Constant Ad Effectiveness = 0.01 Dimensionless
Product adoption rate	Flow rate variable AdoptionRate = (PotentialAdopters)(AdEffectiveness) Units: Person / day	Flow rate variable Adoption Rate = (Potential Adopters)(Ad Effectiveness) Units: Person / day
Demand	Stock variable changing by the net effect of inflows AdoptionRate and BackToDemandRate and outflow SupplyRate. Units: Person	Stock variable changing by the net effect of inflows Adoption Rate and Back To Demand Rate and outflow Supply Rate 1. Units: Person
Clients	Stock variable changing by the net effect of the inflows SupplyRate and outflows BackToPotentialAdoptersRate and BackToDemandRate Units: Person/day	Stock variable changing by the net effect of the inflows Supply Rate and outflows Back To Potential Adopters Rate and Back To Demand Rate Units: Person/day
Product discard rate w/o demand	Flow rate variable BackToPotentialAdoptersRate; function in Clients level and DiscardTime Units: Person / day	Flow rate variable Back To Potential Adopters Rate; function in Clients level and Discard Time Units: Person / day
Product discard rate w/ demand	Flow rate variable BackToDemandRate; function in Clients level and DiscardTime. Units: Person / day	Flow rate variable BackToDemandRate; function in Clients level and DiscardTime. Units: Person / day
Product useful service life	Parameter DiscardTime = 10 Units: day	Constant Discard Time = 10 Units: day
Production supply	Flow rate variable SupplyRate that is function in input from the DES unit Units: Person/day	Flow rate variable Supply Rate that is function in input from the DES unit. Flow rate variable Supply Rate 1 is used as outflow to Demand while Supply Rate is used as inflow to Clients. The two flow rates are equal and both are based on DES input. Units: Person/day
DES		
Entities creation	Source object supply that creates a number of entities equal to the imported value of the Demand level	Create module Supply that creates a number of entities equal to the imported value of the Demand level
Raw materials storage	Queue object arrivingMaterials. Entities wait until production capacity units are available at the production object. Entities then proceed to use available capacity	Seize module Seize Production Resource. Entities wait at the module's queue until resource units are available at the Production module. Entities are matched with available resource units then they proceed.

Model Element	AnyLogic	SDDES
DES		
Production	Delay object production where entities are delayed for the specified processing time. Processing time is assigned at the delay module	Delay module Production where entities are delayed for the specified processing time. Processing time is assigned at the Assign module Assign Time.
Final product storage	Queue object finishedProducts where product units are stored until pulled to the SD model unit	Hold module Finished Products where product units are held in its queue until released by the SDDES controller to be exported to the SD module

Let the SD module of SDDES be referred to as SDmodule and the DES module be referred to as DESmodule. In the SDDES formalism format, SDmodule is specified as follows:

$$SD\mathrm{mod}ule = (SD, X_{SD\mathrm{mod}ule}, Y_{SD\mathrm{mod}ule}, P_{SD\mathrm{mod}ule}, CONT)$$

The sets of inputs and outputs of SDmodule are presented in Table 6-17. The DESmodule is expressed in the SDDES formalism as given below. The sets of inputs and outputs of DESmodule are given in Table 6-18.

$$DES\mathrm{mod}ule = (DES, X_{DES\mathrm{mod}ule}, Y_{DES\mathrm{mod}ule}, P_{DES\mathrm{mod}ule}, TB)$$

Table 6.17 Inputs and outputs of the SDmodule module

$X_{SD\text{module}}$							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
SDmodule	FINISHED PRODUCTS	DESmodule	OP_DESmodule_01	IP_SDmodule_01	SUPPLY RATE	TB	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
					SUPPLY RATE 1	TB	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
$Y_{SD\text{module}}$							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
SDmodule	OP_SDmodule_01	DEMANDi	DESmodule	IP_DESmodule_01	DEMAND SIZE	STARTUP	NONE
SDmodule	OP_SDmodule_02	DEMAND	DESmodule	IP_DESmodule_02	DEMAND SIZE	TB	NONE

FINISHED PRODUCTS: number of finished product units as given by the Finished Products module in DESmodule
SUPPLY RATE: the flow rate variable Supply Rate in the SDmodule
SUPPLY RATE 1: the flow rate variable Supply Rate 1 in the SDmodule
OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE: input variable is based on observational data from DES that was collected over TB, and should be converted into a rate variable over the simulation base time unit to be usable in SD.
DEMANDi: initial demand level
DEMAND: the current Demand stock level
DEMAND SIZE: corresponding demand level variable at DESmodule

Table 6.18 Inputs and outputs of the DESmodule module

$X_{DES\text{module}}$							
m	vi	m_s	op_{ms}	U_m			
				ip	u	t	f
DESmodule	DEMANDi	SDmodule	OP_SDmodule_01	IP_DESmodule_01	DEMAND SIZE	STARTUP	NONE
DESmodule	DEMAND	SDmodule	OP_SDmodule_02	IP_DESmodule_02	DEMAND SIZE	TB	NONE
$Y_{DES\text{module}}$							
m	op	vo	D_{Ym}				
			m_d	V_{md}			
				ip_{md}	u_v	t	f
DESmodule	OP_DESmodule_01	FINISHED PRODUCTS	SDmodule	IP_SDmodule_01	SUPPLY RATE	TB	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE
					SUPPLY RATE 1	TB	OBSERVATIONAL_DES_TB >> TB_BASE_TIME_RATE

6.3.4 Comparing SDDES to AnyLogic

The models were set to simulate the performance of the system on a daily basis. The SD and DES modules/objects exchange the demand and production level. The current demand and current production are updated twice a day. For the simple AnyLogic model (Figure 6-45), the dynamic event Ordering updates the DES model part with the current demand level every 0.5 day starting at time zero. Demand level is inserted at the source object supply as the number of material units to be processed. The dynamic event Supply checks for the availability of the finished product units at the finishedProducts object, and for the demand level value. It matches demand and production and communicates the current production rate to the SD flow rate variable: SupplyRate to update the Demand and Clients stocks.

When the looping structure is implemented, the DES is removed to a separate object. The dynamic event Ordering (in the SD object) is scheduled to occur every 0.5 time units starting at time zero, to perform the instantiation of the DES object and the simulation engine and to run the discrete instance for 30 replications. The event collects the production rate data and the state of the production line at the end of the object instance run.

Since the DES is required to provide productivity data every 0.5 time unit, the DES instance of the object and the simulation engine instance are destroyed upon completing the 30 replications. By default the DES instance would run for the entire simulation run length. In the current analysis, the simulation model is run for 100 days while interactions between the objects are executed every 0.5 day. The DES object instance will run for 100 days in each replication unless the object is destroyed at time 0.5. In AnyLogic the simulation run length is set for the experiment object and it affects all objects referenced in the experiment. AnyLogic does not allow running more than one experiment at a time.

Further, and since the dynamic events in AnyLogic are discrete, their occurrences are timeless. Once the replications of the DES object instance are completed the simulation experiment's focus returns to the SD object. Although DES may contain discrete objects that perform time-consuming tasks (e.g. processing) the focus of the simulation run returns to the SD object at the same point in time when the event occurred. The DES object is not aware of the simulation time. Programmed delays must be included in order to instruct the SD object not to use the DES inputs until the correct time to use them. In the SDDES framework, synchronizing the modules run and the use of data is controlled completely by the SDDES controller.

To compare the SDDES model and the AnyLogic model, the models were run for a period of 100 days. The TB for the DESmodule of SDDES was set at 0.5 day and 30 replications were performed in each segment. The dynamic events in the AnyLogic model were scheduled to occur every 0.5 days. The Java for-loop subroutine in the AnyLogic model was set to perform 30 replications. The Demand, Clients, and Potential Adopters levels were monitored for the two models. The initial potential adopters' population is 1000. The initial Demand level is five. The initial Clients level is zero. The ad effectiveness constant is 0.01 and the product useful service time is 10 days. It is assumed that any unused final product units are discarded.

6.3.5 Results and discussion

Figures 6-49 through 6-51 compare the levels of Demand, Clients, and Potentials Adopters for the AnyLogic and SDDES models. The results show similar and equivalent results from the two simulations. The 2-sample t-test for the difference between the means shows no evidences at 95% confidence level, to reject the null hypothesis that the results from the two simulations are equivalent. The test results are shown in Tables 6-19 through 6-21.

