SIMULATION MODELING METHODOLOGY: PRINCIPLES AND ETIOLOGY OF DECISION SUPPORT

by

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(ABSTRACT)

Investigation in discrete event simulation modeling methodology has persisted for over thirty years. Fundamental is the recognition that the overriding objectives for simulation must involve decision support. Rapidly advancing technology is today exerting major influences on the course of simulation in many areas, e.g. distributed interactive simulation and parallel discrete event simulation, and evidence suggests that the role of decision support is being subjugated to accommodate new technologies and system-level constraints. Two questions are addressed by this research: (1) can the existing theories of modeling methodology contribute to these *new* types of simulation, and (2) how, if at all, should directions of modeling methodological research be redefined to support the needs of advancing technology.

Requirements for a *next-generation modeling framework* (NGMF) are proposed, and a *model development abstraction* is defined to support the framework. The abstraction identifies three levels of model representation: (1) modeler-generated specifications, (2) transformed specifications, and (3) implementations. This hierarchy may be envisaged as consisting of either a set of narrow-spectrum languages, or a single wide-spectrum language. Existing formal approaches to discrete event simulation modeling are surveyed and evaluated with respect to the NGMF requirements. All are found deficient in one or more areas. The Conical Methodology (CM), in conjunction with the Condition Specification (CS), is identified as a possible NGMF candidate. Initial assessment of the CS relative to the model development abstraction indicates that the CS is most suited for the middle level of the hierarchy of representations – specifically functioning as a form for analysis.

The CS is extended to provide wide-spectrum support throughout the entire hierarchy via revisions of its supportive facilities for both model representation and model execution. Evaluation of the pertinent model representation concepts is accomplished through a complete development of four models. The collection of primitives for the CS is extended to support CM facilities for set definition. A higher-level form for the report specification is defined, and the concept of an *augmented* specification is outlined whereby the object

specification and transition specification may be automatically transformed to include the objects, attributes and actions necessary to provide statistics gathering. An experiment specification is also proposed to capture details, e.g. the condition for the start of steady state, necessary to produce an experimental model.

In order to provide support for model implementation, the semantic rules for the CS are refined. Based on a model of computation provided by the action cluster incidence graph (ACIG), an implementation structure referred to as a direct execution of action clusters (DEAC) simulation is defined. A DEAC simulation is simply an execution of an augmented CS transition specification. Two algorithms for DEAC simulations are presented.

Support for parallelizing model execution is also investigated. Parallel discrete event simulation (PDES) is presented as a case study. PDES research is evaluated from the modeling methodological perspective espoused by this effort, and differences are noted in two areas: (1) the enunciation of the relationship between simulation and decision support, and the guidance provided by the life cycle in this context, and (2) the focus of the development effort. Recommendations are made for PDES research to be reconciled with the "mainstream" of DES.

The capability of incorporating parallel execution within the CM/CS approach is investigated. A new characterization of inherent parallelism is given, based on the time and state relationships identified in prior research. Two types of inherent parallelism are described: (1) inherent event parallelism, which relates to the independence of attribute value changes that occur during a given instant, and (2) inherent activity parallelism, which relates to the independence of attribute value changes that occur over all instants of a given model execution. An analogy between an ACIG and a Petri net is described, and a synchronous model of parallel execution is developed based on this analogy. Revised definitions for the concepts time ambiguity and state ambiguity in a CS are developed, and a necessary condition for state ambiguity is formulated. A critical path algorithm for parallel direct execution of action clusters (PDEAC) simulations is constructed. The algorithm is an augmentation of the standard DEAC algorithm and computes the synchronous critical path for a given model representation. Finally, a PDEAC algorithm is described.

For Ernest H. Page, 1921 - 1977. We're having a lovely time, wish you were here.

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To say that thanks is due my major advisor, Dick Nance, would be an egregious understatement. During the past six years he has played the simultaneous roles of mentor, role model, employer, friend, partner-in-crime, and father to me, and perhaps most importantly, he has been "Nook" to my children. Similar sentiments apply to Marc Abrams, Sean Arthur, Osman Balci and Mike Overstreet. All of these gentlemen have enriched my life beyond my capacity to thank them. Clearly, of the many things I take with me from my tenure at this university, the relationships I have built – both personal and professional, particularly with the members of my committee – are most prized.

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Finally, I must thank my wife, Larenda, and children Julia and Ernie, who have too often been neglected during the completion of this work.

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AC	Action Cluster
ACAG	Action Cluster Attribute Graph
ACD	Activity Cycle Diagram
ACIG	Action Cluster Incidence Graph
ASG	Action Sequence Graph
CAC	Contingent Action Cluster
CAP	Condition-Action Pair
CF	Conceptual Framework
CFG	Control Flow Graph
CM	Conical Methodology
CS	Condition Specification
DAC	Determined Action Cluster
DEAC	Direct Execution of Action Clusters
DES	Discrete Event Simulation
DEVS	Discrete EVent system Specification
DIS	Distributed Interactive Simulation
DOMINO	multifaceteD cOnceptual fraMework for vIsual simulatioN mOdeling
ESGM	Elementary Simulation Graph Model
GSMP	Generalized Semi-Markov Process
MIMD	Multiple-Instruction stream, Multiple-Data stream
NGMF	Next-Generation Modeling Framework
PDEAC	Parallel Direct Execution of Action Clusters
PDES	Parallel Discrete Event Simulation
SGM	Simulation Graph Model
SIMD	Single-Instruction stream, Multiple-Data stream
SMDE	Simulation Model Development Environment
SMSDL	Simulation Model Specification and Documentation Language
SPL	Simulation Programming Language
VSMSL	Visual Simulation Model Specification Language
VSSE	Visual Simulation Support Environment

Chapter 1

INTRODUCTION

Those who can, do. Those who can't, simulate.

Anonymous

As the decade of the 1990s nears its midpoint, computer simulation – particularly discrete event simulation (DES) – is a well studied and widely utilized problem-solving technique. In the over fifty years since its inception on digital computers, a truly substantial body of literature in discrete event simulation has evolved (see [56, 121, 159, 229, 232] for historical perspectives on discrete event simulation). Much of this history demonstrates that *modeling methodology,* which defines a theory of models and the modeling process and their relationship to decision support, is central to the efficacy of simulation. Of particular significance in this area has been work in time flow mechanisms (see [56, 122, 152]), conceptual frameworks (see [65, 121]), simulation programming languages (see [159]), statistical analysis (see [17, 55, 240]), and model life cycles (see [181]).

Recently, technological advances have enabled discrete event simulation to be utilized in contexts barely conceivable only a few years ago: simulation is now being targeted for execution on distributed networks, and multiprocessors, as well as sequential architectures. Simulation is no longer simply a tool for "analysis" per se; simulation in the 1990s is expected to provide support for a wide variety of purposes including, training, interaction, visualization, hardware testing, and decision support in real-time, just to name a few. At first glance, it would appear that these new approaches for simulation are so advanced that techniques developed two and three decades ago could not possibly be of any use, and that to take full advantage of these new technologies, our modeling approaches must be

fundamentally altered. Evidence suggests that many ongoing research efforts adopt this view. But is this perspective the correct one?

The research described here addresses the modeling methodological implications of the coming of a "new age" for discrete event simulation. The investigation treats discrete event simulation at its most fundamental level as a tool for decision support. Based on this observation, and other fundamental characteristics of discrete event simulation, the question is posed: "Is the existing knowledge base in modeling methodology wholly inadequate to accommodate new technologies and contexts for discrete event simulation, or has there simply been a failure to recognize and properly exploit over 30 years of modeling methodology investigation?" The answer to this question is both yes, and no. Many of the new contexts for simulation challenge our knowledge base in modeling methodology. Still, if the fundamental nature of simulation as a decision support tool persists, existing modeling methodological investigation should provide a framework within which new techniques and system-level requirements can be accommodated.

1.1 Problem Definition

Discrete event simulation is in the midst of what could justifiably be referred to as a revolution. A mere two decades ago, the *typical* simulation study could be easily described: it involved systems analysis using a single model generated by a relatively small group of modelers, analysts, users, and decision makers. Today, no such description can be given. Discrete event simulation models may adopt myriad forms:

- A single, large, relatively static model that serves over a protracted period of use, e.g. a weather simulation.
- A single model which evolves rapidly during experimentation for system design or optimization, e.g. a cache model.
- A model which consists of a synthesis of results from several existing models in an effort to answer questions on a *metasystem* level.
- Models used for analysis.
- Models used to animate and visualize systems.
- Models used to provide an interactive training environment.
- Models used to stimulate hardware prior to operational deployment.

- Models used for real-time decision support.
- Models which provide various combinations of the above.

Furthermore, these models may be developed by groups distributed throughout a company, or across continents. Model analysis may be the purview of an entirely separate group or groups. And the model users may represent yet another diverse collective.

This revolution is the progeny of two factors: (1) advances in computing technology, which have made many of these approaches computationally feasible, and (2) restricted budgets and the affordability of computer hardware and processor time which makes simulation *potentially* very cost-effective. To illustrate this point, consider the increasing reliance on (and diversity of) simulation within the U.S. military.[1] According to the 1992 Defense Modeling and Simulation Initiative (DMSI) [64]:

> ...the United States today faces great uncertainty due to a rapidly changing world. New conflict scenarios visualizing operations at any large number of locations worldwide, at varying levels of conflict, and in conjunction with new weapon systems will lead to the development of new operational concepts. Modeling and simulation, drawing on existing and new technology, must be able to support test and validation of these concepts, provide the means for war fighting rehearsals and preparation of forces, and allow commanders and their staffs to design, assess, and visualize the simulated consequences of execution of their campaign plans. Similarly, modeling and simulation must be prepared to support all phases of the acquisition process that will be used to provide the new and upgraded weapon systems for employment in these potential future conflicts. Finally, in light of the constrained budgets, the modeling and simulation community will have to be more resourceful with available assets and, at the same time, be ready to respond to an increased demand for its services.

At the highest levels within the military, simulation is seen as *the* answer to declining budgets in the post-Cold War era. The call has been made to do *more* with simulation and, if possible, do it in the context of a single development effort. For example, projects such as the Navy's Multiwarfare Assessment and Research System (MARS) (see [165]) are designed to support both acquisition and training through the distributed interactive simulation (DIS) protocol [110], as well as providing a forum for the integration of extant models to enable multiple fidelity, multiple force-level analysis.

[1] As cited in [237, p. 129], Market Intelligence Research Corporation estimates U.S. military revenues in the simulation market to have been around $2.5 billion in 1989 and $2.7 billion in 1993. With an estimated percentage growth increasing from 2.5% in 1993 to 6.7% in 1999, the projected revenues for U.S. military simulation in 1999 are $3.7 billion.

This revolution in simulation, and the fact that technology is today exerting major influences on the course of simulation research in many areas, provides the motivation for this research effort, which may be stated as follows:

> *The cost-effective application of simulation in any context hinges fundamentally on the underlying principles of model development, and model representation, and the precepts of the supporting methodology.*

1.2 Thesis Objectives

This research seeks to identify an answer to a central question of discrete event simulation modeling methodology:

> *What is the nature of the ideal framework for simulation model development where the models may be used for a wide variety of purposes, and implemented on varying architectures?*

Obviously, a direct answer to this fundamental question cannot be realistically formulated within the very limited scope of a doctoral dissertation; indeed an *ideal* framework may be incapable of definition. Our aim is to identify the challenges new technologies have brought to simulation modeling methodology and to describe a modeling framework based on the fundamental recognition that the overriding objective of *any* simulation is making a correct "decision" (although the decision may take many forms). To focus the development of concepts, parallel discrete event simulation (PDES) is presented as a case study – contrasting the prevalent PDES approaches with the framework suggested here. Thus, two specific objectives are identified for this research:

1. Identify an extensible framework for model development which permits the integration of emerging technologies and approaches, and demonstrate its feasibility using an existing methodology and representation form(s).
2. Recognize a potential problem with the focus of parallel discrete event simulation research, and demonstrate how the framework described above may be utilized to cost-effectively incorporate parallel execution within the discrete event simulation life cycle.