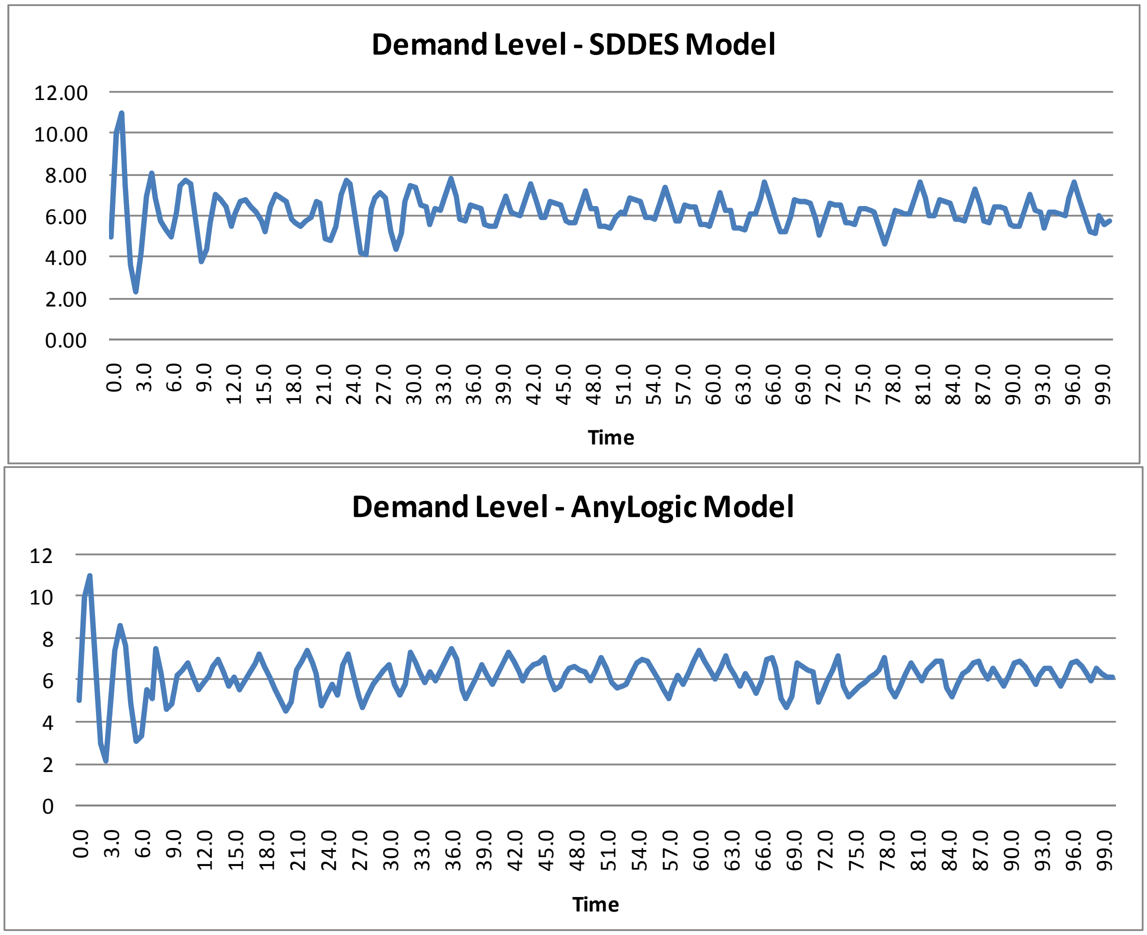


Figure 6.49 Equivalent demand level and behavior from SDDES and AnyLogic

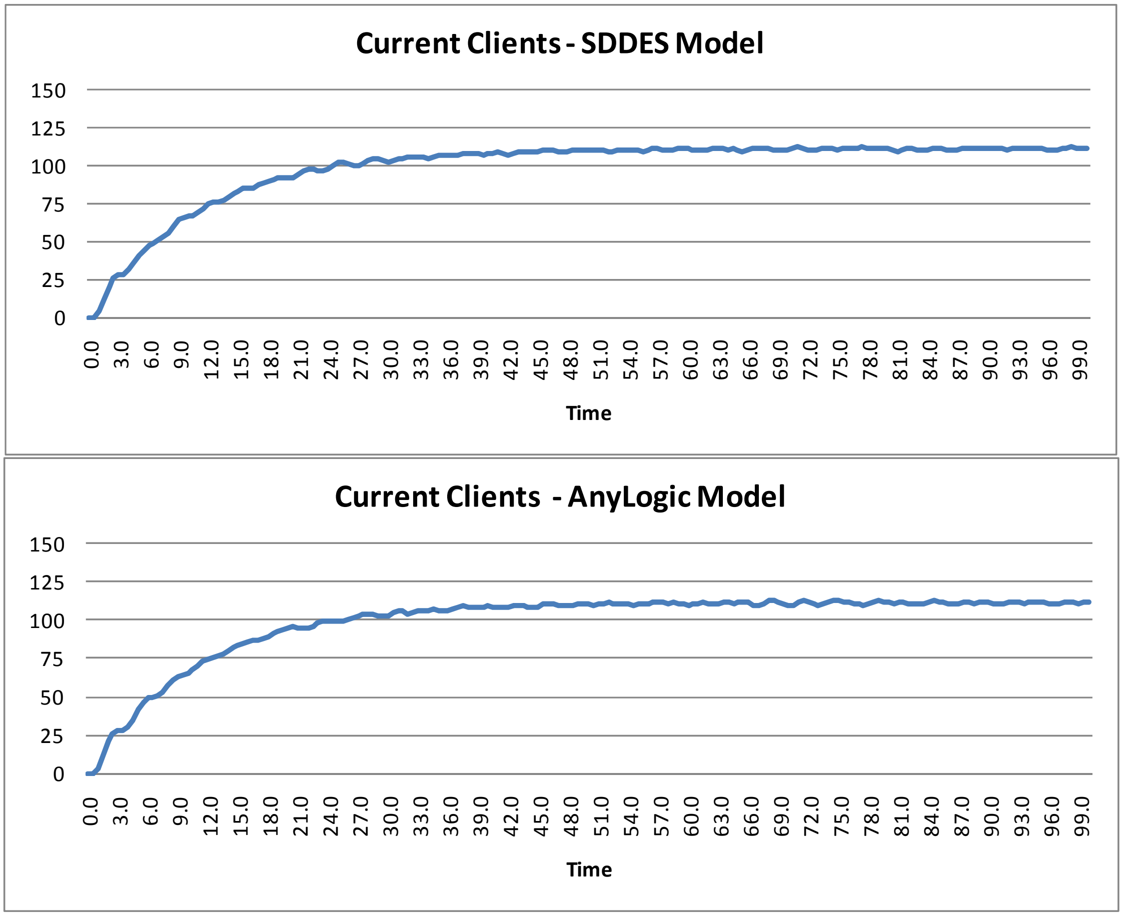


Figure 6.50 Equivalent clients level and behavior from SDDES and AnyLogic

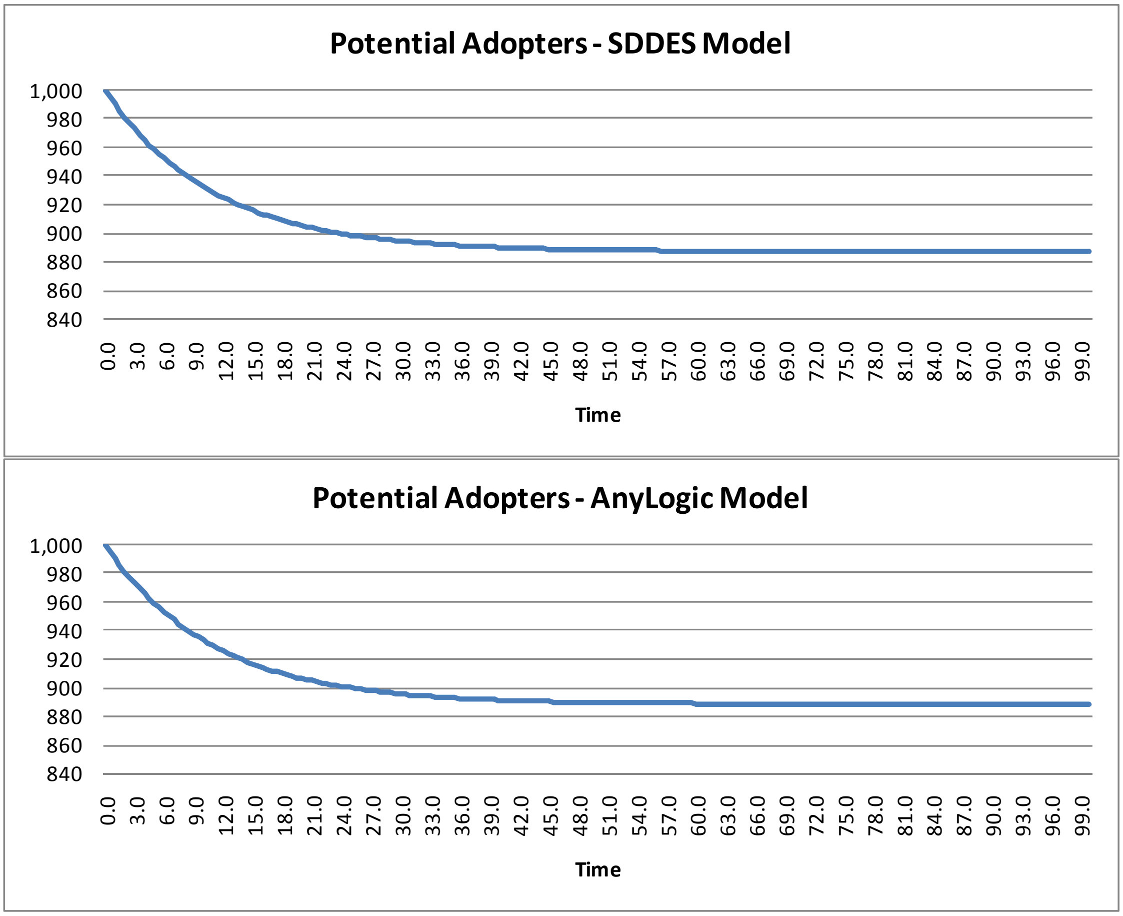
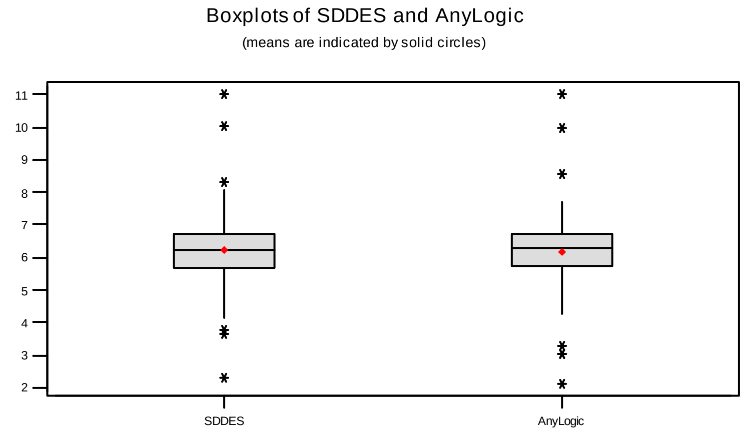


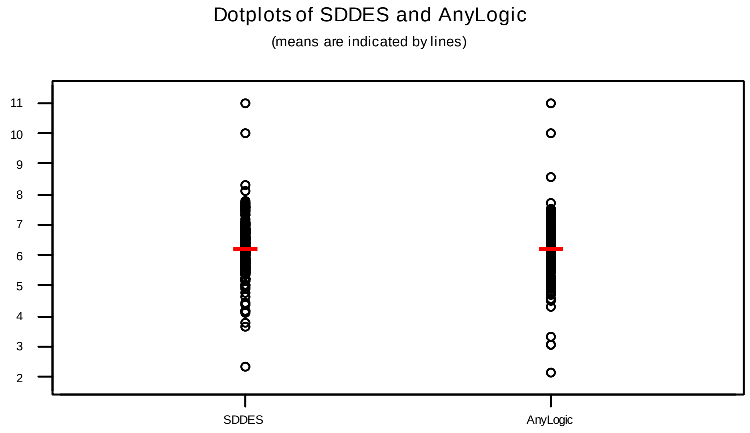
Figure 6.51 Equivalent potential adopters level and behavior from SDDES, AL_1, and AL_2

Table 6.19 2-sample t-test for the difference between mean demand levels – SDDES and AnyLogic

```
Two-sample T for SDDES vs AnyLogic

            N      Mean     StDev   SE Mean
SDDES     201     6.213     0.939     0.066
AnyLogic  201     6.189     0.935     0.066

Difference = mu SDDES - mu AnyLogic
Estimate for difference:  0.0238
95% CI for difference: (-0.1599, 0.2075)
T-Test of difference = 0 (vs not =): T-Value = 0.25  P-Value = 0.799  DF = 399
```


Boxplots of SDDES and AnyLogic

(means are indicated by solid circles)


Dotplots of SDDES and AnyLogic

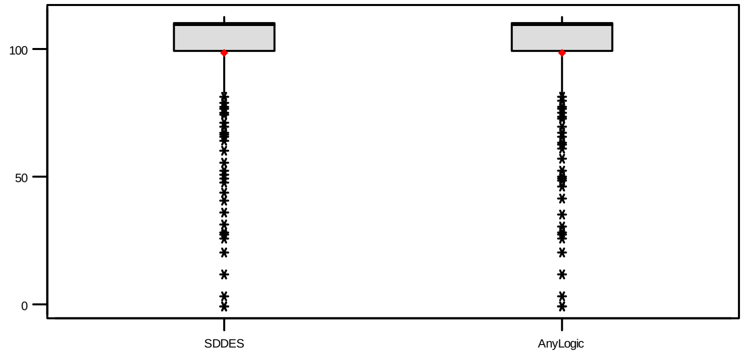
(means are indicated by lines)

Table 6.20 2-sample t-test for the difference between mean clients levels – SDDES and AnyLogic

```
Two-sample T for SDDES vs AnyLogic

            N      Mean     StDev   SE Mean
SDDES     201      98.5      23.7       1.7
AnyLogic  201      98.5      23.7       1.7

Difference = mu SDDES - mu AnyLogic
Estimate for difference:  0.02
95% CI for difference: (-4.63, 4.67)
T-Test of difference = 0 (vs not =): T-Value = 0.01  P-Value = 0.994  DF = 399
```

Boxplots of SDDES and AnyLogic

(means are indicated by solid circles)



Dotplots of SDDES and AnyLogic

(means are indicated by lines)

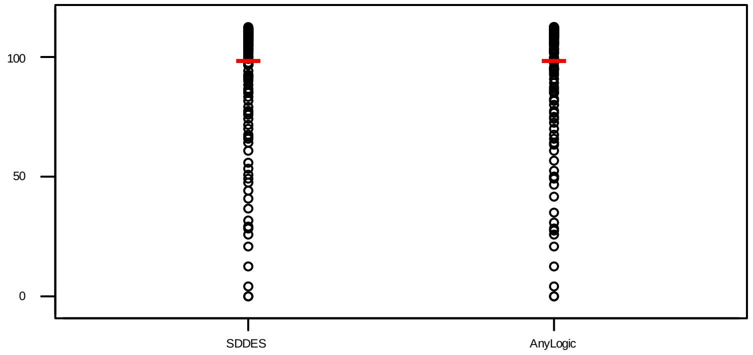
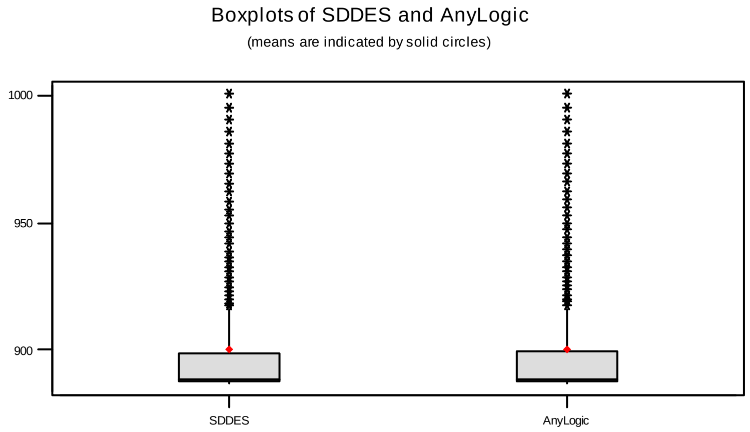


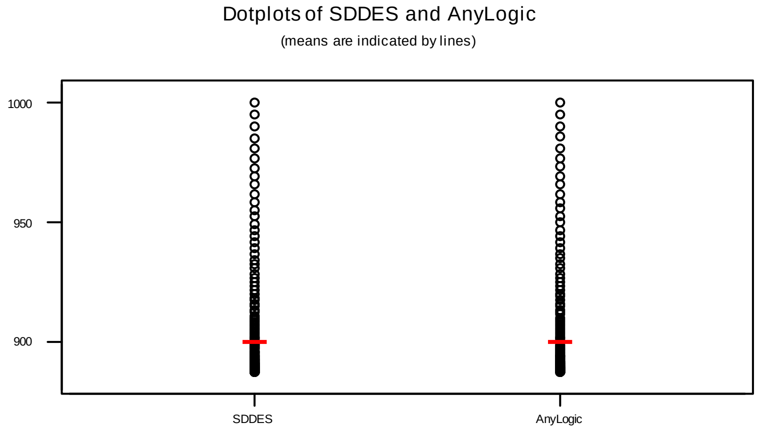
Table 6.21 2-sample t-test for the difference between mean demand levels – SDDES and AnyLogic

```
Two-sample T for SDDES vs AnyLogic

            N      Mean     StDev   SE Mean
SDDES     201     900.0      23.7       1.7
AnyLogic  201     900.2      23.8       1.7

Difference = mu SDDES - mu AnyLogic
Estimate for difference:  -0.13
95% CI for difference: (-4.79, 4.53)
T-Test of difference = 0 (vs not =): T-Value = -0.06  P-Value = 0.956  DF = 399
```



Boxplots of SDDES and AnyLogic

(means are indicated by solid circles)



Dotplots of SDDES and AnyLogic

(means are indicated by lines)

It is concluded that the SDDES hybrid simulation framework can compare to AnyLogic for integrating SD and DES simulations. SDDES could generate equivalent outputs to AnyLogic. Further, it could integrate autonomous simulations built using different software without necessitating additional programming efforts (as does AnyLogic) or modifications to the simulation models

Synchronizing SD and DES model objects in AnyLogic requires advanced programming skills (using Java) even when working inside the same environment. The use of discrete events (the dynamic event object or the state chart triggered actions) necessitates introducing information delays for the correct timing of using the data generated by the DES objects. Since the dynamic events as all events, are discrete and their occurrences of events are timeless, the instance of any DES objects running within the execution of the event cannot be aware of the simulation time (assuming using a looping structure as in this section). All data generated by the DES object instance will be returned to the simulation experiment (and the calling SD object) at the same point in time when the DES object was instantiated. A forced programmatic information delay is needed to delay using the DES data to the right point in time.

Easier synchronization would be possible if each DES and SD object could be run in a separate AnyLogic experiment object such that the run time can be set for each separately and data exchange transactions can be simpler. However, AnyLogic does not allow running more than one experiment at the same time. In response to our quest to whether Java can be used to allow parallel experiments, the head of the consulting department at XJ Technologies (an AnyLogic modeler and Java programmer) stated that “I would not go into any parallel execution for now due to its implementation is more difficult”.

It is worth noting that XJ Technologies stopped supporting HLA’s RTI for synchronizing separate simulations in AnyLogic 6.0. Instead, Java programmers can use Java to develop and utilize tools based on the TCP/IP protocols to synchronize such simulation objects. Stopping the support for HLA/RTI follows a trend among simulation software vendors who do not see demand for using HLA/RTI in the manufacturing and industrial applications (See Boer, 2006a, and Poer, 2006b).

Thus we can conclude that SDDES can compare to AnyLogic in integrating SD and DES models and unlike AnyLogic, modelers and users of SDDES do not need to learn new modeling skills and they need no programming efforts to achieve the integration. Moreover, autonomous SD and DES simulations built using different software packages can be interfaced using SDDES. Existing/legacy simulation models can be used with SDDES without any specific modifications to them.

6.4 The Control Function of SDDES

The stated purpose of using SDDES is the management policy design and testing. As a simulation model, the uses of the SDDES model are not limited to policy design. The control function is the first that should be mentioned. The common uses of simulation in the manufacturing system control applications are focused at the operational/shop floor level and are generally concerned the ability to monitor the system on the short term basis (commonly in realtime) and the scheduling/rescheduling situations in response to uncertainties at the schedule execution levels (Jones et al., 2001; Cowling and Johansson, 2002; Aytug et al, 2005; Son et al, 2005; Cho et al., 2006; Sinreich and Shints, 2006; Pfeiffer et al., 2008).

SDDES has been designed such that it maintains the integrity of the SD and DES simulation methodologies. Thus, in addition to the ability of the SDDES to develop comprehensive simulations of the manufacturing system and explain its behavior, the feedback loops in SDDES can provide the tools to assess the ability of the system to perform self-control and act to handle the deviations from the desired levels of behavior due to unexpected events at the operational or at the aggregate level as well. This can indicate if the system is adequately robust and well-structured.

In this section we discuss the control applicability of SDDES to the manufacturing system, with a focus on the designing a self-control capability in the simulation model.

6.4.1 Decoupling the SD and DES modules

It has been shown in section 6-1 that the exchange of data between the SD and DES modules allowed the system to react to unexpected shortages in production at the shop floor. The weekly planned material usage and desired production rates along with the assigned capacity and other operational settings were estimated and decided by SD and communicated through the controller to the PREF and PRES modules. Daily feedback from PREF and PRES provided the basis for the SD to assess the performance and update its estimates. Figure 6-29 (section 6-1) showed that the finished goods inventory level could be adjusted when it was found to fall below the desired level to support the planned shipping performance. In such situations, extra raw materials were ordered and released at the production lines to increase productivity for the inventory level to recover to equilibrium and maintain the desirable shipping performance.

In this section, the SD and DES modules are decoupled. The estimated customer order rate, desired shipping and productivity performance, and the allocated resources are decided at the beginning of the planning horizon at SD. The DES modules are run to execute the plan but and they provide their feedback data to SD. SD is assumed to be unable to react to the deviations in DES until the end of the planning horizons (s quarter). The performance of the system was observed for the finished inventory and shipping performance.

Figure 6-52 describes the interactions between the SD and DES modules in the decoupled run of SDDES. The SD modules are allowed to interact as described in section 6-1. Initial system settings are provided by the SD modules for the PREF and PRES modules. Feedback from DES is not reacted to by SD. Instead the planned material usage, production, and shipping rates hold during the planning horizon. The * in variables names indicate initial values estimated at the beginning of the planning horizon and are expected to hold valid. This creates an open feedback loop structure between the SD and DES modules.

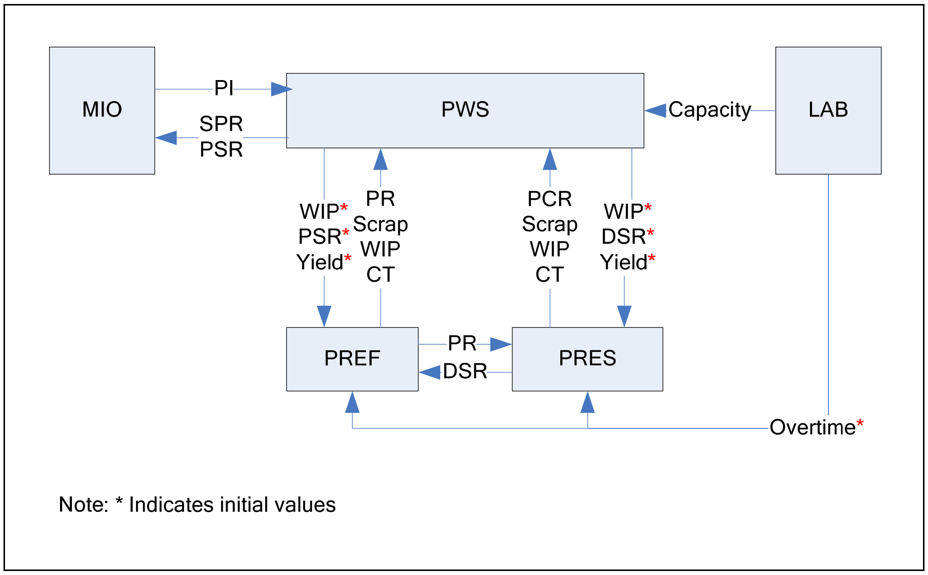


Figure 6.52 Data exchanged between the SD and DES modules – open feedback loop communications

6.4.2 Results and implications

Figure 6-53 shows the behavior of the final product inventory relative to the customer order rate. As was the case in section 6-1, the inventory level fell short of the customer order rate after the first week. By comparing Figure 6-53 with Figure 6-29 in section 6-1, it is observed that the system could correct itself within one and a half week (Figure 6-29) when SD was able to react to the deviations from the planned product and inventory level. When no control performed, the system could recover the inventory level to the customer order rate in three work weeks (Figure 6-53).

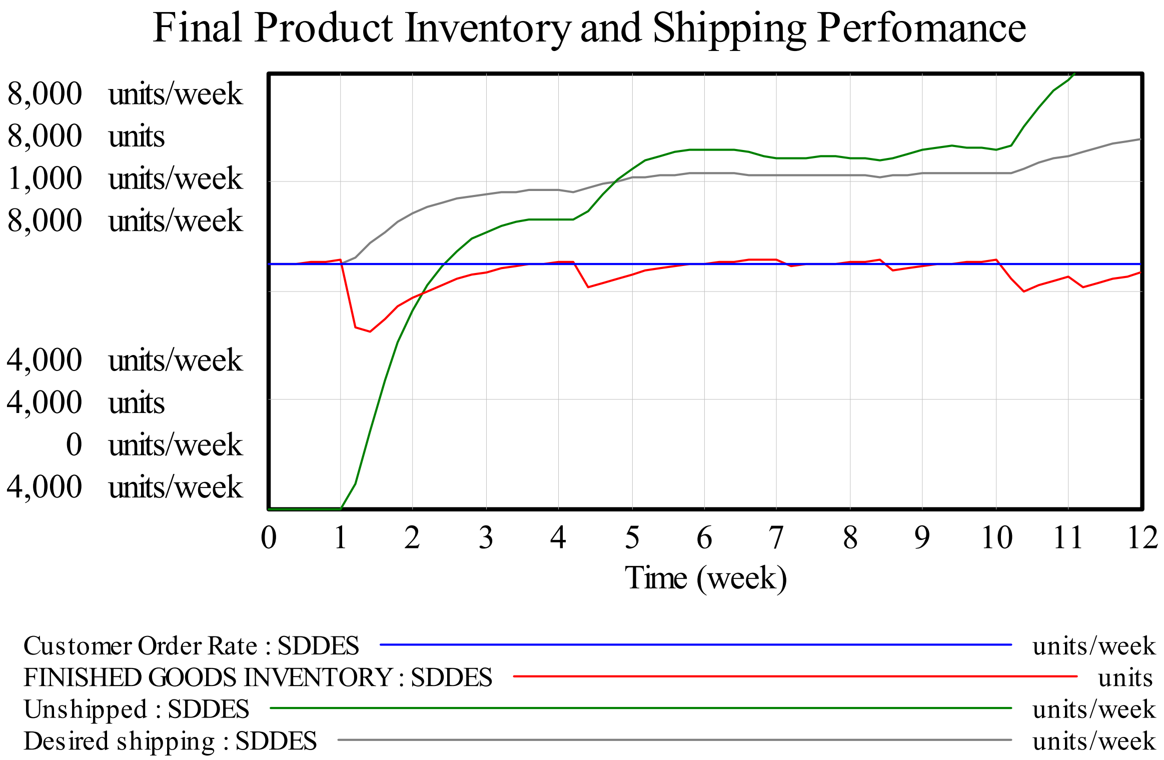


Figure 6.53 Final product inventory level and shipping performance – Decoupled SDDES

The drop in the product inventory level is caused by the sharp drop in production in the PREF and consequently in PRES as shown by Figure 6-54. The recovery of the inventory level to the customer order rate is driven by the fluctuating productivity on PREF. And since PRES is run a pull system and it pulls preforms based on the current customer order then it does not exceed the stated customer order rate and the system is never able to make up for the unshipped products. It is assumed for the purpose of this experiment that no correction actions are by SD. This in fact, gives more credit to SDDES as used in section 6-1 since it could easily capture the system's natural behavior represented by reactions of the decision makers.

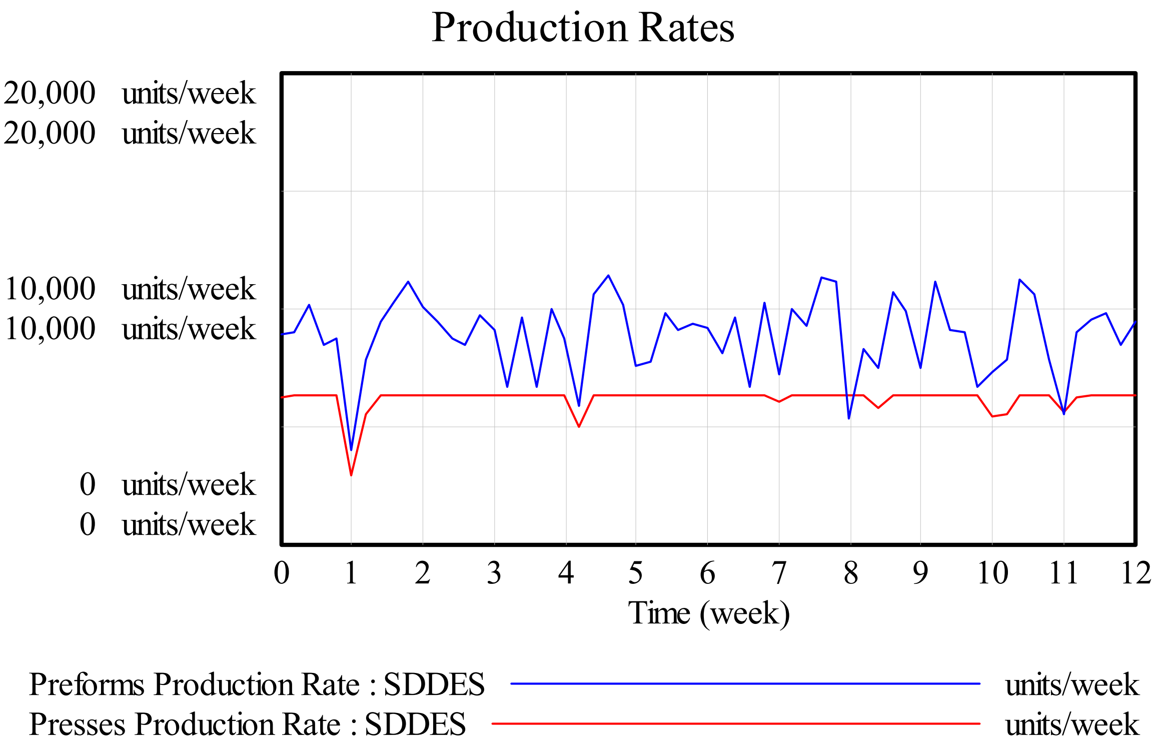


Figure 6.54 Production rates from PREF and PRES - Decoupled SDDES

As production is designed to meet the current customer order rate (raw materials from SD are from the current customer order rate only), the unshipped products accumulate as shown in Figure 6-53. Compared to Figure 6-29 in section 6-1, it is clear how the correction control actions at the SD level could drive the system to handle the unshipped products. Further, without the control effect the system is unable to respond to the customer orders on time and the delivery delay builds up as shown in Figure 6-55. A delay of up to 20% (compared to about 5% in Figure 6-30 in section 6-1) in the quoted delivery delay is experienced and it continues to increase.

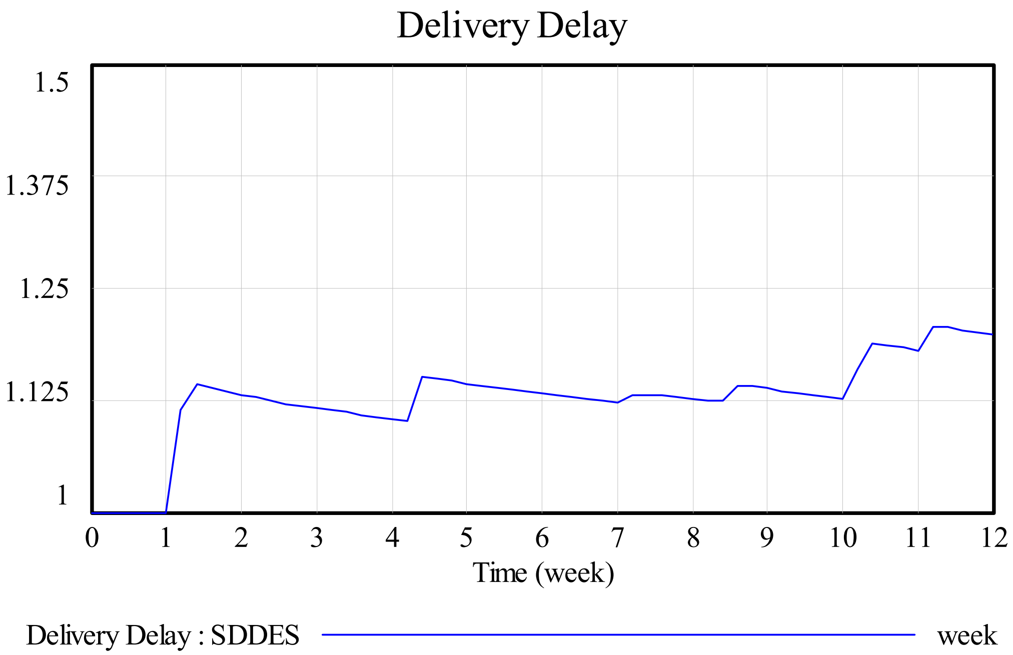


Figure 6.55 Delivery delay performance - Decoupled SDDES

In addition, the raw materials inventory level shows an increasing trend (Figure 6-56). This is driven by the scheduled production rate as also shown in Figure 6-56. The scheduled production rate in the PWS module is estimated to respond to the current customer order rate and to any unshipped orders. As the unshipped orders accumulate the scheduled production rate increases. Had the scheduled production been communicated to the PREF module, the system would have corrected its product inventory level and decreased or eliminated the delayed orders. This is compared to Figure 6-31 in section 6-1 in which the raw materials inventory follows the actual production performance at the shop floor in a responsive manner with less excess inventory. The fluctuations in the scheduled production rate in Figure 6-56 are due to the behavior of the work-in-process levels of PREF and PRES.

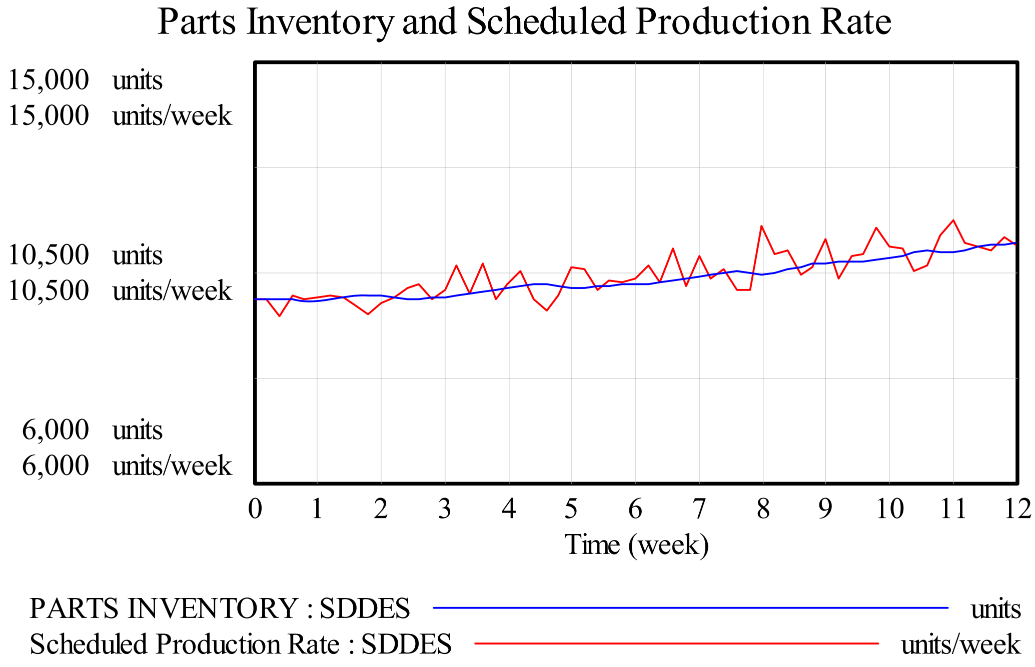


Figure 6.56 Raw materials inventory level and scheduled production rate - Decoupled SDDES

In conclusion, it was shown that the SDDES simulation model, in addition to simulating and providing explanation for the system behavior it could also provide insights on the robustness of the system structure and management policies in effect. The potential of using SDDES for robustness assessment and, possibly, longer term real-time control has been highlighted. A potential use of SDDES in relation to the real-time control application would be accumulating knowledge and developing libraries of reference modes (by running the model for different settings) of the system behavior for the planning horizon. The reference modes can be used in conjunction with defining the threshold levels commonly used in the short term real-time control systems to support the decision making process in reaction to the deviations from the expected performance.

In section 6-1, it was shown that the PMO manufacturing system is designed adequately well to correct itself whenever deviations from the planned performance occur and given that the SDDES model captured the self-control capability of the system. However, due to the inherent sources of fluctuations, the system undergoes periods of out-of control performance that can persist and it cannot fully recover to equilibrium. Decoupling the SD and DES modules has emphasized the effect of these sources of fluctuations and supported the analysis made in section 6-1.

CHAPTER 7: CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

This research proposed a framework to integrate the SD and DES methodologies for simulating the manufacturing enterprise system. This SDDES simulation framework can build inexpensive, comprehensive, scalable simulations that support the management policy design and analysis on an enterprise-wide level. This chapter summarizes the conclusions and contributions of this research and highlights directions for future research.