1.3 Thesis Approach

At the core of this research is a familiar message: with very few exceptions, research in any area should be conducted while "standing on the shoulders" of those that have

preceded us. Accordingly, the approach taken relies heavily on the years of research that comprise the Simulation Model Development Environment Project (see [21]). The Conical Methodology [155, 158, 160] and the Condition Specification [178] play central roles. The tasks defined to meet the stated objectives are the following.

Describe a simulation model development philosophy. Frame the context of this research effort by describing a philosophy of simulation model development in which the role of decision support takes a preeminent position.

Identify a set of criteria for a next-generation modeling framework. Using the discrete event simulation modeling methodology literature as a basis, identify criteria for a next-generation modeling framework.

Define a model development abstraction to support the framework. Based on the philosophy described above and the identified requirements for a next-generation modeling framework, define a "model of model development," or model development *abstraction,* consistent with the discrete event simulation model life cycle and suitable to permit the integration of new technologies and system-level requirements.

Survey the formal approaches to discrete event simulation model development. Formal descriptions of models and model behavior are required to realize the requisite level of automatability in the envisaged modeling framework. Survey the existing formal approaches to discrete event simulation model development and evaluate each according to the criteria identified above.

Evaluate the Condition Specification. Through the development of several example models, evaluate the Condition Specification (CS) relative to the Conical Methodology (CM). Extend the representational facilities of the CS, as necessary, to fully and effectively support the CM provisions for model development.

Evaluate methods for generating a Condition Specification. Evaluate the extant methods for automated assistance in the generation of a CS. Using the development of examples

given above as a reference point, identify needed improvements or alternative methods for generating a CS.

Define algorithms for directly executing a Condition Specification. Investigate the graph representations provided by the Condition Specification to determine if a model of computation may be defined based upon the direct execution of these graphs. Define algorithms for for the direct execution of a CS suitable for sequential architectures.

Define model analysis and algorithms to support direct execution of Condition Specifications on a multiprocessor. Define methods to assess the "inherent" parallelism within a CS representation. Define procedures to map a CS onto a multiprocessor, and define algorithms for execution such that the inherent parallelism may be exploited.

Examine parallel discrete event simulation from a modeling methodological perspective. Parallel discrete event simulation (PDES) research has persisted nearly 15 years, and yet PDES has failed to make a significant impact within the general discrete event simulation community. Examine PDES from a modeling methodological perspective and identify any potential problems. Based on the philosophy guiding this research, suggest possible solutions.

1.4 Thesis Organization

The remainder of this thesis is organized as follows. Chapter 2 provides definitions for the discrete event simulation terminology used throughout this work.

The guiding philosophy of this research is presented in Chapter 3. The philosophy is based upon the rich history of discrete event simulation modeling methodology. The concepts of life cycle, paradigm, methodology, method and task are reviewed, and a life cycle model for a simulation study suggested by Nance and Balci is described. The Simulation Model Development Environment, which represents a realization of this philosophy is also discussed. The framework for model development underlying the SMDE is abstracted into a form suitable to permit the integration of new technologies and system-level requirements. This type of framework is described as a "next-generation modeling framework." Based

on the independent observations of Nance and Sargent, an evaluative criteria for a next-generation modeling framework is developed.

A survey of formal approaches to discrete event simulation model development appears in Chapter 4. These approaches are evaluated with respect to the criteria identified in Chapter 3.

The Conical Methodology and the Condition Specification, which provide the foundation for remainder of the thesis, are described in Chapter 5. The Condition Specification is analyzed regarding its support for model representation relative to the provisions and tenets of the CM in Chapter 6. The analysis is accomplished through detailed development of a collection of example models.

Methods for generating a Condition Specification are surveyed in Chapter 7. Based on observations from Chapter 6, new methods are proposed.

Chapter 8 defines a model of computation based on graph forms of the CS. The CS semantics are reformulated to support this model of computation, and algorithms for (sequential) execution of these graph forms are presented. The provisions for model analysis in the CS are reviewed in terms of the language extensions (Chapter 6) and redefined semantics.

Issues involving the execution of a simulation model in a parallel processing environment are described in Chapter 9. The research comprising the field of parallel discrete event simulation (PDES) is briefly surveyed, and PDES is examined from the modeling methodological perspective adopted by this research effort. Prospects for supporting parallel execution in the CS are investigated. The concept of "inherent parallelism" is defined and a critical path algorithm constructed such that the inherent parallelism in a CS model representation may be identified. Finally, an algorithm for the direct parallel execution of a CS is given.

A summary and evaluation of the research, along with an identification of future research needs, appears in Chapter 10.

1.5 Summary of Results

The primary contributions of this effort may be assessed in relationship to: (1) modeling methodology, and (2) parallel discrete event simulation.

1.5.1 Modeling methodology

The contributions of this research to discrete event simulation modeling methodology are identified as follows.

Requirements for a Next-Generation Modeling Framework. In a 1977 report, Nance identifies six criteria for a simulation model specification and documentation language. Sargent, in a 1992 conference paper, offers fourteen requirements for a modeling paradigm. These two sets of criteria are reconciled to produce a list of ten requirements for a next-generation modeling framework.

Critical evaluation of formal approaches to discrete event simulation. In Chapter 4, a survey of formal methods for developing discrete event simulation models is undertaken. The approaches surveyed are Lackner's Calculus of Change, the systems theoretical approaches including DEVS and the system entity structure, activity cycle diagrams, event graphs, simulation graphs, control flow graphs, Petri net approaches, logic-based approaches, and generalized semi-Markov processes. Also discussed are current efforts to formalize important modeling concepts such as abstraction and hierarchy. The approaches are evaluated based on proposed criteria for next-generation modeling frameworks. The evaluation reveals that all the extant approaches are deficient in one or more respects. The observation is made that a methodology-representation synergism is lacking.

Rigorous investigation of the Condition Specification. This effort represents the first extensive application of the CS since its original definition. Subsequent to its development by Overstreet in 1982, the CS has been investigated piecewise: some efforts examining analysis using the CS, other research examining methods to coerce a CS from a modeler. In this thesis, the CS is thoroughly, and holistically exercised. In terms of the hierarchy of representations described in Chapter 3, the CS fits naturally into the middle level. The tasks comprising this effort widen the spectrum of the CS, such that it provides support for both the higher and lower levels of model representation. This widened spectrum is achieved *without* sacrificing the utility of the language at the middle level.

In Chapter 6, the CS is evaluated in terms of the provisions and tenets of the Conical Methodology. Although the CS has long been adopted as the primary specification form

for the CM, the efforts of Chapter 6 uncover and resolve several "disconnects" between the representational provisions of the language, and the tenets underlying the methodology.

Support for implementation is derived from utilizing the action cluster incidence graph as a model of computation. Based on this model of computation, the CS semantics are reformulated in Chapter 8. Algorithms for direct (sequential) execution of a CS are also presented. A claim of architecture independence results from the developments in Chapter 9. Through the characterization of inherent parallelism, and a model for (synchronous) parallel execution of a CS, methods are defined such that a model developed in the CS – solely with regard to a natural description of the underlying system, to facilitate the establishment of model correctness – may be executed in a parallel processing environment.

1.5.2 Parallel discrete event simulation

The contribution of this research to the field of parallel discrete event simulation is identified as follows.

Critique of current approach based on a new perspective. In Chapter 9, parallel discrete event simulation (PDES) research is evaluated from the modeling methodological perspective identified in Chapter 3. Differences are evident in two areas: (1) the enunciation of the relationship between simulation and decision support, and the guidance provided by the life cycle in this context, and (2) the focus of the development effort. Four recommendations are made for PDES research to be reconciled with the "mainstream" of DES: (1) return the focus of the development effort to the model, (2) formulate examples with enunciation of simulation study objectives, (3) examine methods to extract speedup in terms of the particular model development approach and envisaged model purpose, and (4) examine the relationship of speedup to software quality.

Chapter 2

DISCRETE EVENT SIMULATION TERMINOLOGY

You can measure distance by time.
"How far away is that place?"
"About 20 minutes."
But it doesn't work the other way.
"When do you get off work?"
"About three miles."

Jerry Seinfeld, *SeinLanguage*

A common occurrence in disciplines that are at the center of widespread, multifaceted research by individuals with varied interests and backgrounds, is the slow development of a standard terminological system. Such has been the case in discrete event simulation. Nance [156] discusses some precipitate causes of this lack of a "common language of discourse" and proposes a set of definitions based on the fundamental relationship between time and state in a discrete event simulation. The definitions presented here conform to the premise advanced by Nance and have, over the past fifteen years, begun to gain general recognition within the discrete event simulation community.

According to Shannon [215], **digital computer simulation** is the process of designing a model of a real system and conducting experiments with this model on a digital computer for a specific purpose of experimentation. Based on the taxonomy given in [159], digital computer simulation may be divided into three categories: (1) **Monte Carlo,** (2) **continuous,** and (3) **discrete event.** Monte Carlo simulation is a method by which an inherently non-probabilistic problem is solved by a stochastic process; the explicit representation of time is not required. In a continuous simulation, the variables within the simulation are continuous functions, e.g. a system of differential equations. If value changes to program

variables occur at precise points in simulation time (i.e. the variables are "piecewise linear"), the simulation is discrete event. Nance [159] notes that three related forms of simulation are commonly used in the literature. A **combined** simulation refers generally to a simulation that has both discrete event and continuous components.[1] **Hybrid** simulation refers to the use of an analytical submodel within a discrete event model. Finally, **gaming** can have discrete event, continuous, and/or Monte Carlo modeling components. The focus of this thesis is limited to discrete event simulation.

As noted, a simulation involves modeling a system. Adopted here is the definition contained in the Delta project report [102, p. 15]:

> A **system** is a part of the world which we choose to regard as a whole, separated from the rest of the world for some period of consideration, a whole which we choose to consider as containing a collection of components, each characterized by a selected set of data items and patterns, and by actions which may involve itself [a component] and other components.

The system may be real or imagined and may receive input from, and/or produce output for, its **environment.**

A **model** is an abstraction of a system intended to replicate some properties of that system [178, p. 44]. The collection of properties the model is intended to replicate (for the purpose of providing answers to specific questions about the system) must include the **modeling objective.** The importance of the modeling objective cannot be overstated; a proper formulation of the objective is essential to any successful simulation study. Only through the objective can meaning be assigned to any given simulation program. Since by definition a model is an abstraction, details exist in the system that do not have representation in the model. In order to justify the level of abstraction, the model assumptions must be reconciled with the modeling objective.

According to Nance [156, p. 175], a model is comprised of **objects** and the relationships among objects. An object is anything characterized by one or more **attributes** to which **values** are assigned. The values assigned to attributes may conform to an attribute typing similar to that of conventional high level programming languages.

[1] Typically, a discrete event submodel is encapsulated within a continuous model.

Within a discrete event simulation, the two concepts of *time* and *state* are of paramount importance. Nance [156, p. 176] identifies the following primitives which permit precise delineation of the relationship between these fundamental concepts:

- An **instant** is a value of system time at which the value of at least one attribute of an object can be altered.
- An **interval** is the duration between two successive instants.
- A **span** is the contiguous succession of one or more intervals.
- The **state of an object** is the enumeration of all attribute values of that object at a particular instant.

These definitions provide the basis for some widely used (and, historically, just as widely misused) simulation concepts [156, p. 176]:

- An **activity** is the state of an object over an interval.
- An **event** is a change in an object state, occurring at an instant, and initiates an activity precluded prior to that instant. An event is said to be **determined** if the only condition on event occurrence can be expressed strictly as a function of time. Otherwise, the event is **contingent.**
- An **object activity** is the state of an object between two events describing successive state changes for that object.
- A **process** is the succession of states of an object over a span (or the contiguous succession of one or more activities).