7.1 Conclusions

Simulation modeling has been and will continue to be the most effective way for analyzing the performance and designs of the manufacturing systems. But the evolution of the manufacturing system and the continual changes in the business environment have created serious challenges for the use of simulation in that area. This research asserts that the simulation of modern manufacturing systems should be approached using hybrid tools that can incorporate, in the same simulation, the operational and the aggregate management levels in a dynamic feedback-based structure. They need to be comprehensive in scope, scalable, and able to accommodate the continuous and discrete modes of behavior, the stochastic and deterministic natures of the various business units, and the detail complexity and dynamic complexity perspectives in the decision making processes. They also need to be practical to build and inexpensive.

We have presented a definition of the scope of the manufacturing enterprise that consists of five key components to cover the strategic, tactical, and operational functions and activities, the external business environment, and the business “partners” (customers and suppliers). And it could be justified to state that the existing simulation tools and frameworks (hybrid and distributed simulations) fall short in meeting these characteristics of the simulation models of the modern manufacturing enterprise system, for being based on certain assumptions that do not make them able to accommodate all the decision making situations in the modern business systems. We identified a gap in simulating the modern manufacturing enterprise system that is not fulfilled by the existing simulation approaches.

This research proposed and developed a novel approach to integrate the system dynamics (SD) and discrete event simulation (DES) paradigms in response to the indentified gap. The new simulation framework (called the SDDES framework) utilizes SD for modeling the aggregate management levels and DES for the detailed levels and facilitates the integration and synchronization of them within a unified simulation arrangement (See Figure 7-1).

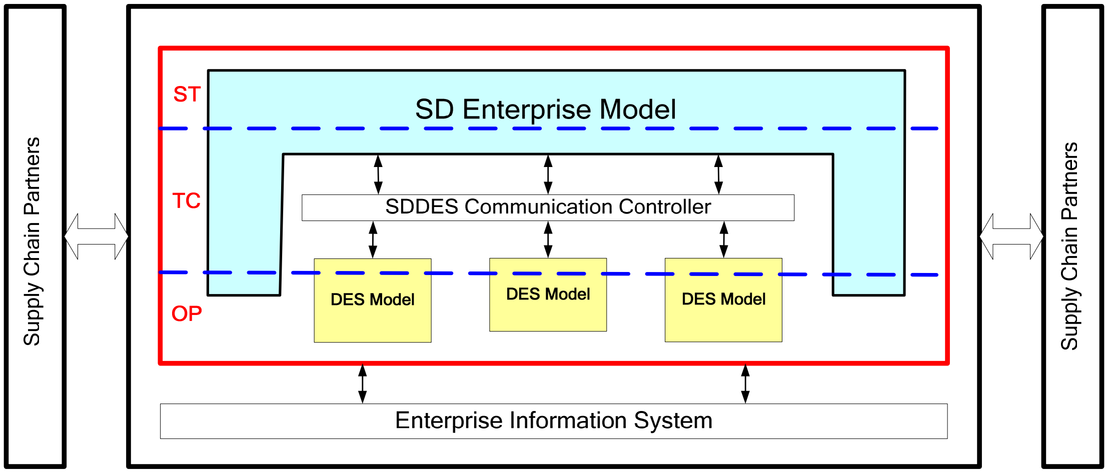


Figure 7.1 Layout of the hybrid SDDES simulation

The new framework consists of four main processes, namely the modularization, resumption, formalization, and synchronization. By executing the four processes, separate SD and DES simulations are interfaced and synchronized to be members of the comprehensive SDDES simulation (See Figure 7-2). By modularization, autonomous SD and DES simulation models are treated as modules in a more comprehensive simulation of the manufacturing enterprise. The novel concept of resumption divides the DES run within the comprehensive SDDES model into segments. Each segment is regular discrete simulation run with replications. This allows the stochastic DES modules to be synchronized with the SD modules while generating statistically valid data during the SDDES simulation run, not only at the end of the run. Formalization uses the proposed SDDES formalism to provide a generic format for specifying the SD and DES modules and their interactions, for the better management and easier scalability of the simulation model. The SDDES synchronization algorithm provides the mechanism for the data and information sharing between the modules.

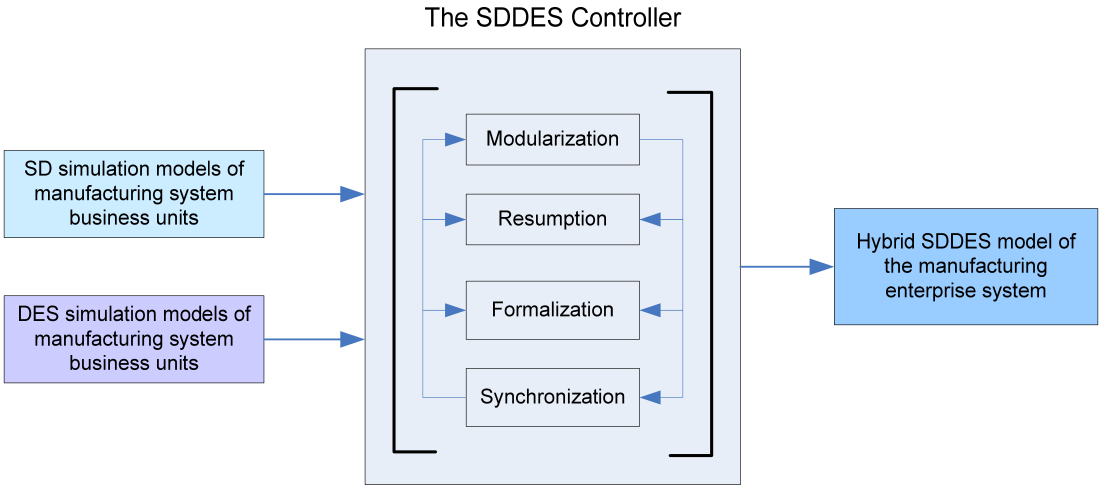

The SDDES Controller
SD simulation models of manufacturing system business units
DES simulation models of manufacturing system business units
Modularization
Resumption
Formalization
Synchronization
Hybrid SDDES model of the manufacturing enterprise system

Figure 7.2 The SDDES framework processes for integrating SD and DES simulations into unified SDDES model

The SDDES simulation framework processes are executed and managed by the SDDES controller. The SDDES controller executes the data formatting and exchange transactions, manages the simulation run, and provides the user/modeler interface to interact with the SDDES model. The specific functions of the SDDES controller were described and an IDEF functional model has been proposed.

The experimental analysis has shown that the new simulation framework has the potential to enable modelers to develop simulation models that meet the requirements of comprehensiveness, scalability, and the accommodation of the different modes of behavior and needs of decision making processes at the different management levels. Two case studies of using the proposed simulation methodology to simulate the manufacturing enterprise and the manufacturing value chain have been conducted. It was concluded that the design of the SDDES simulation framework is satisfactorily effective and efficient in modeling the manufacturing enterprise and achieving the desirable characteristics in the simulation models.

The manufacturing system control applicability of the SDDES simulation framework has been highlighted. SDDES was shown to be able to support the long term analysis of the manufacturing system robustness and stability.

It was found that SD and DES when combined in a distributed-simulation-like arrangement and synchronized in a way that maintains the integrity of each paradigm and avoids one paradigm dominating the other, they can provide powerful tools to build the desirable simulation models of the modern manufacturing enterprise. The SDDES simulation framework was shown to facilitate this environment to integrate SD and DES.

Finally, the performance of the new SDDES methodology has been compared to the available commercial hybrid simulation software and was found to generate equivalent performance and results without requiring the modelers to learn new modeling and/or computer programming skills as required by these software. Further, the new simulation framework can utilizes the existing/legacy simulations without any particular modification in them.

7.2 Research Contributions

This research followed a unique approach to address a gap that has been identified in the area of simulating the manufacturing enterprise system. Simulation modeling is known to be a tedious, time consuming, and expensive process. And it is familiar that these simulations have limited useful life spans since systems evolve, assumptions lose validity, and the objectives of using the models could become obsolete. In addition, the desirable comprehensiveness with respect to scope, view of the world, and accommodation of the different management levels' perspectives and needs is hard to achieve. Dedicated simulation modeling languages have been developed to enhance the efficiency of the simulation modeling process. Commercial software packages have then been developed for more in that direction.

But the manufacturing system combines different types of behavior, perspectives, and decision making situations. A single simulation tool cannot be adequate for modeling the total system. Theorems, algorithms, and protocols to develop hybrid and distributed simulations have been investigated and implemented to help and guide modelers in their efforts towards comprehensiveness. Yet the outcomes have been of limited applicability in the manufacturing applications.

This research has identified a need for new simulation modeling approaches that can respond to the changing business environments towards more integration. These tools should be able to develop comprehensive models that are inexpensive, scalable, and able to accommodate the continuous and discrete modes of behavior, the stochastic and deterministic natures of the various business units, and the detail complexity and dynamic complexity perspectives in decision making.

In response to that gap in simulating the modern manufacturing system, the research has proposed and developed a new simulation framework that combines the SD and DES simulation paradigms. The new SDDES simulation framework is directed towards building hybrid continuous-discrete simulation models in a distributed-simulation-like arrangement. These models can satisfy the requirements in modeling the modern manufacturing systems. Combining SD and DES accommodates the coexistence of the continuous and discrete behaviors and the deterministic and stochastic natures in the system. They also accommodate the different perspectives in decision making and views of the system being focused on the dynamic complexity of the business unit or on the detail complexity in managing it. The comprehensive and scalability dimensions in the simulation models of the manufacturing systems were achieved by using a modular structure that regarded autonomous SD and DES models as modules contributing to the same simulation. This also simplified the model building process as several SD or DES modules can be built with well defined, relatively narrow scopes to model the various business units and then be interfaced. The addition and deletion of the modules as the system evolves over time is not restricted.

The research proposed and implemented a new synchronization algorithm that recognizes and maintains the integrity of the two simulation paradigm of SD and DES. Unlike the existing synchronization approaches the new algorithm is not driven by the occurrences of discrete events.

This research also presented the concept of resumption to breakdown the DES simulation run into segments, each is a complete traditional discrete simulation run with replications and statistically valid structure and measures of performance. Resumption allows the DES modules to offer statistically valid outputs at anytime during the simulation run; not only at the end of the simulation run. This allowed stochastic, not only deterministic DES models to be interface with SD models and exchange data and information over the planning horizons. An algorithm for implementing the resumption of the DES models has been proposed and implemented in this research.

Further, and for the purpose of better communications and model management, the SDDES formalism has been introduced that provides a generic format to describe, specify, and document the SD and DES modules. The SDDES formalism simplifies the modification of the SDDES simulation model when needed and standardizes the interactions with the modelers/user of the model.

The research presented and implemented the functional model of the SDDES controller that implements the new simulation framework, manages the simulation model and simulation run, and provides the user interface to interact with the simulation model.

It was shown that the components of the new simulation framework can be used to build valid simulation models of the manufacturing system. A case study of a real manufacturing system was presented. The experimental analysis also showed that the new simulation methodology could generate equivalent results to commercial simulation software without requiring any programming efforts or learning new simulation as required by these commercial software packages.

This research contributed to the body of knowledge a view of the manufacturing enterprise system that maps the various functions and decision making processes at the strategic, tactical, and operational levels (See Figure 7-3) to SD or DES simulation modules. The modules are specified by the proposed SDDES formalism that offers a generic format to characterize the simulation models and the process they represent along with the data generated and used by each allowing for integrating the simulation modules in a comprehensive model of the enterprise system. Decision criteria to guide the mapping of the various business units to continuous or discrete module are proposed.

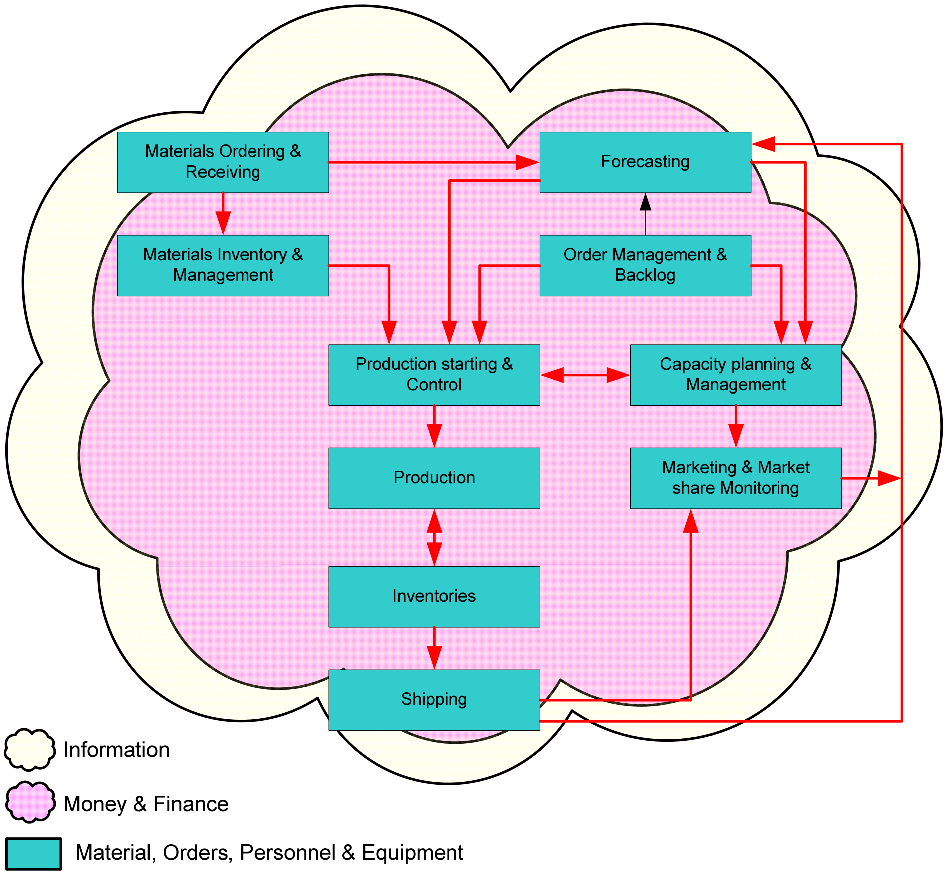

Materials Ordering & Receiving
Forecasting
Materials Inventory & Management
Order Management & Backlog
Production starting & Control
Capacity planning & Management
Production
Marketing & Market share Monitoring
Inventories
Shipping
Information
Money & Finance
Material, Orders, Personnel & Equipment

Figure 7.3 Abstract representation of the manufacturing enterprise system

The research proposed a pioneering hybrid SD-DES simulation framework for simulating the total enterprise system based on modularizing the business units as mentioned. The new framework is comprehensive in accommodating all modes of behavior, perspectives, and scopes in modeling and managing the manufacturing system business units. The new framework is uniquely practical, flexible, inexpensive, and requires no new modeling or computer programming skills. The

A new synchronization algorithm has also been contributed that is, to the best of our knowledge, the first synchronization algorithm usable in the distributed simulation field that is not discrete-event driven.

The research also contributed the functional model and implementation of the SDDES controller for managing the synchronization and the simulation runs of the hybrid, distributed-like simulations of the manufacturing enterprise system.