These concepts may be viewed as illustrated in Figure 2.1. Keep in mind that an activity for an object is bounded by two successive events *for that object* [156, p. 176]. Event, activity and process form the basis of three primary **conceptual frameworks** (**world views**) within discrete event simulation.

- In an **event scheduling** world view, the modeler identifies when actions are to occur in a model.
- In an **activity scanning** world view, the modeler identifies why actions are to occur in a model.
- In a **process interaction** world view, the modeler identifies the components of a model and describes the sequence of actions of each one.

In his thesis, Derrick [65] classifies these and other conceptual frameworks for simulation modeling, discussing the relative strengths and weaknesses of each regarding their influence on model development.

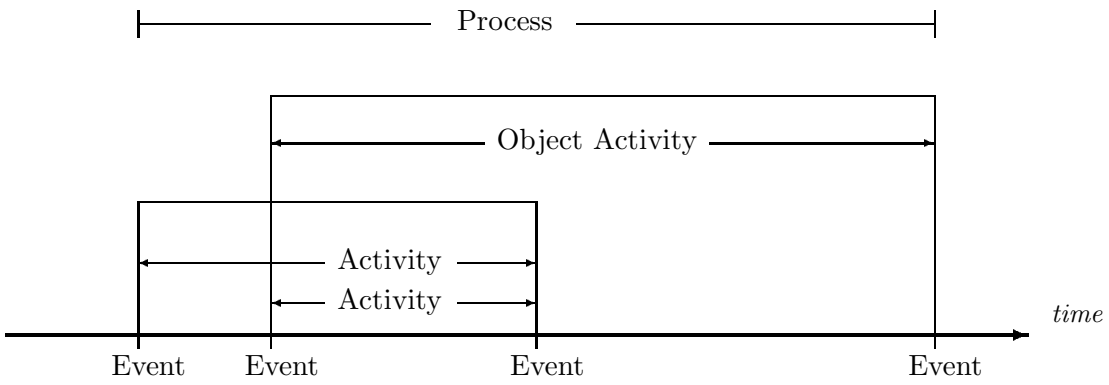


Figure 2.1: Illustration of Event, Activity and Process.

To briefly summarize, modeling is the process of describing a system – producing a model of that system – with the goal of experimenting with that model to gain some insight into the behavior of the system. The model itself is a collection of interacting objects, these objects being described by attributes. This last assertion should not go unqualified. An object-based view of a model is not the *only* possible description of a system. For example, a system may be modeled as a set of functions that act on streams of input to produce output (e.g. [99]), or as a set of data structures (e.g. [111]) with some prescribed behavior. A gamut of perspectives has been utilized with varied success within the field of software engineering. Within discrete event simulation, models have been organized along temporal and state – as well as object – lines (the definitions of the traditional conceptual frameworks need not *necessarily* contain an explicit notion of object). It may be fairly argued then that not all systems of interest are composed of clearly identifiable objects. For example, in a model of the decision making process, is intuition an object? Still, most systems do admit a well-defined object-based classification, and so these definitions – while perhaps not *ideal* – are widely applicable. Finally, *any* method of description *must* contain a set of attributes whose value changes describe the lifetime of the model. And an object-based description would seem to provide the best available means of organizing these attributes.

Chapter 3

A PHILOSOPHY OF MODEL DEVELOPMENT

> *But there is yet another consideration which is more philosophical and architectonic in character; namely to grasp the idea of the whole correctly and thence to view all . . . parts in their mutual relations . . .*
>
> Immanuel Kant, *Critique of Practical Reason*

In this chapter, a philosophy of simulation model development is described. The philosophy is based on a singular tenet: *the primary function of discrete event simulation involves decision support.* The philosophy stipulates that this *fundamental characteristic* persists even in the face of new technologies and applications, and that any failure to recognize this basic fact is a failure to address simulation in its total context. Of course, the role of philosophic discussion in scientific endeavors is a subject of some debate. As the existential philosopher Karl Jaspers observes [112, p. 7]:

> What philosophy is and how much it is worth are matters of controversy. One may expect it to yield extraordinary revelations or one may view it with indifference as a thinking in the void. One may look upon it with awe as the meaningful endeavor of exceptional men or despise it as the superfluous broodings of dreamers. One may take the attitude that it is the concern of all men, and hence must be basically simple and intelligible, or one may think of it as hopelessly difficult. . . . For the scientific-minded, the worst aspect of philosophy is that it produces no universally valid results; it provides nothing we can know and thus possess.

The veracity and merit of a philosophical position, such as outlined in this chapter, is not readily demonstrable. Some elements of the following discussion may be either accepted or dismissed, as matters of "faith." On the other hand, philosophies of simulation model development *can* be empirically evaluated, albeit indirectly and over a perhaps considerable

period of time. The products, in this case simulation models and studies, in their degrees of success or failure reflect the credibility of the philosophy underlying each. Accordingly, what is described here, while perhaps at times taking an almost *evangelical* tone, can – and is – being validated by ongoing practice of simulation model development.

3.1 A Modeling Methodological View of Discrete Event Simulation

In Chapter 1, modeling methodology is characterized as illuminating the nature of models and the modeling process. The primary role of modeling methodological research is to identify how simulation models *should* be constructed and used so that simulation is cost-effective as a problem-solving technique. The importance of modeling methodology within the field of discrete event simulation is evidenced by its prominence within the preeminent DES conferences and journals, such as, respectively, the *Winter Simulation Conference,* and the *Transactions on Modeling and Computer Simulation,* published by the Association for Computing Machinery. The precepts that comprise the "modeling methodological view" stem from a basic recognition of the nature of simulation.

3.1.1 What is simulation?

To understand fully the role of modeling methodology, one question must be addressed, what *is* a simulation? Any number of definitions can be gleaned from a variety of distinguished texts (see [72, 76, 126, 215]). The definition advanced by Shannon [215] is given in Chapter 2, but for purposes of this discussion simulation may be regarded simply as:

> *The use of a mathematical/logical model as an experimental vehicle to answer questions about a referent system.*

This definition seems to be efficient in the use of words and careful not to presume certain conditions or implicit purposes. For example, computer simulation is not mandated; the model could follow either discrete event or continuous forms; the answers might not be correct; and the system could exist or be envisioned.

Essentially, a simulation provides the basis for making some decision – this decision being based on the "answers" provided by the simulation. The relative importance of the decision, once made, and the subsequent action (or inaction) taken as a result of the decision are myriad. Often, the simulation provides an assessment of some system which is

not readily amenable to other types of analysis; thus the simulation provides the only means by which to assess a given situation. The ramifications of making an incorrect simulation-based decision can range from a mere nuisance, to loss of investment, to more catastrophic consequences such as the loss of lives. Therefore,

arriving at the correct decision is the overriding objective of simulation.

One may want a simulation to provide a variety of behaviors and possess a multitude of characteristics, but none of these should be achieved at the expense of a correct decision.

3.1.2 Enhancing decision support through model quality management

While computer architecture and compiler design technology have often driven model development in terms of how a simulation model *can* be constructed, modeling methodology has focused on the question of how a simulation model *should* be constructed. Investigation in modeling methodology has persisted some 35 years, beginning with the General Simulation Program of Tocher in 1958 (see [231, 232]), and continuing in the writings of Lackner [124, 125], Kiviat [120, 121], Nance [152, 155, 156, 158, 160], and Zeigler [250, 251, 252], to cite the most prominent. The lessons of this history identify several factors that are positively correlated with the probability of making a correct decision. These factors include (but are by no means limited to):

1. *An adequate understanding of the problem to be solved.* If the problem to be solved is not well-defined and manageable, then little hope exists that a solution to the problem is readily forthcoming. (This is fundamental to every known problem-solving technique and certainly not unique to simulation.)

2. *An error-free model.* The correctness of the model is paramount to a cost-effective solution in light of the overall objective. Errors induced in the model, if never detected, could lead to the acceptance of results based on an invalid model – a potentially disastrous action. If an error *is* detected, but its detection comes late in the development stream, the cost of correction involves the cost of correcting the model and repeating the development steps. To be cost-effective, the methods for model development should foster the initial development of correct (error-free) models.

3. *An error-free program.* Recognizing that the program is but one representation of a model – usually the last in a line of development, a correct program can only be generated from a correct model. The arguments for program correctness mirror those for model correctness.

4. *Experiment design.* Construction of the model and program must reflect the objectives in carrying out the simulation; the right *questions* must be asked of the program in

order that the appropriate answers can be derived. The problem understanding must be sufficient and the model and program designed to facilitate the experiment design process.

5. *Interpretation of results.* A key recognition here is that no simulation program ever built produced *the* answer to anything. Typically, simulation output measures are observations of random variables, and a proficiency in statistical methods, including variance reduction and multivariate analysis, is required to successfully – and correctly – interpret the results provided by a simulation.

These observations establish that *simulation* involves more than merely a program. Only with careful attention to all of the factors identified above can the overall objective of simulation, a correct decision, be consistently achieved. With this recognition, considerable effort has been undertaken to impose a management structure onto the framework of using simulation as a problem-solving technique. Perhaps of greatest significance in this area has been the development of life-cycle models for simulation. A life-cycle model of a simulation study, proposed by Nance and Balci, is presented below. We preface the presentation with a brief discussion of the *concepts* of life cycle, paradigm, and methodology.

3.1.2.1 Life cycle, paradigm and methodology

Allusion to the concepts of life cycle, paradigm and methodology are frequent, but rarely are they accompanied by definitions. Their mutual influences make it difficult to delineate where one stops and the other starts. In terms of the philosophy described here, the relationship among these basic concepts may be viewed as illustrated in Figure 3.1, and discussed below.

Life cycle. We begin with an axiom: *the* simulation life cycle *exists.* When a simulation model is developed and used, it passes through the evolution prescribed by the life cycle – regardless of whether or not the existence of the life cycle is recognized, or accepted.

A *life-cycle model* is the codification of the life cycle. In all likelihood no life-cycle model precisely depicts the actual simulation life cycle. In the remainder of the thesis, the terms life cycle and life-cycle model are often used interchangeably. In all cases, these are references to life-cycle models. Italics are used when describing *the* life cycle.

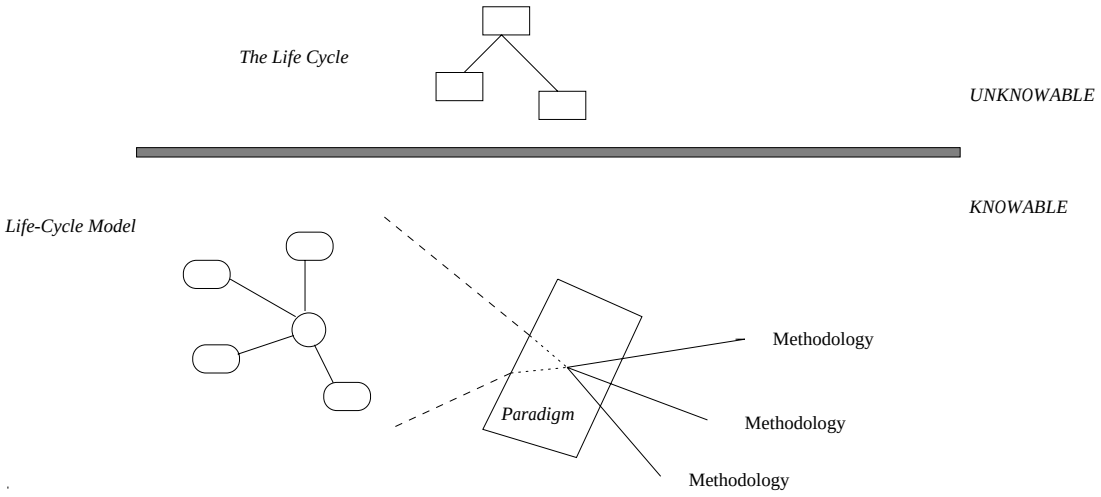


Figure 3.1: The Relationship Between Life Cycle, Paradigm, and Methodology.