7.3 Directions For Future Research

We believe we have made a step forward yet we do not claim to have exhausted this research area. Potential directions for more research to enhance and strengthen the SDDES simulation framework's usefulness and effectiveness can include the following:

- Enriching the SDDES synchronization mechanism by defining module interaction control rules and criteria to improve the efficiency of the synchronization and overall scalability of the SDDES simulation model. For applications that can involve numerous modules behaving at varying dynamic levels better synchronization and data and information sharing process can be achieved by optimizing the use of the computing resources. This can include defining prioritization and significance assessment criteria to guide the SDDES controller in performing its synchronization function. Exchanging more data and information or more frequent information can be expensive for the business and for the simulation model as well. Careful evaluation of the benefits of sharing the information and the amount of information transfer versus the associated cost should be made (Simchi-Levi et al, 2008). SDDES can benefit from the Nyquist Sampling Theorem and Shannon's information theory in determining the appropriate level of information exchange frequency.

- Conducting more statistical analyses of the useful of the resumption process and how it may improve the validity of the DES models as the system being modeled evolves over time. Resumption offers an opportunity for modelers or other intelligent agents, to modify the DES models during the simulation run in order to reflect the updated system characteristic in the random distributions being uses in the models. This can be done without losing the statistical validity of the data generated by the model "so far" in the simulation run.
- Exploring the potential uses of SDDES for the long-range real time control of the manufacturing systems at the strategic management level and the coordination with the common short term real time control applicability of simulation at the operational level.
- Developing dynamic balanced scorecards on top of the simulation model. Such a

dynamic balanced scorecard can utilize the scalability and flexibility of the SDDES simulation to evolve over time as appropriate in addition to reflecting the dynamic nature of the system.

- Extending the SDDES methodology to be used over a network to integrate geographically distributed simulation.
- Extending the applicability of SDDES to other systems; most notable is the supply chain as well as other industrial and service systems. This also can include using SDDES as a decision support tool for developing the virtual enterprise (VE) that can be used to evaluate the potential partners of the proposed VE at the strategic and the operational levels.
- Investigating the potential of SDDES to enhance the capabilities of the SD methodology to process detailed data and perform more sophisticated designed experiments.
- Developing a SDDES ontology as step toward automating the process of modifying the SDDES model and standardizing its applicability. This also can support integrating SDDES to other systems such as the ERP system of the enterprise to enhance the real time control of the system and possibly improve the flexibility of the ERP operations.
- Exploring the potential of using the unified modeling language (UML) as a modeling approach of the manufacturing enterprise business units that can map directly to the continuous and discrete modules in the SDDES model in a way that make SDDES

useful in concurrently and/or iteratively designing the manufacturing system, evaluating its operational effectiveness, and assessing the robustness of its structure.

APPENDIX A: PMOC INC.’ SD MODEL MATHEMATICAL FORMULATION

The SD modules were built using Vensim DSS 5.0

The Internal Supply Chain

```
Average customer order rate=
        Customer Order Rate
Units: units/week
Customer Order Rate=
                (6250*Effect of delivery delay on market share)+STEP(625, 2)*0
        Units: units/week
Delivery Delay=
        Desired shipping / Shipping Rate
Units: week
Desired days supply of PI=
        1
Units: week
Desired production rate=
        (Average customer order rate+Finished inventory correction)/Yield+WIP correction Preforms
+WIP correction Presses/Preforms Yield Rate
Units: units/week
Desired shipping=
                Unshipped+Desired Shipping Rate
Units: units/week
Desired Shipping Rate  = A FUNCTION OF( Customer Order Rate,Preforms cycle time
,Presses cycle time)
Desired Shipping Rate=
                DELAY FIXED(Customer Order Rate, Preforms cycle time+Presses cycle time+Supplier delivery
delay
        , Customer Order Rate)
Units: units/week
DSR Plus FGI Correction=
        Desired Shipping Rate+IF THEN ELSE(Finished inventory correction>0, (Finished inventory goal
-FINISHED GOODS INVENTORY), 0)
Units: units/week
FINISHED GOODS INVENTORY= INTEG (
        Production Completion Rates-Shipping Rate,
                initial finished inventory)
Units: units
Finished inventory correction=
         (Finished inventory goal-FINISHED GOODS INVENTORY)/Time to correct inventory
Units: units/week
Finished inventory goal=
        Desired shipping
Units: units
Indicated parts order rate  = A FUNCTION OF( Parts inventory correction,Parts on order correction
,Scheduled Production Rate)
Indicated parts order rate=
                (Scheduled Production Rate+Parts inventory correction+Parts on order correction
        )*Effect of cash constraints on parts ordering
Units: units/week
Initial finished inventory=
        INITIAL(Finished inventory goal)
Units: units
Initial parts inventory=
        INITIAL(Parts inventory goal)
Units: units
Initial parts on order=
        INITIAL(Parts on order goal)
Units: units
Initial WIP Preforms= INITIAL(
        WIP goal Preforms)
Units: units
Initial WIP Presses= INITIAL(
        WIP goal Presses)
Units: units
Parts Arrival Rate=
                PARTS ON ORDER/Supplier delivery delay
Units: units/week
PARTS INVENTORY= INTEG (
        +Parts Arrival Rate-Production Start Rate,
                Initial parts inventory)
Units: units
Parts inventory correction=
        (Parts inventory goal-PARTS INVENTORY)/Time to correct parts inventory
Units: units/week
Parts inventory goal=
        Desired days supply of PI*Scheduled Production Rate
Units: units
PARTS ON ORDER= INTEG (
        +Parts Order Rate-Parts Arrival Rate,
                Initial parts on order)
Units: units
Parts on order correction=
        (Parts on order goal-PARTS ON ORDER)/Time to correct parts inventory
Units: units/week
Parts on order goal=
                Scheduled Production Rate*Supplier delivery delay
Units: units
Parts Order Rate  = A FUNCTION OF( Indicated parts order rate)
Parts Order Rate=
                Indicated parts order rate*Effect of supplier capacity on parts order rate
Units: units/week
Preforms cycle time=
        1.35
Units: week
Preforms Production Rate:=
        GET XLS DATA( 'C:\PPR.xls', 'PREFORMS', 'A','I2')
Units: units/week
Preforms Scrap Rate:=
        GET XLS DATA( 'C:\ PSR.xls', 'PREFORMS', 'A','E2')
Units: units/week
Preforms WIP Level:=
        GET XLS DATA( 'C:\WIP.xls', 'PREFORMS', 'A','L2')
```

```
Units: units
Preforms Yield=
        Preforms PR/(Preforms PR+Preforms Scrap)
Units: units/week
Presses cycle time=
        0.2
Units: week
Presses Production Rate:=
        GET XLS DATA( 'C:\PPRS.xls', 'PRESSES', 'A','I2')
Units: units/week
Presses Scrap Rate:=
        GET XLS DATA( 'C:\PSRS.xls', 'PRESSES', 'A','E2')
Units: units/week
Presses WIP Level:=
        GET XLS DATA( 'C:\WIPS.xls', 'PRESSES', 'A','L2')
Units: units
Presses Yield=
        Presses PR/(Presses PR+Presses Scrap)
Units: units/week
Production Completion Rates=
        Presses PR
Units: units/week
Production Start Rate= ACTIVE INITIAL (
                MIN(PARTS INVENTORY,Potential Production Rate From Labor),     Initial parts inventory)
Units: units/week
Scheduled Production Rate=
                MIN(Maximum Capacity,Desired production rate)
Units: units/week
Shipping Rate=
        MIN(FINISHED GOODS INVENTORY,Desired shipping)
Units: units/week
Time to correct inventory=
        1
Units: week
Time to correct parts inventory=
        1
Units: week
Time to correct WIP Preforms=
                Supplier delivery delay
Units: week

Time to correct WIP Presses=
        1
Units: week
WIP correction Preforms=
        (WIP goal Preforms-Preforms WIP Level)/Time to correct WIP Preforms
Units: units/week
WIP correction Presses=
        (WIP goal Presses-Presses WIP Level)/Time to correct WIP Presses
Units: units
WIP goal Preforms=
        Average customer order rate*Preforms cycle time/Preforms Yield Rate
```

```
Units: units
WIP goal Presses=
        Customer Order Rate*Presses cycle time/Presses Yield Rate
Units: units
Yield=
        SMOOTH(Preforms Yield Rate*Presses Yield Rate, 2)
Units: Dmnl
```

Labor

```
Average length of employment=
        144
Units: week
Correction to labor=
        IF THEN ELSE(Overtime=0.4, (Desired labor-LABOR)/Time to adjust labor, 0)
Units: Persons/week
Correction to labor being recruited=
        (Desired labor being recruited-LABOR BEING RECRUITED)/Time to adjust labor
Units: Persons/week
Desired labor=
                MIN(44,2*Scheduled Production Rate/Labor productivity)
        Units: Persons
Desired labor being recruited=
        (Labor Attrition Rate)*(Labor recruiting delay)
Units: Persons
Effect of debt equity ratio on capacity expansion= WITH LOOKUP (
        Perceived debt equity ratio for capacity,
                ([(0,0)-(4,1)],(0,1),(0.25,1),(0.5,1),(0.75,1),(1,1),(1.25,0.9),(1.5,0.8)
,(1.75,0.5),(2,0.2),(2.25,0.1),(2.5,0),(2.75,
                0),(3,0),(3.25,0),(3.5,0),(3.75,0),(4,0),(10,0) ))
Units: Dmnl

Effect of debt equity ratio on price= WITH LOOKUP (
        Perceived debt equity ratio for capacity,
                ([(0,1)-(4,1.4)],(0,1),(0.25,1),(0.5,1),(0.75,1),(1,1),(1.25,1.02),(1.48012
,1.03684),(1.75,1.06),(2,1.08),(2.25,1.1),(
                2.5,1.125),(2.75,1.16),(3,1.2),(3.25,1.25),(3.5,1.3),(3.75,1.35),(4,1.4)
))
Units: Dmnl
Indicated hiring rate=
        Labor Attrition Rate+Correction to labor+Correction to labor being recruited
Units: Persons/week
Indicated overtime=
                MAX(0,Scheduled Production Rate/Regular Time PR)
Units: Dmnl
Initail labor being recruited=
        INITIAL(Desired labor being recruited)
Units: Persons
LABOR= INTEG (
        +Labor Hiring Rate-Labor Attrition Rate-Labor Firing Rate,
                32)
Units: Persons
Labor Attrition Rate=
        LABOR/Average length of employment
Units: Persons/week
LABOR BEING RECRUITED= INTEG (
        Labor Recruting Rate-Labor Hiring Rate,
                Initail labor being recruited)
Units: Persons
Labor Firing Rate=
        -1*MIN(0,MAX(Indicated hiring rate,-LABOR))
Units: Persons/week
Labor Hiring Rate=
        LABOR BEING RECRUITED/Labor recruiting delay
Units: Persons/week
Labor productivity=
        800
Units: units/week/Persons
Labor recruiting delay=
        1
Units: week
Labor Recruting Rate=
                MAX(0,Indicated hiring rate)*Effect of cash constraints on hiring
        Units: Persons/week
Maximum Capacity=
        Regular Time PR*1.4
Units: units/week
Overtime= WITH LOOKUP (
        Indicated overtime,
                ([(0,0)-(6,2)],(0,0),(0.2,0),(0.4,0),(0.6,0),(1,0),(1.25,0.2),(1.4,0.3),(
1.5,0.4),(4,0.4) ))
Units: Dmnl

Perceived debt equity ratio for capacity=
        SMOOTH(Committed debt projected equity ratio, Time to perceive debt equity ratio for capacity
)
Units: Dmnl
Potential Production Rate From Labor=
        Regular Time PR*(1+Overtime)
Units: units/week
Press Operators=
        MIN(LABOR*0.5, 20)
Units: Persons

Regular Time PR=
        Press Operators*Labor productivity
Units: units/week
Time to adjust labor=
        1
Units: week
```

Finance and Accounting

```
ACCOUNTS PAYABLE= INTEG (
        Accounts Payable Increases-Accounts Payable Payments,
            Initial accounts payable)
Units: $
Accounts Payable Increases=
    Cost of parts arrival rate+Fixed costs+Labor costs
Units: $/week
Accounts Payable Payments=
    ACCOUNTS PAYABLE/ Time to pay AP
Units: $/week
ACCOUNTS RECEIVABLE= INTEG (
    +Dollar Value of Sales-Collections,
        Initial accounts receivable)
Units: $
Average cash flow from operations=
    SMOOTH(Collections-Cash Outflow+Investment+Long Term Debt Payments+Short Term Payments
, Time to average cash flow from operations for borrowing)
Units: $/week
Average debt equity ratio=
    SMOOTH(Debt equity ratio, Time for market to average financial variables)
Units: Dmnl
Average dollar value of sales=
    SMOOTH(Dollar Value of Sales, Time to average dollar value of sales for fixed costs
)
Units: $/week
Average earnings growth rate per year=
    SMOOTH(Earnings growth rate per year, Time for market to average financial variables
)
Units: Dmnl
Average earnings per share per year=
    SMOOTH(Earnings per share per year, Time to average earnings per share)
Units: $/share
Average inflation rate=
    SMOOTH(Inflation rate, Time to perceive inflation rate for interest rates)
Units: 1/year
Average long term debt maturity=
    240
Units: week
Average net profits=
    SMOOTH(Net Profits, Time to average net profits)
Units: $/week
Average percent excess cash=
    SMOOTH(Percent Excess cash, Time to average percent excess cash)
Units: 1
Average price=
    SMOOTH(PRICE, Time to average price)
Units: $/units
```

```
Average retained earnings=
          SMOOTH(Retained Earnings, Time to average retained earnings)
Units: $/week
Average return on equity per year=
          SMOOTH(Return on equity per year, Time for market to average financial variables
)
Units: Dmnl
Average salary per month=
          Average salary per month initial
Units: $/Persons
Base price=
          35
Units: $/units
CASH= INTEG (
          Cash Inflow-Cash Outflow,
                    Initial cash)
Units: $
Cash Inflow=
          Collections+Equity Issuing+Long Term Borrowing+Short Term Borrowing
Units: $/week
Cash Outflow=
          Accounts Payable Payments+DIVIDENDS+Interest payments+Investment+Long Term Debt Payments
+Short Term Payments+Taxes
Units: $/week

Change in Dividend Payout Ratio=
          (Indicated dividend payout ratio-DIVIDEND PAYOUT RATIO)/Time to adjust dividend payout ratio
Units: 1/week
Change in Dividends=
          (Indicated dividends-DIVIDENDS)/Time to adjust dividends
Units: $/(Month*Month)
Collections=
          ACCOUNTS RECEIVABLE/Time to collect accounts receivable
Units: $/week
Committed debt=
          Total liability+CAPITAL EQUIPMENT ON ORDER*Cost per unit of capital equipment per week
Units: $
Committed debt adjusted for equity=
          MAX(0,Committed debt-Time to acquire capital equipment*Average cash flow from operations
)
Units: $
Committed debt projected equity ratio=
          Committed debt adjusted for equity/Projected equity
Units: Dmnl
Cost of labor turnover=
          Average salary per month initial*(Labor Hiring Rate+Labor Firing Rate)
Units: $/week
Cost of material shipped=
                    Cost of unit in finished inventory*Shipping Rate
          Units: $/week
Cost of parts arrival rate=
                    Unit cost of parts*Parts Arrival Rate
```

```
        Units: $/week
Cost of parts inventory=
        Unit cost of parts
Units: $/units
Cost of unit in finished inventory=
        Unit cost of parts+Value added in process
Units: $/units
Cost of WIP=
        0.5*Cost of unit in finished inventory+0.5*Unit cost of parts
Units: $/units
Current assets=
        MAX(ACCOUNTS RECEIVABLE+CASH+Dollar value of inventory,0)
Units: $
Current liabilities=
        ACCOUNTS PAYABLE+SHORT TERM DEBT
Units: $
Current ratio=
        Current assets/Current liabilities
Units: Dmnl
Current ratio initial=
        2.5
Units: Dmnl
Debt equity ratio=
        Total liability/EQUITY
Units: Dmnl
Desired cash=
        Desired days dollar value of sales as cash*Dollar Value of Sales
Units: $
DIVIDEND PAYOUT RATIO= INTEG (
        Change in Dividend Payout Ratio,
                Indicated dividend payout ratio)
Units: 1
DIVIDENDS= INTEG (
        Change in Dividends,
                Initial dividends)
Units: $/week
Dollar value of inventory=
                (Cost of unit in finished inventory*FINISHED GOODS INVENTORY+Cost of parts inventory
        *PARTS INVENTORY+Cost of WIP*The WIP Inventory
        )
        Units: $
Dollar Value of Sales=
                Shipping Rate*PRICE
        Units: $/week
Earnings per share per year=
        Year length*Net Profits/SHARES
Units: $/share
Effect of cash conditions on dividends payments= WITH LOOKUP (
        Average percent excess cash,
                ([(-1,0)-(1,2)],(-1,0),(-0.7,0.1),(-0.5,0.7),(-0.4,0.9),(-0.2,1),(0,1),(0.2
,1),(0.4,1.1),(0.6,1.2),(1,1.3) ))
Units: Dmnl
```

```
Effect of cash conditions on LTD payments= WITH LOOKUP (
        Average percent excess cash,
                ([(-0.6,0)-(3,2)],(-0.5,0.7),(0,0.9),(0.5,1),(1,1.05),(1.5,1.15),(2,1.25)
,(2.5,1.35),(3,1.5) ))
Units: Dmnl
Effect of cash conditions on STD payments=
        Indicated change in cash
Units: $/week
Effect of cash constraints on hiring= WITH LOOKUP (
        Average percent excess cash,
                ([(-1,0)-(0,1)],(-1,0),(-0.8,0),(-0.6,0.1),(-0.4,0.2),(-0.2,0.5),(0,1),(10
,1) ))
Units: Dmnl
Effect of cash constraints on parts ordering= WITH LOOKUP (
        Average percent excess cash,
                ([(-1,0)-(0,1)],(-1,0.9),(-0.8,0.97),(-0.6,0.98),(-0.4,0.99),(-0.2,1),(0,
1),(10,1) ))
Units: Dmnl
Effect of current ratio on short term borrowing= WITH LOOKUP (
        Current ratio,
                ([(0,0)-(2,1)],(0,0),(0.5,0.4),(1,0.7),(1.5,0.9),(2,1),(2.5,1),(3,1),(5,1
),(10,1),(20,1) ))
Units: Dmnl
Effect of debt equity ratio on capacity expansion= WITH LOOKUP (
        Perceived debt equity ratio for capacity,
                ([(0,0)-(4,1)],(0,1),(0.25,1),(0.5,1),(0.75,1),(1,1),(1.25,0.9),(1.5,0.8)
,(1.75,0.5),(2,0.2),(2.25,0.1),(2.5,0),(2.75,
                0),(3,0),(3.25,0),(3.5,0),(3.75,0),(4,0),(10,0) ))
Units: Dmnl
Effect of debt equity ratio on price= WITH LOOKUP (
        Perceived debt equity ratio for capacity,
                ([(0,1)-(4,1.4)],(0,1),(0.25,1),(0.5,1),(0.75,1),(1,1),(1.25,1.02),(1.48012
,1.03684),(1.75,1.06),(2,1.08),(2.25,1.1),(
                2.5,1.125),(2.75,1.16),(3,1.2),(3.25,1.25),(3.5,1.3),(3.75,1.35),(4,1.4)
))
Units: Dmnl
Effect of debt equity ratio on short term borrowing= WITH LOOKUP (
        Debt equity ratio,
                ([(0,0)-(4,1)],(0,1),(0.25,1),(0.5,1),(0.75,1),(1,1),(1.25,0.95),(1.5,0.9
),(1.75,0.8),(2,0.7),(2.25,0.5),(2.5,0.3),(2.75
                ,0.2),(3,0.1),(3.25,0.05),(3.5,0),(3.75,0),(4,0),(10,0) ))
Units: Dmnl
Effect of debt equity ratio on stock price= WITH LOOKUP (
        Average debt equity ratio,
                ([(0,0.6)-(4,1)],(0,0.9),(0.5,0.95),(1,1),(1.5,0.95),(2,0.9),(2.5,0.85),(
3,0.8),(3.5,0.75),(4,0.7) ))
Units: Dmnl
Effect of delivery delay on market share= WITH LOOKUP (
        Delivery delay quoted by company/Adjustment,
                ([(0,0)-(10,2)],(0,0),(0,0),(0,0),(0,1),(1,1),(1.5,1),(2,1),(2.5,1),(3,0.97
),(4,0.95),(6,0.9),(8,0.75),(10,0.6),(20,0.1) ))
Units: Dmnl
```

```
Effect of earning growth rate on stock price= WITH LOOKUP (
        Average earnings growth rate per year,
                ([(-0.8,0)-(0.8,2)],(-0.5,0.5),(-0.4,0.6),(-0.3,0.7),(-0.2,0.8),(-0.1,0.9
),(0,1),(0.1,1.1),(0.2,1.2),(0.3,1.25),(0.4,1.275),(0.5,1.3),(0.6,1.3),(0.7
,1.3) ))
Units: Dmnl
Effect of price on market share= WITH LOOKUP (
        Price acted on by customers/Competitor price,
                ([(0,0.8)-(6,1.2)],(0.75,1.1),(0.85,1.09),(0.9,1),(1,1),(2,1),(3,1),(4,0.99
),(5,0.97),(6,0.9) ))
Units: Dmnl
Effect of return on equity on stock price= WITH LOOKUP (
        Average return on equity per year,
                ([(0,0)-(0.6,6)],(0,0.1),(0.0495413,0.631579),(0.102752,1.13158),(0.157798
,1.76316),(0.2,2.25),(0.255046,2.92105),(0.3,3.5),(0.35,4.25),(0.4,5),(0.45
,6) ))
Units: Dmnl
EQUITY= INTEG (
        Retained Earnings+Equity Issuing,
                Initial equity)
Units: $
Equity Issuing  = A FUNCTION OF( Indicated long term financing,Percent debt financing
)
Equity Issuing=
                IF THEN ELSE(Customer Order Rate <2500, 0, Indicated long term financing*
        (1-Percent debt financing))
        Units: $/week
Gross profits=
        Dollar Value of Sales-Cost of material shipped-Fixed costs-Depreciation-Interest payments
Units: $/week
Indicated dividend payout ratio=
        Payout ratio indicated by return on equity*Effect of cash conditions on dividends payments
Units: 1
Indicated long term financing=
        MAX(0,Investment+Long Term Debt Payments-Average cash flow from operations
)
Units: $/week
Inflation rate initial=
        0
Units: 1/year
Initial accounts payable=
        Accounts Payable Increases*Time to pay AP
Units: $
Initial accounts receivable=
        Dollar Value of Sales*Time to collect accounts receivable
Units: $
Initial cash=
        INITIAL(Desired cash)
Units: $
Initial equity=
        Total assets/(1+Debt equity ratio initial)
Units: $
```

```
Initial long term debt=
        (Debt equity ratio initial*EQUITY-Current liabilities)
Units: $
Initial shares=
        3e+006
Units: share
Initial short term debt=
        MAX(0,(Current assets/Current ratio initial)-ACCOUNTS PAYABLE)
Units: $
Interest payments=
        Interest rate*(LONG TERM DEBT+SHORT TERM DEBT)/48
Units: $/week
Investment=
        Capital Equipment Arrivals*Cost per unit of capital equipment per week
Units: $/week
LONG TERM DEBT= INTEG (
        +Long Term Borrowing-Long Term Debt Payments,
                0)
Units: $
Long Term Debt Payments=
        (LONG TERM DEBT/Average long term debt maturity)*Effect of cash conditions on LTD payments
Units: $/week
Net Profits=
        Gross profits-Taxes
Units: $/week
Percent debt financing= WITH LOOKUP (
        Debt equity ratio,
                ([(0,0)-(2,1)],(0,1),(0.25,1),(0.5,0.9),(0.75,0.5),(1,0.1),(1.25,0),(1.5,
0),(1.75,0),(2,0) ))
Units: 1
Percent Excess cash=
        IF THEN ELSE(Desired cash>0, (CASH-Desired cash)/Desired cash, 0)
Units: 1
Price earning ratio per year=
        Price earning ratio normal*Effect of return on equity on stock price*Effect of earning growth rate on stock
price
*Effect of debt equity ratio on stock price
Units: $/$
Profit=
        SMOOTH( Net Profits, 4)
Units: $
Projected equity=
        EQUITY+Time to acquire capital equipment*Average retained earnings
Units: $
Retained Earnings=
        MAX(0,Net Profits-DIVIDENDS)
Units: $/week
Return on equity per year=
        Year length*Net Profits/EQUITY
Units: Dmnl
Return on Investment=
        Net Profits/Investment
```

```
Units: Dmnl
Risk free interest rate=
        0.02
Units: 1/year
Risk premium of debt= WITH LOOKUP (
        Debt equity ratio,
                ([(0,0)-(4,0.08)],(0,0.015),(0.5,0.0175),(1,0.02),(1.5,0.0225),(2,0.025),
(2.5,0.03),(3,0.04),(3.5,0.055),(4,0.075) ))
Units: 1/year
SHARES= INTEG (
        (Equity Issuing/STOCK PRICE),
                Initial shares)
Units: share
Short Term Borrowing=
        MAX(0,Indicated change in cash)*Effect of current ratio on short term borrowing
*Effect of debt equity ratio on short term borrowing
Units: $/week
SHORT TERM DEBT= INTEG (
        +Short Term Borrowing-Short Term Payments,
                1000000)
Units: $
Short Term Payments=
        Indicated short term payments*Effect of short term debt on payments+0*SHORT TERM DEBT
 / (Time to pay STD)
Units: $/week
Taxes=
        IF THEN ELSE(Gross profits>0, Gross profits*Tax rate, 0)
Units: $/week

Total assets=
        BOOK VALUE OF FIXED ASSETS+Current assets
Units: $
Total liability=
        Current liabilities+LONG TERM DEBT
Units: $
Value added in process=
        Running costs of tools+Labor costs/Average production completions
Units: $/units
```

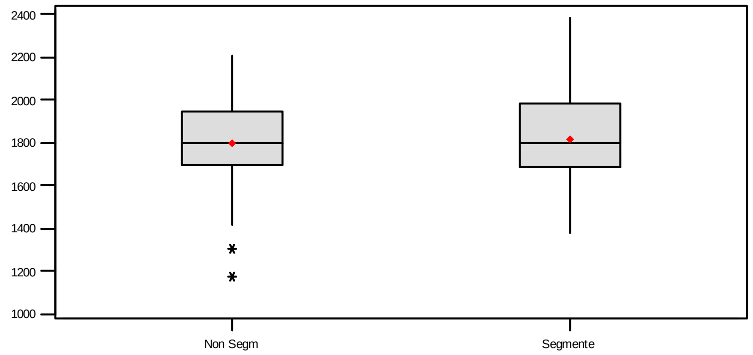
APPENDIX B: 2-SAMPLE T-TEST RESULTS FOR THE DIFFERENCE BETWEEN MEANS FOR THE RESUMPTION ALGORISM

B-1: t-test results for the mean production rate - PREF module

```
Two-sample T for Non Segmented PREF vs Segmented PREF

               N      Mean     StDev   SE Mean
Non Segmented  50      1796       215        31
Segmented      50      1816       242        35

Difference = mu Non Segmented PREF - mu Segmented PREF
Estimate for difference:  -20.4
95% CI for difference: (-113.0, 72.3)
T-Test of difference = 0 (vs not =): T-Value = -0.44  P-Value = 0.663  DF = 92
```

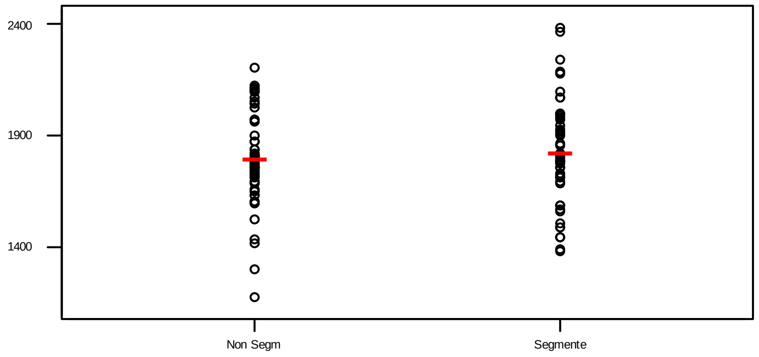
Boxplots of Non Segm and Segmente

(means are indicated by solid circles)



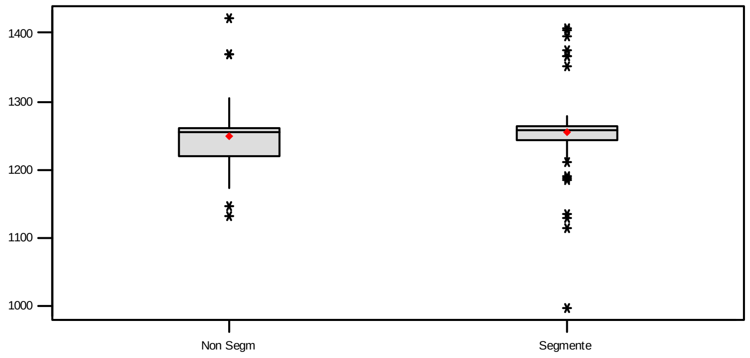
Dotplots of Non Segm and Segmente

(means are indicated by lines)

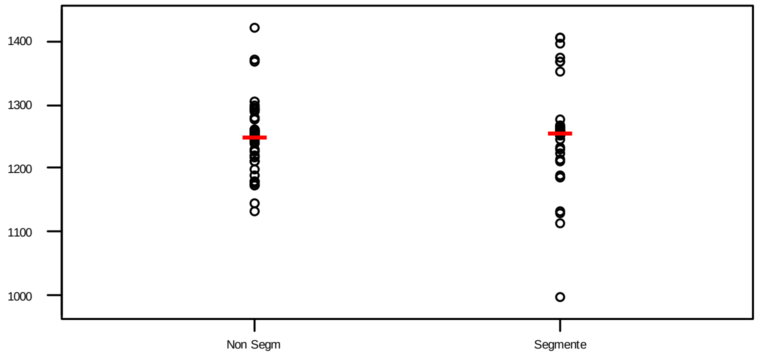


B-2: t-test results for the mean production rate - PRES module

```
Two-sample T for Non Segmented PRES vs Segmented PRES

           N      Mean     StDev   SE Mean
Non Segm  50    1248.9      52.8       7.5
Segmente  50    1254.1      71.6        10

Difference = mu Non Segmented PRES - mu Segmented PRES
Estimate for difference:  -5.2
95% CI for difference: (-30.2, 19.8)
T-Test of difference = 0 (vs not =): T-Value = -0.41  P-Value = 0.679  DF = 90
```


Boxplots of Non Segm and Segmente

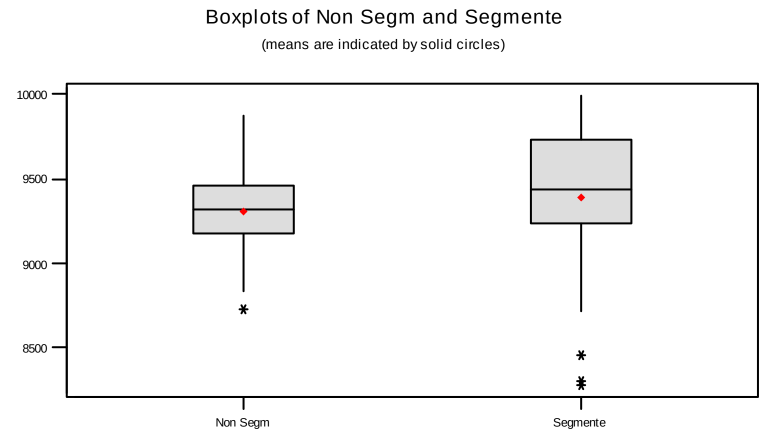
(means are indicated by solid circles)