Paradigm. A paradigm dictates that to get from point a to point b the journey should be viewed as taking a particular form. In this sense, a paradigm is analogous to a philosophy, e.g. metaphysics or existentialism. Paradigms – like philosophies – may differ widely. Each seeks to explain the same universe; but each may differ in its underlying axioms and thus may yield substantially different descriptions of equivalent concepts.

The highest level concept attainable (i.e. capable of being reasoned about) is that of the paradigm. The shape of the life-cycle models we construct is a direct reflection of the tenets and principles of the paradigms we adopt; that is,

> *a life-cycle model is the realization of* the *life cycle as viewed through one or more paradigms.*

Methodology, method and task. One step (philosophically) below the paradigm is the methodology.[1] A methodology typically prescribes a set of complementary methods and the rules for using them to support the evolution of software through one or more phases of a life-cycle model. The methodology itself reflects the influence of one or more paradigms. At the lowest level in this hierarchy are method and task. Generally, a method is considered to

[1]Here the discussion regards a *single* methodology, e.g. the Conical Methodology or the DEVS approach, as opposed to the more abstract notion of "discrete event simulation modeling methodology."

describe the means of accomplishing a specific task by identifying the ordering of constituent decisions as well as providing guidelines for their resolution.

Nance and Arthur [161] discuss the influence a modeling methodology exerts on the design of an environment for model development and support. The authors indicate that the role of a methodology is to identify those *principles,* e.g. life-cycle verification and specification-derived documentation, that should govern the modeling process so that a given set of *objectives* can be attained. The intent of a modeling methodology is to define a process by which factors inherent in the task at hand, e.g. the number of objects comprising the model, the frequency of interactions among them, and the degree of concurrency, can be overcome. The value of a methodology is derived from its ability to produce a product (a model) that exhibits validity in conformance with the tolerance level prescribed for the study.

3.1.2.2 A life-cycle model for simulation

With the above discussion in context, this section begins on a more pragmatic note. According to Blum [33, p. 18], all systems initiate development with some statement of need, or requirements, and end (hopefully) with a protracted period of use. The description of the management process between these two points is commonly the domain of a life-cycle model. Life-cycle models serve two primary functions. First, they determine the order of the stages involved in development and evolution. But just as importantly, a life-cycle model establishes the criteria for transition from one stage to the next [34, p. 14].

A life-cycle model of a simulation study is illustrated in Figure 3.2. The life-cycle model contains ten phases (designated by ovals), ten processes (designated by dashed vectors) and thirteen credibility assessment stages (11 of which are illustrated in the figure using solid vectors). Detailed descriptions of the components of the life-cycle model are provided in Appendix A.

The origins of the life-cycle model pictured in Figure 3.2 can be traced to a group of guidelines identified by Nance [155] as the "model life cycle." This early form of the life cycle described primarily those phases which comprise model development (the phases which form the circle in Figure 3.2). Nance and Balci [162] subsequently extend the original concepts, and Balci [20] defines the form presented here. Note that the entire structure serves to

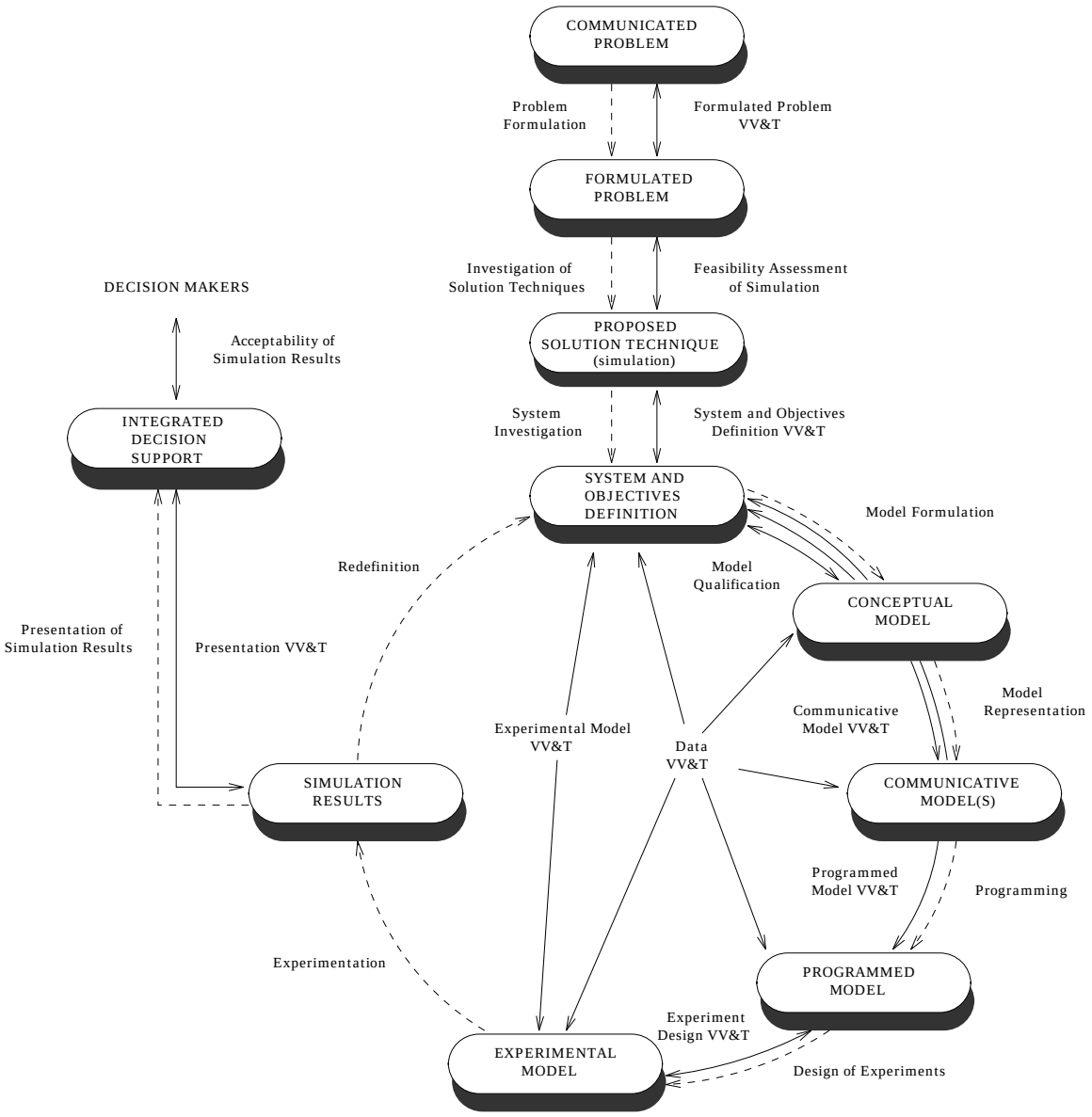


Figure 3.2: A Life-Cycle Model of a Simulation Study.

support one thing: the decision process. Note also the very limited role of the program within the life-cycle model. While program-related (implementation) decisions, especially in the presence of new technologies, *may* necessarily have impact outside of the program phase of the life-cycle model, the impact of program design should not be so pervasive that it is allowed to significantly encumber other phases.

3.1.3 Some issues in model representation

According to Nance [157], beginning in the late 1970s a shift in the focus of the discrete event simulation community from a *program*-centric view of the simulation process to a *model*-centric view occurred. Motivating this shift was an evolving recognition of two factors: (1) programming language representations contain implementation-related information that obscures the clear enunciation of model behavior, and (2) the use of a particular language has direct, often hidden, influences on the structure of the model formulation.

3.1.3.1 The programming language impedance

As identified in [159] a simulation programming language (SPL) must provide:

- Generation of random numbers, so as to represent the uncertainty associated with an inherently stochastic model.
- Process transformers, to permit uniform random variates obtained through the generation of random numbers to be transformed to a variety of statistical distributions.
- List processing capability, so that objects can be manipulated or created and deleted as sets or as members, added to and removed from sets.
- Statistical analysis routines, to provide the descriptive summary of model behavior so as to permit comparison with system behavior for validation purposes and the experimental analysis for both understanding and improving system operation.
- Report generation, to furnish an effective presentation of potentially large reams of data to assist in the decision making that initially stimulates the use of simulation.
- A time flow mechanism, to provide an explicit representation of time.

Despite the best efforts of any SPL designer, the syntax concomitant with each of these capabilities clutters a programmed model with details that contribute nothing to the description of the behavior of the underlying system. Since ideally, in order to facilitate model analysis, a description free of these and other *implementation* details is preferable, the need for higher level model representational forms becomes evident.

3.1.3.2 The conceptual framework problem

While no etiology of software errors exists, many errors seem to arise as the result of a poor mesh between the models of problems as they form in the mind (or minds) of a modeler (modeling team), and the representational capabilities provided by extant programming languages and techniques.

The developers of simulation programming languages sought to close this conceptual distance through the provision of a *conceptual framework* (or "world view") within the language. The conceptual framework provides a modeler with a means to construct a *mental picture* of the model. Theoretically, if the model in the modeler's mind and the SPL utilize the same conceptual framework, the distance is closed.

As Overstreet [178, p. 164] observes, the traditional conceptual frameworks can best be described as providing a perspective on system representation through varying *localities.* The behavior of a system can be modeled according to:

1. the times at which things "happen" (the event scheduling world view; *locality of time*),
2. a state precondition on the occurrence of something happening (the activity scanning world view; *locality of state*), or
3. the ordered sequence of actions performed on (or by) a given model object (the process interaction world view; *locality of object*).

In his thesis, Derrick [65] classifies thirteen conceptual frameworks and identifies both positive and negative aspects of their influence on model representation.

The provision of conceptual frameworks within simulation programming languages ostensibly affords significant benefits for modeling as compared to general purpose languages. These conceptual bridges are *not* without their drawbacks however – the tendency to use the language best known by the modeler often results in a contrived "fitting" of the natural model description into the form provided by the simulation programming language, serving only to recreate the original impedance problem once removed. To illustrate this point, consider the classical machine interfence model (see Chapter 6) in which a technician monitors and repairs a set of machines that fail intermittently.

- A SIMULA implementation of this model may contain a description of the *lifetime* of a machine class object and a technician class object – a machine operates for some time, fails, waits for repair, and then repeats the cycle; a technician detects a machine failure, travels to the machine and repairs it.

- A GPSS implementation of this model is very different: defining the technician as a static facility and defining machine failures as transactions which queue for the technician facility.
- A SIMSCRIPT implementation of this same model might adopt an entirely different view by describing the model behavior that corresponds to identifiable *events* in the model, such as a machine failure or an end of repair.

This example raises the question: which implementation provides the most "natural" description of the machine interference model? Obviously no *definitive* answer to this question exists; different people often view the same thing in different ways. Clearly though, a representation (such as GPSS) that characterizes machine failures as "moving" objects does not conform with the physical reality. Consequently, the *programming* of a correct model and its verification and validation are subject to difficulties. The "conceptual bridge" supposedly provided by the SPL becomes a "conceptual chasm." An important result from [65] is the identification of the need to *select* a conceptual framework suitable for a particular model and a given set of objectives.

3.2 An Environment for Simulation Model Development

One effort to put the modeling methodological perspective of discrete event simulation into practice is the Simulation Model Development Environment (SMDE). The SMDE is an ongoing research effort at Virginia Tech that dates to 1983. Over forty publications have appeared and some ten Master's and Doctoral theses have been produced within the SMDE research effort. For an historical overview of the SMDE project and a complete bibliography, see [21].