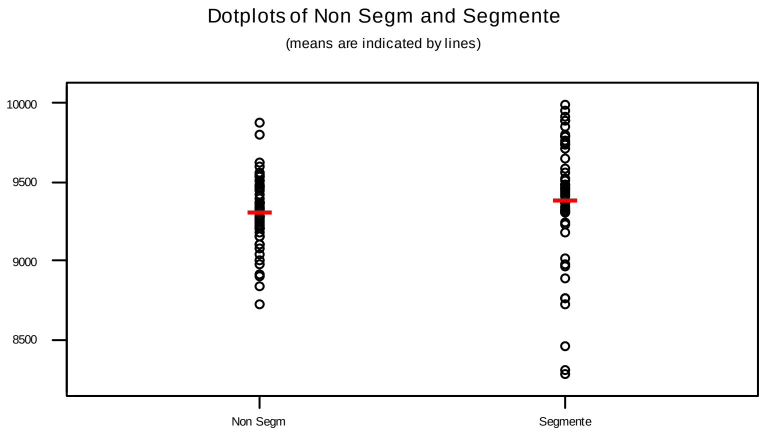

Dotplots of Non Segm and Segmente

(means are indicated by lines)

B-3: t-test results for the mean work-in-process level - PREF module

```
Two-sample T for Non Segmented PREF vs Segmented PREF

               N      Mean     StDev   SE Mean
Non Segmented  50      9305       230        33
Segmented      50      9385       410        58

Difference = mu Non Segmented PREF - mu Segmented PREF
Estimate for difference:  -80.6
95% CI for difference: (-213.0, 51.8)
T-Test of difference = 0 (vs not =): T-Value = -1.21  P-Value = 0.229  DF = 77
```



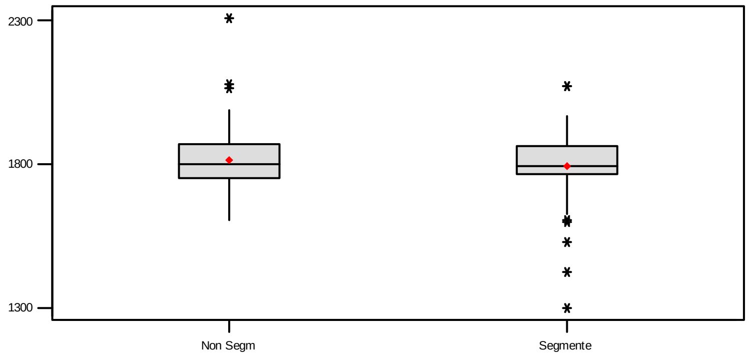


B-4: t-test results for the mean work-in-process level - PRES module

```
Two-sample T for Non Segmented PRES vs Segmented PRES

           N      Mean     StDev   SE Mean
Non Segm  50      1816       124        18
Segmente  50      1793       135        19

Difference = mu Non Segmented PRES - mu Segmented PRES
Estimate for difference:  23.5
95% CI for difference: (-28.0, 75.0)
T-Test of difference = 0 (vs not =): T-Value = 0.90  P-Value = 0.368  DF = 97
```

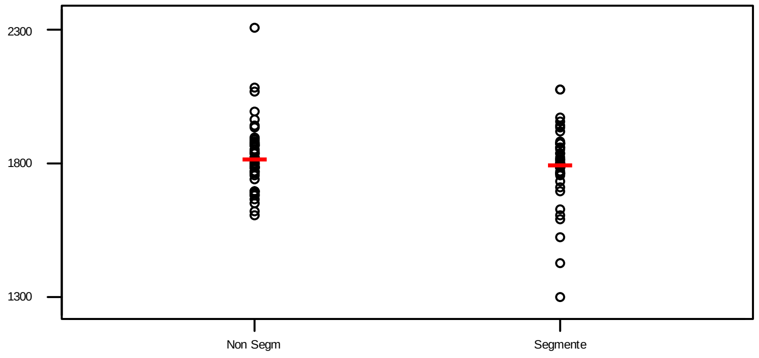
Boxplots of Non Segm and Segmente

(means are indicated by solid circles)



Dotplots of Non Segm and Segmente

(means are indicated by lines)



LIST OF REFERENCES

Adamides E. (2006). A system dynamics computer-based learning environment for the formulation of manufacturing strategy. 25th International Conference of the System Dynamics Society, July 23-27, Nijmegen, The Netherlands

Aguilar-Saven, R. S. (2004). Business process modeling: Review and framework. International Journal of Production Economics, 90(2), 129-149

Alexopoulos, C. (2006). Statistical estimation in computer simulation. Chapter 8 in Henderson, S. and Nelson, B.; Eds. Handbooks in Operations Research and Management Science, Vol. 13: Simulation. North-Holland Elsevier, The Netherlands

Alur, R., Henzinger, T., Lafferriere, G., Pappas, G., (2000). Discrete abstraction of hybrid systems. IEEE, 88(7), 971-984

An, L., Jehn, J. (2005). On developing system dynamics model for business process simulation. The Winter Simulation Conference WSC’05, Dec 5-8, Orlando FL

Anthony, N. (1965). Planning and control systems: a framework for analysis. 9th printing at 1977, Division of Research at the Graduate School of Business Administration, Harvard University, Boston, MA

Anthony, R. (1988). The management control functions. Harvard Business School Press, Boston, MA

Anthony, R., Dearden, J., Bedford, N. (1989). Management Control Systems. 6th Ed., IRWIN, IL

Anthony, N., Govindarajan, G. (1998). Management control systems. 9th Ed. Irwin McGraw-Hill

Ashayeri, J., Keij R., Broker, A. (1998). Global business process re-engineering: a system dynamics-based approach. International Journal of Operations and Production Management, 18 (9/10), 817-831

Aull-Hyde, R., Erdogan, S., Duke, J. (2006). An experiment on the consistency of aggregated comparison matrices in AHP. European Journal of Operational Research, (171), 290–295

Aytug, H., Lawley, M., McKay, K., Mohan, S., Uzsoy, R. (2005). Executing production schedules in the face of uncertainty: A review and some future directions. European

Journal of Operational Research, (161), 86-110

Babat, V., Sturrock, D. (2003). The Arena product family: Enterprise modeling solutions. The Winter Simulation Conference WSC'03, Dec 7-10, New Orleans, USA

Baines, T., Harrison, D. (1999). An opportunity for system dynamics in manufacturing system modeling. Production Planning and Control, 10(6), 542-552

Banks, J., Carson II, J., Nelson, B., Nicol, D. (2005). Discrete event System Simulation. Perntice-Hall, NJ, USA

Barton, J., Love, D., Taylor, G. (2001). Evaluating design implementation strategies using simulation. International Journal of Production Economics, (72), 285-299

Baudin; M. (1990). Manufacturing systems analysis. YOURDON PRESS; Prentice Hall, NJ

Bauer; C., Whitehouse; G., Brooks; G. (1982). Computer simulation of production system: Phase I, Technical Report: COE No. 82-83-1, The university of Central Florida, Orlando

Bezemer, J., Akkermans, H. (2003). Not with a bang, but with a whimper: Understanding delays in semiconductor supply chain dynamics. 21st International Conference of the System Dynamics Society, July 20-24, New York, USA

Bodoh, D., Wieland, F. (2003). Performance Experiments with the high level architecture and the total airport and airspace model (TAAM). 17th Workshop on Parallel and Distributed Simulation, IEEE, San Diego, CA, June 10-13, 31-39

Boer, C., Bruin, A., Verbraeck, A. (2006a). Distributed Simulation in industry – A survey, Part 1 – the COTS vendors. The Winter Simulation Conference WSC'06, Dec 3-6, Monterey CA, 1053-1060

Boer, C., Bruin, A., Verbraeck, A. (2006b). Distributed Simulation in industry – A survey, Part 2 – Experts on distributed simulation. The Winter Simulation Conference WSC'06, Dec 3-6, Monterey CA, 1061-1068

Bonder, D., McGinnis, L. (2002). A structured approach to simulation modeling of manufacturing systems. IIE's IERC, May 19-21, Orlando FL

Borshchev, A. (2001). AnyLogic 4.0: Simulating hybrid systems with extended UML-RT. Simulation News Europe, 31, 1-2

Borshchev, A., Filippov, A. (2004). From system dynamics and discrete event to practical agent based modeling: reasons, techniques, tools. 22nd International Conference of the System Dynamics Society, July 25 - 29, Oxford, England

Borshchev, A., Karpov, Y., Kharitonov, V. (2002). Distributed Simulation of Hybrid Systems with AnyLogic and HLA. Future Generation Computer Systems, 18(6)

Borshchev, A, Kolesov, Y., Senichenkov, Y. (2000). Java engine for UML based hybrid state machines. The Winter Simulation Conference WSC'00, Orlando, FL, 1888-1894

Bononi, L., D'angelo, G., Donatello, L. (2003). HLA-based adaptive distributed simulation of wireless mobile systems. 17th Workshop on Parallel and Distributed Simulation, IEEE, San Diego, CA, June 10-13, 40-49

Botta-Genoulaz, V., Millet, P., Grabort, B. (2005). A survey on the recent research literature on ERP systems. Computers in Industry, 56, 510-522.

Bradl, P. (2003). The use of SD in management: reasons and applications. 21st International Conference of the System Dynamics Society, July 20-24, New York, USA

Brennen, R. (2000). A simulation test bed to evaluate multi-agent control of manufacturing systems. The Winter Simulation Conference, WSC'00, Dec 10-13, Orlando, FL

Bryant, R. (1977). Simulation of packet communication architecture computer systems. Computer Science Laboratory, MIT, Cambridge, MA

Bouchhima, F., Nicolescu, G., Aboulhamid, E., Abid, M. (2005). Discrete-Continuous Simulation Model for Accurate Validation in Component-Based Heterogeneous SoC Design. IEEE International Workshop on Rapid System Prototyping 2005, 181-187

Carrie; A. (1988). Simulation of manufacturing systems. John Wiley & Sons, GB.

Chandy, k., Misra, J. (1978). Distributed simulation: A case study in the design and verification of distributed programs. IEEE Transactions on Software Engineering, 5(5), 440-452

Chang, Y., Makatsoris, H. (2001). Supply chain modeling using simulation. International Journal of Simulation, 2(1), 24-30

Chatha, K., Weston, R. (2005). Combined enterprise and simulation modeling in support of process engineering. International Journal of Computer integrated manufacturing. 18(8), 652-670

Cho, H., Son, T., Jones, A. (2006). Design and conceptual development of shop-floor controllers through the manipulation of process plans. International Journal of Computer Integrated Manufacturing. 19(4), 359-376

Choi K, Bae D, Kim T. (2005). DEVS-based software process simulation modeling: formally specified, modularized, and extensible SPSM. The International Workshop on Software

Process Modeling and Simulation (ProSim '05), St. Louis, MO.

Choi, K.; Bae, D., Kim, T. (2006). An approach to a hybrid software process simulation using the DEVS formalism. Software Process: Improvement and Practice, 11(4), 373-383

Chouikha, M., Decknatel, G., Darth, R., Frey, G., Muller, C., Simon, C., Thieme, J., Wolter, K. (2000). Petri net-based descriptions of discrete-continuous systems. Automatisierungstechnik, 48 (9), Oldenbourg Verlag, Germany

Cowling, P., Johansson, M. (2002). Using real time information for effective dynamic scheduling. European Journal of Operational Research, (139), 230-244

Dai, J., Zhu, F., Ma, X. (1996). Computer integrated hybrid modeling support systems for enterprise decisions making. IEEE International Conference on Systems, Management, and Cybernetics, Oct 14-17, Vol. 2, 947-952

Davenport, T. (1998). Putting the enterprise into the enterprise system. Harvard Business Review, July/Aug 1998, 121-131.

Davenport, T. (2000). Mission critical: realizing the promise of enterprise systems. Harvard Business School Press, Boston, MA.

De Souza, R., Huynh, R., Chandrashekar, M., Thevenard, D. (1996). A comparison of modeling paradigms for manufacturing line. IEEE International Conference on Systems, Management, and Cybernetics, Oct 14-17, Beijing, China, 1253-1258

Dillard, J., Yuthas, K. (2006). Enterprise resource planning systems and communicative actions. Critical Perspectives on Accounting. (17) 202-223

Donzelli, P., Iazeolla, G. (1996). Performance modeling of the software development processes. The 8th Simulation Symposium, Genova, Italy, Oct. 24-26

Ehrahardt, N., Brigham, E. (2003), Corporate finance; a focused approach. THMOSON South-Western, USA

Eskandari, H., Rabelo, L. (2006). Handling uncertainties in the analytic hierarchy process: a stochastic approach. International Journal of Information Technology and Decision Making, (5)3

Filippov, A., Borshchev, A. (2001). Modeling S-class car seat control with AnyLogic, 2001 OMER-2: Object-Oriented Modeling of Embedded Real-Time Systems, GI- Workshops, pp 46-50, Herrsching am Amersee, Germany

Forman, E., Peniwati, K. (1998). Aggregating individual judgments and priorities with the analytic hierarchy process. European Journal of Operational Research, (108) 65–169

Forrester, J. (1965). Industrial Dynamics. MIT Press, 4th Ed., MA, USA

Forrester, J. (1968). Market growth as influenced by capital investment. Industrial Management Review (currently Sloan Management Review) 9(2), Winter 1968, 83-105

Forrester, J. (1973). World Dynamics. Productivity Press, USA

Forrester, J. (1975). Industrial dynamics after the first decade. Chapter 8 in "Collected papers of Jay W. Forrester", Wright-Allen Press, Inc.

Forrester, J. (1991). System dynamics and lessons of 35 years. Sloan School of Management, Document # D-4224-4, Online at www.sysdyn.clexchange.org/sdep/papers/D-4224-4.pdf

Fishwick, P. (1995). Simulation Model Design and Execution. Prentice-Hall, USA

Fowler, J., Rose, O. (2004). Grand Challenges in Modeling and Simulation of Complex Manufacturing Systems. Simulation, 80(9) 469-476

Fox, M., Gurninger, M. (1998). Enterprise modeling. AI Magazine, 19(3), 109-121

Frey, P., Carter, H., Wilsey, P. (1997). Parallel synchronization of continuous time discrete event simulators. ICPP; the IEEE international Conference on Parallel Processing, Aug 11-15, Washington DC, pp 227-231

Fujii, S., Tsunoda, H., Ogita, A., Kidani, Y. (1994). Distributed simulation model for computer integrated manufacturing. The WSC'94, Dec 5–8, Orlando, FL, pp 946 - 953

Fujii, S., Ogita, A., Kidani, Y., Kaihara, T. (1999). Synchronization mechanisms for integration of distributed manufacturing systems. Simulation, 72(3), pp 187-197

Fujii, S., Kaihara, T., Morita, H. (2000). A distributed virtual factory in agile manufacturing environment. International Journal Production Research. 38(17), 4113-4128

Fujii, S., Morita, H., Tanaka, T. (2000). A basic study on autonomous characterization of square array machining cells for agile manufacturing". The WSC'02, Dec, Orlando, FL, pp 1282 - 1289

Fujimoto, R. (2000). Parallel and distributed simulation systems. John Wiley & Sons Inc. USA

Fujimoto, R. (2001). Parallel and distributed simulation systems. The WSC'01. Peters, B., Smith, J., Medeiros, D., Rohrer, M. (Eds.), 147-157.