The SMDE is the realization of the life-cycle model illustrated in Figure 3.2, as supported by the Conical Methodology (see Chapter 5). The SMDE seeks to provide an integrated set of software utilities that offer automated support in the development, analysis, translation, verification, archival storage/retrieval, and management of discrete event simulation models, and thereby achieve the automation-based paradigm for simulation modeling through the evolutionary development of prototypes.

Figure 3.3 depicts the architecture of the SMDE in four layers: (0) Hardware and Operating Systems, (1) Kernel SMDE, (2) Minimal SMDE, and (3) SMDEs.

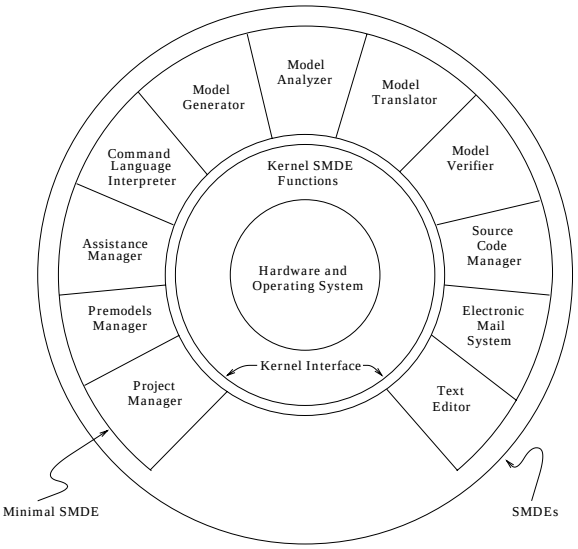


Figure 3.3: The SMDE Architecture.

Layer 0 is comprised of the prototype hardware, currently a SUN workstation (efforts are ongoing to complete a production SMDE, named the Visual Simulation Environment (VSE), using a NeXT platform). The kernel, Layer 1, integrates all SMDE tools into the software environment. Layer 2 provides a *comprehensive set* of tools which are *minimal* for the development and execution of a model. Comprehensive implies that the toolset is supportive of all model development phases; minimal implies that the toolset is basic and general. Layer 3 includes tools that support specific applications and are needed either within a particular project or by an individual modeler [15]. Descriptions of the the minimal SMDE toolset as well as references to efforts on tool development are given in Appendix B.

3.3 A Next-Generation Framework for Model Development

In this section, a framework for model development is described. The framework is designed to facilitate the cost-effective integration of emerging technologies with the constraining objective of decision support. Model representation provides the key to the suggested framework. A brief discussion of the general theories of model representation is warranted.

3.3.1 Theories of model representation

Model representation (or model specification) is the process of describing system behavior and in-so-doing converting the model that exists in the mind(s) of the system designer(s) – conceptual model(s) – into a model that can be communicated to others – communicative model. The primary role assigned specification in the development of software is to enunciate *what* the system is to do as separate from *how* it is to be done [23].

This representation is most often accomplished via a *specification language*. A specification language offers perceptual guidance through the provision of concepts enabling the behavior of a system to be described; but, of equal importance is the fact that a specification language is the medium of communication for expressing this behavior [181, p. 10]. The nature of this medium is the subject of some debate, which is briefly highlighted here.

3.3.1.1 Wide-spectrum versus narrow-spectrum languages

One way to classify specification languages is by the number of phases of a life-cycle model the language addresses, or claims to support. A single language that supports the software process throughout many phases of a life-cycle model is called a *wide-spectrum language.* Whereas, a language that supports only one or two phases of a life-cycle model is known as a *narrow-spectrum language* [167]. Within the software community both approaches have been used with some degree of success and no preponderance of evidence suggests that one approach is superior to the other. The degree to which a language (or languages) "succeeds" – for any given definition of success, e.g. ease of use, expressibility of concepts, etc. – hinges primarily upon how it is applied. A good wide-spectrum language will always produce specifications that are consistent and integrable. But some phases of the life cycle may not be as strongly supported as others, and the language may fail to contain a concise syntax and semantics in its attempts to provide a multiplicity of representations. When using a narrow-spectrum approach, the languages need to work in concert to achieve their goal. Although each language may have vastly different semantics, ideally these differences should reflect *only* the different aspects of a *single* underlying methodology. This aids in the generation of conceptual integrity [39] in the end product – although perhaps *conceptual congruity* is a more suitable term; the idea is to produce representations within a derivation sequence that are congruent to their adjacent representations.

3.3.1.2 Formal approaches

Historically, most specification languages have been formal in nature. Formalism in specification allows the application of mathematical rigor to the analysis of specifications which supports verification and validation in a manner not possible with informal, natural-language specifications. Efforts such as AXES [95], Special [216], PSL/PSA [226, 242], TAXIS [36, 175], PDL [42, 109], GYPSY [7], and RDL [100] are formal narrow-spectrum languages which have been used to specify software at various points in the life-cycle.

Some recent efforts in wide-spectrum languages, PAISLey [247, 248, 249], JSD [43, 111], and Entity-Life Modeling [202] have also been applied to varying degrees of accomplishment.

Wing [241] outlines the use of formal methods in software specification, and a review of a variety of both formal and informal specification languages is provided by way of a comparison matrix in [223]. For a general discussion of formal versus informal methods, and the philosophy of their application, refer to [82, 147].

3.3.1.3 Graphical approaches

Although mathematical formalism is a very powerful tool, the non-technical community (representing software clients and sponsors) has historically been reluctant to accept these types of formal specifications – primarily due to their mathematical nature. Clients who do not fully understand the specification of a proposed system cannot be expected to detect specification errors. This often results in the delivery of a flawed product, and subsequent client dissatisfaction.

Software producers, needing to improve the level of communication between themselves and the marketplace, have responded with the development of less mathematical, graphically-based system specifications. In a paper titled, "Formal Specification Languages: A Marketplace Failure; A Position Paper," Bracket claims that many researchers share the opinion that graphically-oriented specification languages are the best approach to enhancing communication among a wide variety of specification audiences [38]. Indeed much of today's software specification research moves in this direction [40, 83, 136, 199, 243]. Of note is STATEMATE, defined by Harel [97, 98]. STATEMATE provides operational specifications combined with a graphical user interface. Execution of the model provides the user with a clear view of the system which may eliminate many of the communication problems

associated with mathematically formal specifications [97]. Other endeavors in the area of visual languages include: PECAN [198], HI_VISUAL [108], and GARDEN [199] a graphical programming environment developed at Brown University, and Cadre's TEAMWORK.

Despite the implications of Bracket's title, these graph-based, and visual specification languages are, in fact, *formal* in nature: they provide a precise syntax and semantics to facilitate model analysis. However, the claimed advantage of these approaches is that the formalisms are couched in a manner that enhances specification understanding in non-technically oriented personnel much more so than purely mathematical formalisms.

3.3.2 Requirements for a next-generation modeling framework

In a 1977 report to the National Bureau of Standards, Nance [153] surveys the existing modeling methodologies and specification languages and finds that none provide model documentation to a sufficiently high level. The report identifies the characteristics of a simulation model specification and documentation language (SMSDL):[2]

N1. The semantics of a SMSDL must facilitate model specification and model documentation.

N2. A SMSDL must permit the model description to range from a very high to a very low level.

N3. The degree of detail – the level of description – should be controllable within the SMSDL.

N4. A SMSDL must exhibit broad applicability to diverse problem areas.

N5. A SMSDL should be independent of, but not incompatible with, extant simulation programming languages.

N6. A SMSDL should facilitate the validation and verification of simulation models.

In a panel session held at the 1992 *Winter Simulation Conference,* entitled "Discrete Event Simulation Modeling: Directions for the '90s," Sargent outlines the requirements for a modeling paradigm [205]:

S1. General purpose – to allow a wide variety of problem types and domains.

S2. Theoretical foundation – to move the modeling process towards science.

[2]These criteria are also presented in [154].

S3. Hierarchical capability – to facilitate the modeling of complex systems.

S4. Computer architecture independence – sequential, parallel and distributed implementations from same model.

S5. Structured – to guide user in model development.

S6. Model reuse – support a model database for component reuse.

S7. Separation of model and experimental frame – model should be separate from model input and model output.

S8. Visual modeling capabilities – to permit graphical model construction.

S9. Ease of modeling – world view(s) should ease the modeling task.

S10. Ease of communication – the conceptual model(s) should be easy to communicate to other parties.

S11. Ease of model validation – should support both conceptual and operational validity.

S12. Animation – model animation provided without burden to the modeler.

S13. Model development environment – to support modeling process.

S14. Efficient translation to executable form – model automatically converted to computer code, or if not automated, facilitate programmed model verification.

Combining these two sets of criteria produces the list of requirements for a next-generation modeling framework given in Table 3.1. The table lists ten requirements and their relationship to the criteria of Nance and Sargent.

3.3.3 An abstraction based on a hierarchy of representations

In this section, a "model of model development," or model development *abstraction,* is described. The SMDE architecture defines three tools which influence the description of the abstraction: the model generator, the model analyzer, and the model translator. These tools clearly demonstrate the separation of model and program as advocated by discrete event simulation modeling methodology. Without question, the model – particularly the model generator and the representational form it provides – has been the focus of the majority of past SMDE research efforts. However, the view of model development has traditionally been that of a *single* model specification which is *generated* and then *analyzed* and *translated* to *execute* on a given sequential architecture. This view is rather narrow, but is easily extended to describe an abstraction (supportive of a next-generation modeling

Table 3.1: Requirements for a Next-Generation Modeling Framework.

Requirement	*Satisfies*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	N1,S7,S10
Permits model description to range from very high to very low level.	N2,S10
Permits model fidelity to range from very high to very low level.	N3,S3
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	S8,S9
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	N3,S2,S5,S8
Exhibits broad applicability.	N4,S1
Model representation is independent of implementing language and architecture.	N5,S4,S14
Encourages automation and defines environment support.	S2,S13,S14
Support provided for broad array of model verification and validation techniques.	N6,S11,S12
Facilitates component management and experiment design.	S2,S3,S6,S7

framework) which permits the integration of emerging technologies, while sustaining the primary objective of decision support.

Model development may be viewed as taking the form of a transformational hierarchy such as in Figure 3.4. The figure describes three "levels" of model representation:

1. *Modeler-generated specifications.* These representational forms permit a modeler to describe system definitions, assumptions and the set of objectives for a given study, as well as the model behavior in a manner suitable to meet the objectives. While a canonical form is implied by the figure, the nature of this form has not been defined.

2. *Transformed Specifications.* Adhering to the principle of successive refinement, automated and semi-automated transformations are defined to various forms that enable analysis and translation to implementations meeting a specified criteria.

3. *Implementations.* The lowest level of the transformed specifications are the implementations. These executable representations satisfy the particular system level constraints of a given simulation study.

The hierarchy may be envisaged as being composed of either a set of cooperative and congruent narrow-spectrum languages, or a single wide-spectrum language. Subsequent chapters present a realization of this abstraction using the Conical Methodology and the Condition Specification (reviewed in Chapter 5).

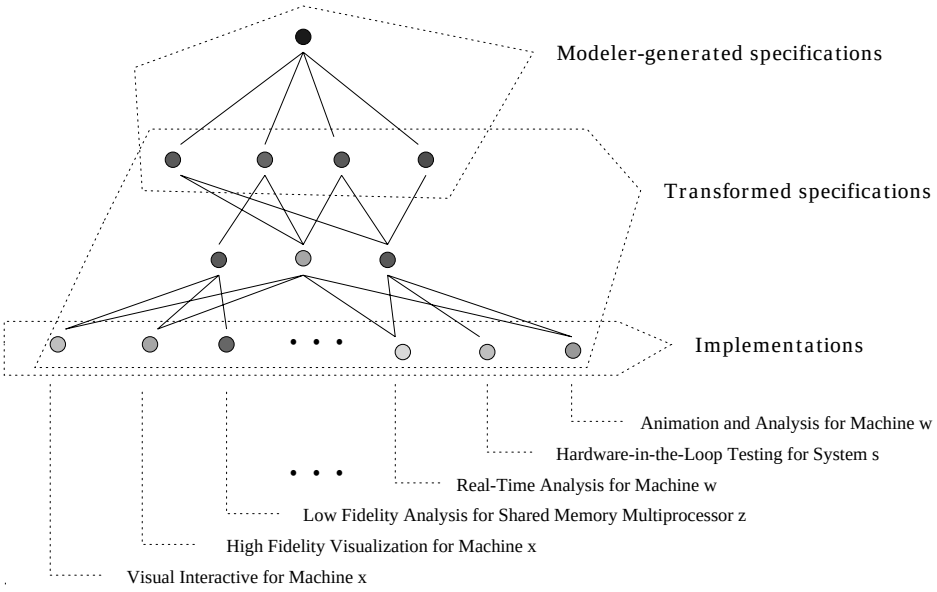


Figure 3.4: A Transformational Hierarchy for Simulation Model Development.