Gheorghe, L., Bouchhima, F., Nicolescu, G., Boucheneb, H. (2006). Formal definitions of simulation interfaces in a continuous/discrete co-simulation. The 17th IEEE International. Workshop on Rabid System Prototyping

Giambiasi, N., Paillet, J., Chane, F. (2003). From Timed Automata to DEVS models. The WSC'03, Dec 5-7, New Orleans, LA

Godding, G., Sarjoughian, H., Kempf, K. (2003). Semiconductor supply network simulation. The WSC,03, Dec 03, New Orleans, LA

Greene, J. (1997). Production and inventory control handbook. 3rd Ed., McGraw-Hill, USA

Gregoriades, A., Karakostas, B. (2003). Unifying business objects and systems dynamics as a paradigm for developing decision support systems. Decision Support Systems (1049), pp 1-5

Größler, A., Stotz, M., Schieritz, N. (2003). A software interface between system dynamics and agent-based simulations – Linking Vensim and RePast. The 21st System Dynamics Society International Conference, July 20-24, New York, USA

Gu, Z., Shin, K. (2004). Synthesis of real time implementation from UML-RT models. 2nd RATS Workshop on model-driven embedded systems, MoDES'04, Toronto, Canada, May 25-28

Haler, D. (1987). Statecharts: A visual formalism for complex systems. Science of Computer Programming (8), 231-274

Hannet, J. (1999). From the aggregate plan to lot-sizing in multi-level production planning", in Brandimarte, P., and Villa, A. (Eds.) Modeling Manufacturing Systems from aggregate planning to real time control. Springer-Verlag Berlin, Germany

Helal, M., Rabelo, L., (2004). An enterprise simulation approach to the development of dynamic balanced scorecards. ASEM'04; The American Society of Engineering Management Conference, Oct 20-23, Alexandria, Virginia

Hermsillo Worley, J., Chata, K., Weston, R., Aguirre, O., Garbot, B. (2005). Implementation and optimization of ERP systems: a better integration of processes, roles, knowledge and user competencies. Computers in Industry, (56), pp 620-638.

Hitomi, K. (1996). Manufacturing systems engineering. 2nd Ed., Taylor and Francis, Great Britain

Huang, G., Lau, J,. Mak, K. (2003). The impact of sharing production information on supply chain dynamics: a review of the literature. International Journal of Production Research, 41(7), 1483-1517

Jacobson, I., Booch, G., Rumbaugh, J. (2001). The unified software development process. Addison-wesley, USA

Jarke, M., Jeusfeld, M., Peters, P., Pohl, K. (1997). Coordinating distributed organizational knowledge. Data & Knowledge Engineering, (23), 247-268

Jefferson, D. (1985). Virtual Time. The ACM Transactions on Programming Languages and Systems. 7(3), 404-425.

Johnson, S., Eberlein, B. (2002). Alternative modeling approaches: a case study in the gas and oil industry. The 2002 System Dynamics Society International Conference, July 27-30, Palermo, Italy

Jones, A., Yih, Y., Wallace, E. (2001) Mentoring and controlling operations. Chapter 65 in The Handbook of Industrial Engineering: technology and operations management, Gavriel Salvendy (Ed.), Wiley, NY

Kaplan, R, Norton, D. (1996). The balanced scorecard: Translating strategy into action. Harvard Business School Press, Boston, MA.

Kaplan, R., Norton, D. (2001). The strategy focused organization. Harvard Business School Press, Boston, MA.

Keenan, P., Paich, M. (2004). Modeling General Motors and North American automobile market. The 22nd International Conference of the System Dynamics Society, July 25 - 29, 2004, Oxford, England

Kelton, W., Sadowski, R., and Sadowski, D. (2002). Simulation with Arena. McGrawHill, USA

Kosturiak, J., Gregor, M. (1999). Simulation in production system life cycle. Computers in Industry, (38), 159-172

Kowalewski, S., Stursberg, M., Fritz, M., Graf, M., Hoffmann, I, Preubig, J, Remelhe, P., Simon, S., Treseler, H. (1999). A case study in tool-aided analysis of discretely controlled continuous systems: The two tanks problem", in Antsaklis, P. et al. (Eds.): Hybrid Systems V, Springer-Verlag Berlin Heidelberg, pp 163-185

Kuhl, F., Weatherly, R., Dahmann, J. (2000). Creating computer simulation systems: an introduction to the high level architecture. Prentice Hall PTR, NJ, USA

Larson, K. (1997). Essentials of Financial Accounting. Irwin McGraw-Hill, USA

Lavoie, P., Kenne, J., Gharbi, A. (2007). Production control and combined discrete continuous simulation in a failure prone transfer lines. International Journal of Production Research

(45) 24, 5667 - 5685

Law, A., Kelton, W. (2000). Simulation modeling and analysis. McGrawHill, USA

Lee, Y., Cho, M., Kim, S., Kim, Y. (2002a). Supply chain simulation with discrete-continuous combined modeling. Computer and Industrial Engineering, (43), 375-392

Lee, J., Hsu, P. (2002). UML-based modeling and multi-threaded simulation for hybrid systems. The 2002 IEEE Int. Conf. on Control Applications, Sept 18-20, Glasgow, Scotland

Lee, S., Ramakrishnan, S., Wysk, R. (2002b). A federation coordinator for simulation based control and analysis. The WSC'02, Orlando, FL, 1986-1994

Lee, S., Wysk, R. (2004). A resource reconciliation mechanism for a manufacturing federation coordinated using MRP/ERP system. The WSC'04, pp 30-38

Lee, J.; Zhou, M.; Hsu, P. (2004). A multi-paradigm modeling approach for hybrid dynamic systems. IEEE Intl. Symposium on Computer Aided Control System design, Taipie, Tiwan, Sept 2-4, pp 77-82

Lendermann, P. (2006). About the need for distributed simulation technology for the resolution of real-world manufacturing and logistics problems. WSC'06: Dec 3-6, Monterey CA, pp 1119-1128

Lertpattarapong, C. (2002). Applying system dynamics approach to the supply chain management problem. A Master thesis, MIT

Levin, T., Levin, I. (2002). Hybrid systems modeling in learning science and technology. Journal of Computers in Mathematics and Science Teaching. 21(4), 313-330

Levin, T., Levin, I. (2003). Integrating hybrid modeling with system dynamics. The 21st International Conference, System Dynamics Society, July 20-24, NY, USA

Lin, C., Baines, T., O'Kane, J, Link, D. (1998). A generic methodology that aids the application of system dynamics to manufacturing system modeling. International Conf. on Simulation. Sept 30 – Oct 2 (IEEE Conf Publ. No. 457)

Love, D., Barton, J. (1996). Evaluation of design decisions through CIM and simulation. Integrated manufacturing systems, 7(4), 3-11

Lyneis, J. (1980). Corporate planning and policy design: A system dynamics approach. The MIT Press, Cambridge, MA, USA

Ma, Q., Judd, R., Lipset, R. (2001). Distributed manufacturing simulation environment. The

Summer Computer Simulation Conf., July 15-17, Orlando, FL

Maler, O., Manna, Z., Pnueli, A. (1992). From timed to hybrid systems. In Real-Time: Theory in Practice, Eds. Bakker, J.; Huizing, C.; Roever, W.; Rozenberg, G.; Springer-Verlag, Germany

Mandal, P., Sohal, A. (1998). Modeling helps in understanding policy alternatives: A case. Journal of Management in Engineering, Jan/Feb , pp 41-48

Martin, R. (2001). A hybrid model of the software development process. PhD Thesis, Portland State University

Morecroft, J., (1985). Rationality of the analysis of behavior simulation models. Management Science, 31(7), 900-916

Morecroft, J., Robinson, S. (2007). Explaining puzzling dynamics: comparing the use of system dynamics and discrete event simulation. The 23rd International Conference, System Dynamics Society, July 17-21, MA, USA

Moustakis, V. (2000). Material requirements planning. Report produced for the EC funded project, Last accessed on Feb 2006: http://www.adi.pt/docs/innoregio_MRP-en.pdf

Pegden, C., Shannon, R., Sadowski, R. (1990). Introduction to simulation using SIMAN", McGraw-hill, USA

Pepyne, D., Cassandras, C. (2000). Optimal control of hybrid manufacturing systems in manufacturing", Proceedings of the IEEE. 88 (7), 1108-1123

Pfeiffer, A., Kadar, B., Monostori, L., Karnok, D. (2008). Simulation as one of the core technologies for digital enterprises: assessment of hybrid scheduling methods. International Journal of Computer Integrated Manufacturing. 21(2), 206-214

Pritsker, A, O'Reilly, J., LaVal, D. (1997). Simulation with Visual SLAM and AweSim", John Wiley & Sons, USA

Popper, K. (1959). The logic of scientific discovery", Basic Books, NY

Porter, M. (1985). Competitive advantage: creating and sustaining superior performance. The FREE PRESS, NY.

Pugh III, R. (1981). Introduction to system dynamics with DYNAMO. The MIT Press, MA

Rabelo, L.; Eskandari, H.; Shaalan, T.; Helal, M.; 2007, "Value Chain Analysis Using Hybrid Simulation and AHP" International Journal of Production Economics, V 105, # 2, pp

536-547

Rabelo, L., Helal, M., Son, Y., Jones, A., Min, J., Deshmukh, A. (2003). A hybrid approach to manufacturing enterprise simulation", The WSC'03, Dec 7-10, New Orleans, LA

Rabelo, L., Helal, M., Jones, A., Min, H. (2005). Enterprise simulation: A hybrid system approach. International Journal of Computer Integrated Manufacturing. 18(6), 498-508

Rabelo, L., Speller, T., Burns, C., Meade, P. (2004). Analysis of sustaining growth in a corporation. In: Y. Hosni and T. Khalil, Editors, Management of Technology, Elsevier Ltd, San Diego, CA, pp. 545–556

Research on modeling and design of manufacturing systems, Cranfield University, UK, http://www.cranfield.ac.uk/sims/mem/mdms/aitoroyarbide/researchaitoroyarbide.html, since 2000, last seen Dec 2003

Reid, R., Koljonen, E. (1999). Validating a manufacturing paradigm: A SD modeling approach. The WSC'99, pp 759-765

Riezebos, J. (2004). Time bucket length and lot-splitting approach. International Journal of Production Research, 42(12), 2325-2338

Ritchie-Dunham, J., Morrice, D., Scott, J., Anderson, E. (2000). A strategic supply chain simulation model. The WSC'00, Dec 10-13, Orlando, FL

Saad, S., Perera, T., Wickramarachchi. (2003). Simulation of distributed manufacturing enterprise: a new approach. The WSC'03, Dec 5-8, New Orleans, LA

Shapiro, J. (2001). Modeling the supply chain. Duxbury, USA

Senge; P, Sterman; J. (1994). System thinking and organizational learning: acting locally and thinking globally in the organization of the future. in Morecroft; J., Sterman; J. (Eds.) "Modeling for Learning Organizations", Productivity Press, Portland; OR.

Sinreich, D., Shints, B. (2006). A robust FMS control architecture with an embedded adaptive scheduling mechanism. Journal of Manufacturing Systems. 25(4), 301-312

Simchi-Levi, D.; Kaminsky, P.; Simchi, E. (2008), Designing and Managing the Supply Chain: Concepts, Strategies and Case Studies. McGraw-Hill Irwin, NY

Smith, J. (2003). Survey on the use of simulation for manufacturing system design and operation. Journal of Manufacturing Systems, 22(2); 157-171

Steinman, J. (1990). Multi-Node Test Bed: A Distributed Emulation of Space Communications for the Strategic Defense System. The 21st Annual Pittsburgh Conference on Modeling and Simulation. 21(3), May, pp 1111-1115.

Steinman J. (1991). SPEEDES: Synchronous parallel environment for emulation and discrete event simulation. The SCS Western Multiconference on Advances in Parallel and Distributed Simulation, 23(1), 95-103.

Steinman, J. (1992). SPEEDES: A multiple-synchronization environment for parallel discrete-event simulation. International Journal in Computer Simulation. (2), 251-286.

Steinman, J. (1993). Breathing Time Warp. The 7th workshop on parallel and distributed simulation, San Diego, CA, May 16-19, pp 109 – 118

Steinman, J., Lee, C., Wilson, F., Nicol, D. (1995). Global Virtual Time and distributed synchronization. The 9th workshop on Parallel and distributed simulation, p.139-148, June 13-16, 1995, Lake Placid, NY

Steinman, J. (1996). Discrete-event simulation and the event horizon part 2: event list management. ACM SIGSIM Simulation Digest, 26(1), 170-178

Sterman, J. (1989). Modeling managerial behavior: misperception of feedback in a dynamic decision making experiment. Management Science. 35(3), pp 321-339

Sterman, J. (2000). Business dynamics: systems thinking and modeling for a complex world. McGraw Hill, New York, USA

Sterman, J., Repenning, N., Kofman, F. (1997). Unanticipated side effects of successful quality programs: Exploring a paradox of organizational improvement. Management Science. (43), 503-521

System Dynamics Society Web site at: http://www.albany.edu/cpr/sds/

Towill, D., Edghill, J. (1989). The use of system dynamics in manufacturing systems engineering. Transactions of the Institute of Measurement and Control, (11), 208-216

Umble, M., Srikanth; M. (1996). Synchronous manufacturing. The Spectrum Publishing Company, USA

Umeda, S., Zhang, F. (2008). Hybrid modeling approach for supply chain simulation. in IFIP International Federation for Information Processing, Tomasz Koch, Ed., Boston: Springer, pp 453-460

Venkateswarana, J., Son, Y. (2005). Hybrid system dynamics discrete event simulation based architecture for hierarchical production planning. International Journal Production Research. 43(20), 4397-4429

Ventana Systems Inc., Vensim User’s Guide, www.vensim.com

Vernadat, F. (2002). Enterprise modeling and integration (EMI): Current status and research perspectives. Annual Reviews in Control, (26), 15-25

Viswanadham; N. (2000). Analysis of manufacturing enterprise: An approach to leveraging value delivery processes for competitive advantage. Kluwer Academic Publishers, USA

Wakeland, W., Gallaher, E., Macovesky, L, Aktipis, C. (2004). A comparison of system dynamics and agent based simulations applied to the study of the cellular receptor dynamics. The 37th Annual Hawaii Intl. Conf. on System Sciences, 4-7 Jan

Welch, P. (1983). The statistical analysis of simulation results. In S. Lavenberg (Ed,) The Computer Performance Modeling Handbook, 268–328. New York: Academic Press.

Wiendahl, H, Breithaupt, J. (1998). Automatic production control: a new approach in production planning and control based on methods of control theory. Drexl, A., Kimms, A. (Eds.) Beyond manufacturing resource planning (MRP II), Springer, Berlin, Germany, 335–356.

Wu; B. (1992). Manufacturing system design and analysis. CHAPMAN & HALL, GB

Wu; B. (2002). Handbook of manufacturing and supply system design. aylor and Francis, London.

XJ-Technologies, (2008) AnyLogic User’s manual; www.xjtek.com

XJ-Technologies, (2008) AnyLogic: Technical Overview ; www.xjtek.com

Zeigler, B. (1976). Theory of modeling and simulation. Wiley, NY

Zeigler, B., Praehofer, P., Kim, T. (2000). Theory of modeling and simulation: Integrating discrete event and continuous complex dynamic systems”; 2nd Ed., Academic Press, USA

Zulch G., Jonsson U., Fischer J. (2002). Hierarchical simulation of complex production systems by coupling of model. International Journal of Production Economics. (77), 39-51