In the next chapter, the other existing (formal) approaches to discrete event simulation model development are surveyed. The criteria presented in Table 3.1 provide the evaluative basis.

3.4 Summary

In this chapter, a philosophy of model development is described. The philosophy outlines the precepts and tenets of discrete event simulation modeling methodology, and is grounded in the recognition that the overriding objective of simulation in *any* context is the production of a correct decision. Factors that influence decision support are identified and a management structure based on the concepts of life cycle, paradigm and methodology is described.

The SMDE research effort, which represents a realization of the philosophy described here, is discussed and its framework for model development extended to permit the integration of emerging technologies in a coherent fashion. Criteria for a next-generation modeling

framework are identified based on the combined observations of Nance and Sargent. These criteria serve as the evaluative basis for the approach described in this thesis.

Chapter 4

FORMAL APPROACHES TO DISCRETE EVENT SIMULATION

It is very easy to be blinded to the essential uselessness of them by the sense of achievement you get from getting them to work at all.

Douglas Adams, *So Long and Thanks for All the Fish*

In this chapter, the existing approaches to discrete event simulation model development are surveyed and evaluated in terms of the requirements for a next-generation modeling framework given in Table 3.1.[1] The focus of the survey is restricted as follows: (1) only "formal" approaches are considered since one of the criteria is to encourage automation, and (2) programming-language-based approaches are not evaluated since the modeling methodological view and the philosophy described in Chapter 3 call for programming-language-independent representations.[2]

4.1 Preface

When confronted with the task of analyzing a complex system, one method of recourse is to build a *model* of that system. In this chapter we address a specific form of model: the discrete event simulation model. The objective is to survey existing approaches and assess the level of support provided for: (1) conceptualizing, (2) representing, (3) analyzing, and (4) implementing these types of models. To preface the survey, discrete event simulation

[1] The CM and CS are reviewed and evaluated in Chapter 5.

[2] For a comprehensive historical survey of simulation programming languages, see Nance [159].

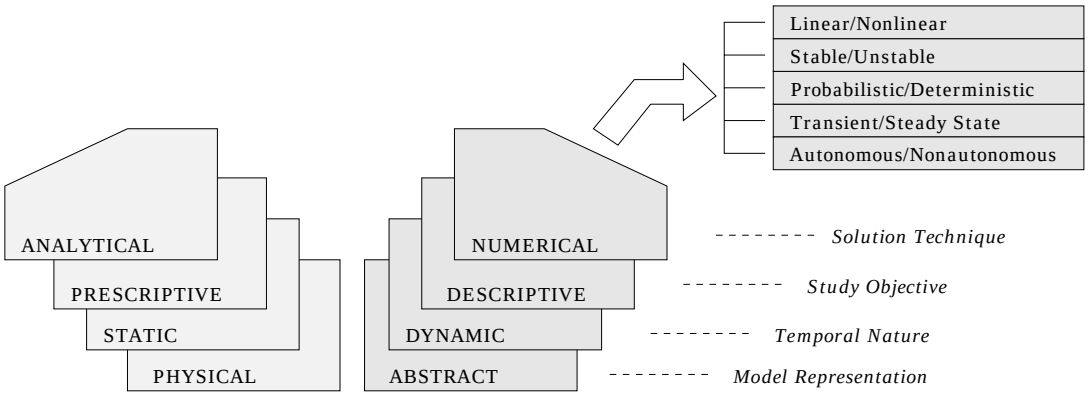


Figure 4.1: A Classification Scheme for Discrete Event Simulation (DES) Models. All DES models fall within the class of *abstract, dynamic, descriptive, numerical* models.

models are placed within a broader taxonomy.

4.1.1 A model classification scheme

The art of modeling is arguably as old as mankind itself. And the uses for models, as well as the forms that models may take, vary significantly. As a result, while the *concept* of model is generally well-understood, a precise description of characteristic properties is difficult to formulate.

The classification scheme for models adopted here is derived from [18]. Figure 4.1 illustrates the scope of discrete event simulation models within this scheme. The classification scheme provides an orthoganality in four dimensions. The first dimension characterizes the model representation. An *abstract* model is one in which symbols constitute the model. A verbal or written description in English is an abstract model. A mathematical model is described in the symbology of mathematics and is a form of abstract model. A simulation model is built in terms of logic and mathematical equations and is considered an abstract model. A *physical* model is a replica, often on a reduced scale, of the system it represents. A physical model "looks like" the system it represents and is also called an *iconic* model.

The second dimension characterizes the study objective underlying the model. A *descriptive* model describes the behavior of a system without any value judgement on the quality of such behavior. A *prescriptive (normative)* model describes the behavior of a

system in terms of the quality of such behavior. When solved, these models provide a description of the solution as optimal, suboptimal, feasible, infeasible, and so on. Linear programming models are prescriptive, for instance.

A third dimension relates to the presence of temporal properties in the model. A *static* model is one which describes relationships that do not change with respect to time. Static models may be abstract or physical. An architectural model of a house is a static physical model. An equation relating the area and volume of a polygon is a static mathematical model. A *dynamic* model is one which describes time-varying relationships. A wind tunnel which shows the aerodynamic characteristics of proposed aircraft design is a dynamic physical model. The equations of motion of the planets around the sun constitute a dynamic mathematical model.

The fourth dimension identifies a solution technique. An *analytical* model is one which provides closed-form solutions using formal reasoning techniques, e.g. mathematical deduction. A *numerical* model is one which may be solved by applying computational procedures.

> Discrete event simulation models are considered in the class of abstract, dynamic, descriptive, numerical models.

As illustrated in Figure 4.1, within this general classification of discrete event simulation models a subordinate classification scheme exists. Discrete event simulation models may be defined with various combinations of the following characteristics: (1) a *linear* model is one which describes relationships in linear from, and a *nonlinear* model describes nonlinear relationships; (2) a *stable* model is one which tends to return to its initial condition after being disturbed, while an *unstable* model is one which may not return to its initial condition after being disturbed; (3) a *steady-state* model is one whose behavior in one time period is of the same nature as any other time period, while a *transient* model is one whose behavior changes with respect to time; (4) a *probabilistic (stochastic)* model is a model in which at least one state change is a function of one or more random variables, otherwise, the model is *deterministic,* and (5) an *autonomous* model is one in which no input is required (or permitted) from the environment, other than at model initiation, while a model that permits input to be received from its environment at times other than model initiation is a *nonautonomous* model.

4.1.2 Formalism and discrete event models

Approaches surveyed in this chapter are considered solely with regard to the construction and use of models for the *explicit* purpose of discrete event simulation.[3] These models are referred to as discrete event simulation models, or discrete event models. The systems underlying these models may be referred to (somewhat misleadingly) as discrete event systems.

Discrete event models may provide a variety of means by which to understand, and reason about, the underlying system. These provisions may range from the highly intuitive to the completely mathematical. While intuitive assistance can be valuable, the ever-increasing investment in discrete event simulation as a problem-solving technique (described in Chapter 1) demands methods through which properties of the simulation may be *formally* established. According to [212, p. 641]:

> A formalism provides a set of conventions for specifying a class of objects in a precise, unambiguous, and paradigm-free manner. The structure of a formalism further provides a basis for measuring the complexity of objects in that class.

Each of the surveyed approaches are formal in nature.

4.2 Lackner's Formalism

Simulation, as a computer-based problem-solving technique, is essentially as old as the computer itself. And like many other computer-related techniques, its use and application preceded the development of a cogent theory. The technique of computer simulation was driven in the earliest years by simulation program language (SPL) developments (see [159]). But during the early 1960s, Michael Lackner became among the first to recognize, and state unequivocally, the need for the development of a general theory of systems and models separate from the development of SPLs. Lackner [125, pp. 25,27] observes:

> What has happened in the development of simulation languages is this: the orderly scheme of relationships has been expressed in computer code, the programs that are a part of every model. A modeler using the language understands that this scheme is supplied; he does not alter the scheme in using the language;

[3] We examine some popular analytic techniques but only in the context of their use in simulation model development.

> he describes system elements in accordance with the category system, which is also invariant. The simulation language is a part of a simulation scheme that is based on a theory of systems, but the theory has been neither elucidated nor developed. ...Only by appeal to this [general] theory [of systems] may a modeler say "this is a model of object system x" and "this is how the model behaves." Only by such appeal may he explain *why*[4] it is a model, and *why* the model so behaves. ...Furthermore, development of system theory should make possible deductions of interesting measures and properties of simulation models that are not dependent on empirical observation of the models' *[sic.]* behavior.

Lackner presents a theory of discrete event systems in which change, not time, is primitive; the theory, and the "Calculus of Change" require that time is defined in terms of change. The following description is adapted from [124, 125].

4.2.1 Defining the theory

4.2.1.1 The problem

Lackner observes that the fundamental dilemma faced in simulation modeling is the necessity of characterizing the dynamic in static terms. Whatever methods are used, limitations are naturally encountered [125, p. 10]. The logical complexity of the model can be increased by introducing conditional procedures, but two essential features of many systems are still lacking in the program structure: (1) the asynchronous operation of related components, and (2) the effects of varying duration of independent processes. These system characteristics are among the most difficult to reduce to mathematical expression [125, p. 13].

4.2.1.2 System and state

According to Lackner, in a digital simulation a computer simulates an *object system* (the system in the real world, or nature space, that is the subject of study) by performing an algorithm to produce a sequence of states, internal to the computer, that may be interpreted as describing the behavior of the object system.

A system state description can be considered to be an n-dimensional vector, where n is equal to the number of variables contained in the system description. The variables

[4] Underlined in the original.

may have arithmetic or logical values, and each member of a time series of system state descriptions may not only contain different values of system variables but be formed of a different set of variables; the particular variables appropriate to describing the state of the system may differ from time to time. Thus, two kinds of changes to a state description may be distinguished: (1) changes in the values of variables, and (2) changes in existence of variables.

4.2.1.3 Weltansicht

Lackner [125, p. 26] gives the first characterization of conceptual frameworks. He makes the observation that the final expression of a digital simulation model is computer code – algorithms and data – but such a categorization of system elements does not produce a useful model. A more restrictive set of categories is necessary to the establishment of a general approach to modeling systems. He points out that GPSS requires that a model be defined in terms of "transactions" which seize "stores" or "facilities" and form "queues." SIMSCRIPT requires a breakdown in terms of "entities, "attributes," "sets," and "events."

Lackner asserts that such a restrictive set of categories is identified with a special view or apprehension of reality as a whole, a *Weltansicht,* which a modeler adopts when contemplating an object system. "A modeler looks at the system in a certain way; certain kinds of things are contemplated, and an orderly scheme of relationships among these kinds of things is assumed."

4.2.2 The Change Calculus

According to Lackner, the notion of change is implicit in the idea of system simulation: the object system is understood to exhibit behavior. The behavior may be entirely due to the actions of an individual agent in the system, or it may be a function of the actions of several agents, and these agents may act sequentially or simultaneously. In the latter case, Lackner notes that the method of modeling must take cognizance of parallel processes and simultaneous changes [125, p. 5].

Lackner [125, p. 28] claims that the formal relations used in traditional mathematical analysis and formal logic are most appropriate to the description of static, unchanging situations. Change has no real place in these methods. Rules governing change are not

expressed, but implied by equations expressing static relationships among those entities that are affected by change. The theory on which the Change Calculus is based stipulates that *all activity is the realization of change.* In Lackner's view, entities are related to each other by their communal "preclusion" or "evocation" of change, that is, one entity often causes or prevents a change in another entity.

The change relation. Change is formalized as a relation, denoted by a colon (:), as a class of antecedent-consequent pairs of logical situations. Logical situations are described in the form of conjunctions of individual, state-descriptive sentences. Individual change relations are written, for example, $\alpha : \beta$ and read "whenever α, then β instead," where α and β are conjunctions (or *state descriptive variables*).

A *complete state description* consists of the conjunction of a number of system descriptive sentences. It is referred to as *the system* in the formalization, and the conjoined sentences are referred to as the *laws of the system.*

The operation of change brings about a *consequent system* which is again described by a conjunction of sentences referred to as the *laws of the consequent system.*[5]

Primitive terms. Five primitive terms are defined: (1) K, a dyadic functor, (2) W, a dyadic change functor, (3) N, a monadic functor, (4) $\wedge$, the null sequence, and (5) $a, b, c, \ldots$, sequential variables.

Rule of definition. A new term can be introduced into the system by formulating a group of terms, called the *definition* and consisting of: (1) an expression that contains the new term and in which all the others are terms of the system; (2) the equality symbol, $=$; (3) an expression that contains only primitive terms or terms already defined.

Rules of formation.

1. A variable is a consequent.
2. $\wedge$ is a consequent.
3. A group of terms consisting of K followed by two consequents is a consequent.

[5]The system evolves as an evolution of consequent systems. Lackner does not formally discuss the mechanism(s) by which this process may be terminated.

4. A consequent is an antecedent.
5. A group of terms consisting of N followed by a variable is an antecedent.
6. A group of terms consisting of K followed by two antecedents is an antecedent.
7. A group of terms consisting of W followed by an antecedent followed by a consequent is a change relation.
8. A group of terms consisting of N followed by a change relation is an antecedent.
9. A change relation is a consequent.
10. A consequent is a sentence.

Definitions.

$$\begin{aligned} WApqr &= KKWKpqrWKNpqrWKpNqr \\ WCpqr &= KKWKNpqrWKpqrWKNpNqr \\ WEpqr &= KWCpqrWCqpr \\ WDpqr &= KKWKpNqrWKNpqrWKNpNqr \end{aligned}$$

Rules of deduction. Five rules of deduction are described.

Rules of substitution. (1) A variable or a change relation may be substituted for a variable, but the same variable or change relation must be substituted for all equiform occurrences of variables in the expression; (2) a sentence or antecedent consisting of a number of K's followed by the same number plus one of sentences or antecedents, in any order, may be substituted for a sentence or antecedent consisting of the same number of K's followed by the same number plus one of sentences or antecedents each of which is equiform with a sentence or antecedent in the expression substituted; (3) a sentence or antecedent may be substituted for a sentence or antecedent consisting of K followed by two occurrences of a sentence or antecedent equiform with the sentence or antecedent substituted.

Rule of substitution by definition. A definition may be substituted for the expression it defines in a sentence, and reciprocally, without being substituted for all equiform occurrences of that expression.

Rule of detachment. If a sentence consisting of K followed by two sentences is a law of the system, a sentence equiform with either the first or second can be posited as a law of the system.

Rule of conjunction. If two sentences are laws of the system, a sentence consisting of K followed by two sentences equiform with the first two sentences may be posited as a law of the system.

Rules of detachment of the consequent system. (1) A change relation is effective if it is a law of the system and if its antecedent, or every antecedent that is conjoined in its antecedent and is not itself a conjunction, is either equiform with a sentence that is a law of the system or consists of N followed by an antecedent that is not equiform with a law of the system; (2) a sentence equiform with the consequent of an effective change relation must be posited as a law of the consequent system; (3) a sentence that consists of a variable or a change relation and that is not and cannot, under the rules of substitution, be made equiform with an antecedent conjoined in the antecedent of an effective change relation must be posited as a law of the consequent system.

Axiom. (1) $\wedge$

4.2.3 Examples

The example of a deduced sequence provided in [125] is reproduced here in Figure 4.2. A less cryptic example of the Change Calculus from [124] is given in Figure 4.3. This example describes a simple producer-consumer simulation using the following notation: (1) Ti/j means "thing i is in state j;" (2) Ni, j means "duration time normally distributed with mean i time units and standard deviation j time units;" (3) Pi means "duration time is Poisson distributed with mean i time units;" (4) Ai, j means "the inclusive disjunction, either i or j." The syntax is:

(antecedent logical situation):(consequent logical situation) (required duration of antecedent)

For this example, Lackner stipulates: (1) given the occurrence, and specified endurance, of an antecedent logical situation (ALS), the ALS yields to the consequent logical situation (CLS); (2) destruction of the ALS before the required endurance precludes the occurrence of the CLS; (3) if a duration time is not stated, duration time is assumed to be 0. All duration time distributions are truncated: $0 < t \leq \infty$. (4) Things and states mentioned on

$$
\begin{aligned}
\varphi^0 &= (\overline{x} : x)(\overline{y}x : y)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x)) \\
\varphi^1 &= x(\overline{x} : x)(\overline{y}x : y)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x)) \\
\varphi^2 &= y(\overline{x} : x)(\overline{y}x : y)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x)) \\
\varphi^3 &= xy(\overline{x} : x)(\overline{y}x : y)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x)) \\
\varphi^4 &= xy(x : \wedge)(y\overline{x} : x)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x)) \\
\varphi^5 &= y(x : \wedge)(y\overline{x} : x)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x)) \\
\varphi^6 &= x(x : \wedge)(y\overline{x} : x)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x)) \\
\varphi^7 &= (x : \wedge)(y\overline{x} : x)(xy(\overline{x} : x)(\overline{y}x : y) : xy(x : \wedge)(y\overline{x} : x))
\end{aligned}
$$

Figure 4.2: A Deduced Sequence in the Change Calculus. A sequence of state descriptions $\varphi^1\varphi^2\ldots$ is produced from an original complete state description φ^0. Notation: $(p : q) = Wpq$; $pq = Kpq$; $\overline{p} = Np$; φ^i = complete state description i.

the ALS and not in the CLS are destroyed; (5) Things and states mentioned in the CLS and not in the ALS are created.

4.2.4 Evaluation

An evaluation of the Change Calculus with respect to the identified requirements for a next-generation modeling framework appears in Table 4.1. The evaluation procedure defines four levels of support for a given requirement: (1) not recognized – no documentation can be found which indicates that the evaluated approach considers the requirement a desirable characteristic; (2) recognized, but not demonstrated – documentation suggests that the requirement is recognized as important, however no mechanism is described to support it; (3) demonstrated – at least one source can be found that indicates support for the requirement; (4) conclusively demonstrated – substantial evidence indicates that the requirement is supported.

Lackner's thesis – the need to define a theory of modeling separate from the purview of SPLs – initiates a line of modeling methodological research that has persisted for over thirty years. This fact, alone, makes his work a significant contribution to the history of

Thing	*Symbol*	*State*
Apple	$T1$	On tree (1); On ground (2); Rotten (3)
Boy	$T2$	Hungry (1); Sated (2); Leaves the scene (3)
Tree	$T3$	Producing apples (1); Not producing apples (2)

Statement	*Comments*
$T1/2T2/1 : T2/2$	Given an apple on the ground and a hungry boy, the apple disappears and the boy is sated.
$T2/2 : T2/1; N6, 1.5$	A sated boy becomes hungry in about 6 time units.
$T2/1 : T2/3; N40, 15$	A hungry boy leaves the scene in about 40 time units.
$T2/A1, 2 : T2/3; P1000$	A boy leaves the scene in about 1000 time units, whether he has been hungry or sated.
$T1/1 : T1/2; P20$	An apple on the tree falls to the ground about 20 time units from first appearance.
$T1/2 : T1/3; P3$	An apple rots if it is on the ground about 3 time units.
$T3/1 : T1/1T3/1; P5$	A tree producing apples does so at a rate of about 1 every 5 time units.
$T3/1 : T3/2; N18, 6$	After a tree has been producing apples for about 18 time units, it stops producing apples.
$T3/2 : T3/1; N18, 4$	When a tree hasn't been producing apples for about 18 time units, it starts producing apples.

Figure 4.3: A Producer-Consumer Model in the Change Calculus.

Table 4.1: Evaluation of the Change Calculus as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	2
Permits model description to range from very high to very low level.	2
Permits model fidelity to range from very high to very low level.	1
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	2
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	2
Exhibits broad applicability.	2
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	2
Support provided for a broad array of model verification and validation techniques.	2
Facilitates component management and experiment design.	1

discrete event simulation, and warrants its treatment here. His calculus, however, is incomplete, cryptic, and difficult to use. The number of antecedent-consequent pairs will likely become quite large for complex models, and no provisions for managing these statements are made. Essentially, the method is reducible to a finite state automaton, a form which may be generally more appealing, and has been adopted – in one form or another – by several modeling approaches. Possibly as a result of this, the Change Calculus has seen no development since the initial publishing during the early and middle 1960s.

4.3 Systems Theoretic Approaches

Several approaches and methodologies (including Lackner's calculus) for discrete event modeling trace their origins to *general systems theory.* General systems theory postulates that real systems obey the same laws and show similar patterns of behavior even if they are physically dissimilar [201].

The most developed appeal to general systems theory in the context of discrete event

simulation modeling is by Zeigler [250] in his creation of the discrete event system specification (DEVS) formalism (discussed below), and his work continues to be by far the most prominent in this arena [250, 251, 252]. Zeigler uses the theory to establish a *hierarchy* of system specifications. These are identified as: (1) system specification input-output relation observation (IORO), (2) system specification input-output function observation (IOFO), (3) system specification, (4) structured system specification, and (5) system specification network. Zeigler demonstrates that specifications in his formalism may be automatically transformed to reflect each level of the hierarchy through a collection of equivalence preserving *morphisms.* Zeigler purports, however, that the hierarchy is independent of any particular modeling formalism; *any* formalism may be employed to specify a system at *any* level. Among the system formalisms Zeigler describes are differential equation system specifications (DESS), discrete time system specifications (DTSS), and discrete event system specifications (DEVS).

4.3.1 The DEVS formalism

Zeigler [250] defines a methodology for discrete event modeling known as the discrete event system specification (DEVS) formalism (see also [253]).

4.3.1.1 Background

DEVS – with its primary influences in general systems theory, and to a lesser extent, mathematical systems theory, and automata theory – identifies three major conceptual elements of a discrete event simulation: (1) the *system,* (2) the *model,* and (3) the *computer.*[6] Two relationships are also described: (1) *modeling,* which deals primarily with the relationship between systems and models, and (2) *simulation,* which refers primarily to the relationships between models and computers.

Zeigler [250, p. 4] defines a system as, "some part of the real world, which is of interest. The system may be natural or artificial, in existence presently or planned for the future." The system is a source, or potential source, of *behavioral data* consisting of XT plots, where

[6]Zeigler expands the model element to include three parts: (1) the *experimental frame,* which provides the basis for model validation, (2) the *base model,* a valid model in all allowable experimental frames (not actually producible), and (3) the *lumped model,* a simpler model generated by "lumping" together and further abstracting the base model.

X is some variable of interest, and T is time. A model is viewed as a set of instructions for generating behavioral data, and a computer as a device (man or machine) capable of producing the data from the instructions given by the model. General systems theory provides five categories for models (in no particular order):

- Models may be classified according to their *time base.* In a *continuous time* model, time is specified to flow continuously – the model clock advances smoothly through the real numbers toward ever-increasing values. In a *discrete time* model, time flows in jumps. The model clock advances periodically, jumping from one integer to the next (the integers represent multiples of some specified time unit).

- A second category relates to the range sets for model descriptive variables. In a *discrete state* model, variables assume a discrete set of values. A *discrete event* model is a continuous time/discrete state model.[7] In a *continuous state* model, variable ranges can be represented by the real numbers (or intervals thereof). A *differential equation* model is a continuous time/continuous state model.

- The third category is based on the cause-effect relationships in the model. A *stochastic (probabilistic)* model contains at least one random variable. In a *deterministic* model, no random variables appear.

- Another category relates the model to its environment. If the environment has no effect on the model, the model is *autonomous.* A *nonautonomous* model has input variables whose values are not controlled by the model, but to which it must respond.

- A fifth category relates to whether the rules of interaction for a model depend on time. A model is *time invariant* if the rules of interaction are independent of time. Otherwise, the model is *time varying.*

The two relations are elaborated as follows:

- The modeling relation deals with the validity of the model. Models may be classified as:

  1. Replicatively valid – if the model matches data already acquired from the system.
  2. Predictively valid – if the model matches data prior to its being generated by the real system.
  3. Structurally valid – if the model not only reproduces the observed system behavior, but truly reflects the way in which the real system operates to produce this behavior.

- The simulation relation concerns the faithfulness with which the computer carries out the instructions intended by the model. The level of this faithfulness is a measure of the *correctness* of the program.

[7] Even though time flows continuously, state changes can occur only in discontinuous jumps. A jump can be thought of as triggered by an *event.* Since time is continuous, these events can occur arbitrarily separated from each other. However, no more than a finite number of events can occur in a finite interval [250, p. 22].

Zeigler observes that one of the most important aspects of modeling, and one of the least appreciated, is communication [250, p. 7]. And while an informal model description may communicate the essential nature of a model, it is open to certain intrinsic problems, e.g. incompleteness, inconsistency, and ambiguity. DEVS is an appeal to formalism in an attempt to resolve these problems.

4.3.1.2 Model definitions

The model definitions below are predicated, in part, on the following presumptions regarding discrete event systems [250, p. 125]:

1. A discrete event system may be simulated using a simulator that is driven by a list of events containing the next clock times at which components are scheduled to undergo an (internally determined) state change. This time is the *hatching time* of the event.
2. The hatching times of some events are *predictable* on the basis of the results of the occurrence (i.e. hatching) of other events. When a hatching time is predicted, it is placed on the events list.
3. If the next hatching time of a component *cannot* be predicted in advance, it will not undergo a state change *until* and *unless* such a change is caused by a state transition of a component that *has* been prescheduled.

Atomic Model. An *atomic model, M*, is given by:

$$M = \langle X, S, Y, \delta_{int}, \delta_{ext}, \lambda, t_a \rangle$$

where

X	Input events set.
S	Sequential states set.
Y	Output events set.
$\delta_{int} : S \to S$	Internal transition function.
$\delta_{ext} : Q \times X \to S$	External transition function.
	$Q = \{(s, e) \mid s \in S, 0 \leq e < t_a(s)\}$ (the *total state of* M)
$\lambda : S \to Y$	Output function.
$t_a : S \to \mathcal{R}^{nonneg}$	Time advance function.

Essentially, an atomic DEVS model is described by a set of states (S), inputs (X), outputs (Y), and four functions that govern the behavior of the model. An atomic model is a *modular*

unit, its I/O interfaces form *ports* through which all environment interaction occurs. The interior of the model is composed of *state variables,* and the dynamic behavior of the model is described by two classes of events:

- *Input events.* These lead to external event transitions, i.e. on the occurrence of an input event, the model appeals to its *external transition function* for the next state.
- *Time scheduled internal events.* For each state the *time advance function* defines the time interval to the next internal event. When this time has elapsed, an internal event occurs, the system produces an output event and transitions to the next state as determined by the *internal transition function.*

Coupled Model. In the DEVS approach, an *atomic model* is constructed, and by connecting together atomic models, *coupled models* may be created for complex systems. A *coupled model, DN*, is given by:

$$DN = \langle D, \{M_i\}, \{I_i\}, \{Z_{i,j}\}, SELECT \rangle$$

where

D	Component names set.
For each i in D	(1) M_i = atomic DEVS for component i in D;
	(2) I_i = set of *influencees* of i.
For each j in I_i	$Z_{i,j} : Y_i \rightarrow X_j$; i-to-j output translation function.
$SELECT$	$E \subseteq D \rightarrow D \ni \forall E \neq \emptyset, SELECT(E) \in E$;
	tie-breaking selector.

The specification of complex models by connecting the I/O ports of atomic models is referred to as *modular coupling.* Coupled models also have their own I/O ports and may be used in even larger coupled models, this is referred to as *hierarchical modeling* [191].[8] From their I/O interface, coupled models are not distinguishable from atomic components.

Praehofer and Pree [191, p. 597] observe that conventional discrete event modeling approaches and simulation languages emphasize the concept of event, or activity, or process, while the DEVS approach emphasizes *state.* Dynamic behavior is organized around the *phase* variable – which denotes global system state. Depending on the current phase of the system, it will react differently to external inputs and the occurrence of internal events. In DEVS modeling, the phase actually defines a partition of the state space of the model.

[8] See Section 4.10.1 for a more detailed characterization of hierarchical modeling.

4.3.1.3 DEVS-based approaches

The basic tenet of general systems theory – that all systems can be described in common terms – leads naturally to the application of the DEVS approach to areas outside discrete event simulation. A substantial proportion of ongoing DEVS-related research addresses modeling issues in areas such as artificial intelligence, continuous and combined simulation; very little of what could be described as *pure* discrete event simulation research is evident.

Zeigler et al. [254] describe DEVS-Scheme. Built on PC-Scheme, a Lisp dialect and object-oriented programming subsystem for microcomputers, DEVS-Scheme exists in four layers:

1. The Lisp-based object-oriented foundation that provides processing capabilities and environment support.
2. A systems model specification layer that provides systems theoretic basis and model specification language.
3. A systems entity structure/model base layer that provides axiomatic specification and model synthesis (see Section 4.3.2).
4. A systems design layer called the frames and rules associated system (FRASES), that embeds the system entity structure in a frame-based knowledge representation scheme.

According to Kim [118, p. 401], the DEVS-Scheme approach supports building models in a hierarchical, modular manner: "a systems oriented approach not possible in conventional languages." Sevinc [213] describes DEVS-CLOS, a close relative of DEVS-Scheme, but based on the Common Lisp Object System. Another object-oriented approach is DEVSIM ++, an object-oriented simulation environment built on C ++ [119].

Praehofer and Pree [191] extend the DEVS formalism to facilitate combined, discrete event and continuous multiformalism modeling (also referred to as *multimodeling*) in an approach called DEVandDESS.

Thomas [227] describes the Hierarchical Object Nets (HON) approach. HON is purported as an open visual object-oriented modeling and simulation system. Based on DEVS and implemented in C ++, HON is designed to support *only* discrete event simulation. Thomas observes [227, p. 651]:

> The [DEVS] formalism provides a basis for extending the view on models, allows handling them as knowledge used to answer a multiplicity of questions rather than as "just simulation models." However, when applied only to simulation

> problems the flexibility becomes a problem. This affects the ease-of-use of a DEVS-based simulation system and its simulation efficiency. We propose HON as a modification of DEVS in order to extend the formalism's practicability to make this powerful means available to practice.

This recognition is also made by Zeigler et al. [254, p. 85] as a basis for DEVS-Scheme: "As a set theoretic concept, the DEVS formalism by itself is not a practical means of specifying models."

4.3.2 System entity structure

According to Cellier et al. [45, p. 60], the *system entity structure* (SES) is a mechanism to describe hierarchically structured sets of objects and their interrelations. The SES is a labeled tree with attached variables types, i.e. a graphical object that describes the decompositions of systems into parts. A knowledge representation scheme, SES formalizes the modeling of systems in terms of decomposition, taxonomic and coupling relationships. SES provides a formal description of *how* physical objects are decomposed into parts.

Rozenblit and Zeigler [201] describe a methodology based on SES called the knowledge-based simulation design (KBSD) methodology. KBSD focuses on the use of modeling and simulation techniques to build and evaluate models of systems being designed. KBSD treats the design process as a series of activities that comprise specification of design levels in a hierarchical manner (decomposition), classification of system components into different variants (specialization), selection of components from specializations and decompositions, development of design models, experimentation and evaluation by simulation, and choice of design solutions. SES is used to capture the decomposition, taxonomy, and coupling relationships. By a process called *pruning,* the SES can be converted into a DEVS.

4.3.3 Evaluation

Evaluation of the systems theoretic approaches with regard to the identified requirements for a next-generation modeling framework appears in Table 4.2. The evaluation indicates that the theoretical basis provided by general systems theory is both sound and powerful. Zeigler's theory has been demonstrated applicable to a wide variety of problem domains, as well as for solution techniques other than strictly discrete event simulation. The formalisms (DEVS, SES) provide a well-defined manner through which to structure model development.

Table 4.2: Evaluation of Systems Theoretic Approaches as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	2
Permits model description to range from very high to very low level.	2
Permits model fidelity to range from very high to very low level.	2
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	1
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	3
Exhibits broad applicability.	4
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	3
Support provided for a broad array of model verification and validation techniques.	3
Facilitates component management and experiment design.	4

This framework *should* enhance the model verification and validation problem as well as contributing to the automatability of approach. Furthermore, Zeigler's identification of an experimental frame stresses the recognition of a *context* for any modeling effort.

While the methodology is sound, these approaches suffer from a lack of representational expressiveness. The existing literature regarding the DEVS-based approaches and the SES fails to demonstrate either an unobtrusive conceptual framework or the ability to describe system behavior at anything other than a low level. Still, such capabilities seemingly could be incorporated within an approach based on general systems theory.

4.4 Activity Cycle Diagrams

Tocher [229] introduces a notation for describing the logical "flow" of a simulation. These flow diagrams represent one of the earliest attempts to provide a graphical description of a simulation model, however they are essentially flowcharts and fail to exploit the narrowed focus provided by the context of discrete event simulation. Possibly, it was this

recognition that led to the development of a notation called "wheel charts" [230]. The wheel chart notation evolved further into a form known as *activity cycle diagrams* (or entity cycle diagrams) first described in [101]. These diagrams have become an integral part of much of the simulation work in the activity scan and three-phase arenas that has persisted, largely in the UK, since the late 1960s.

In the typical activity cycle diagram (ACD) based approach, a simulation model is viewed as a collection of interacting *entities*. An entity is any component of the model which can be imagined to retain its identity through time. Entities are either idle – in notional or real *queues,* or active – engaged with other entities in time consuming *activities*. An active state usually involves the cooperation of different entities. A passive state, or queueing state, involves no cooperation between different entities and is generally a state in which the entity waits for something to happen. The duration of an activity can always be determined in advance, whereas the duration of the queueing state cannot be so determined [188]. The symbology for ACDs is minimal, with one symbol each for a queue and an activity as shown below.

To specify a model using ACDs, a life cycle, or activity cycle, composed of queues and activities must be given for each class of entity in the model. A common restriction is that queues and activities must alternate in the representation. If necessary, dummy queues may be incorporated into the diagram. Typically each activity cycle must be closed.

4.4.1 Example

The quintessential ACD example is the English Pub. The model contains three entities: a man, a barmaid, and a glass.[9] The behavior of each entity is fairly simple. The man either drinks or waits to drink. The barmaid either pours a drink or is idle. The glass is either used to drink from, empty, poured into by the barmaid, or full waiting to be consumed. The ACD for the English Pub model is given in Figure 4.4.

[9]The English, to their credit, have no use for political correctness.

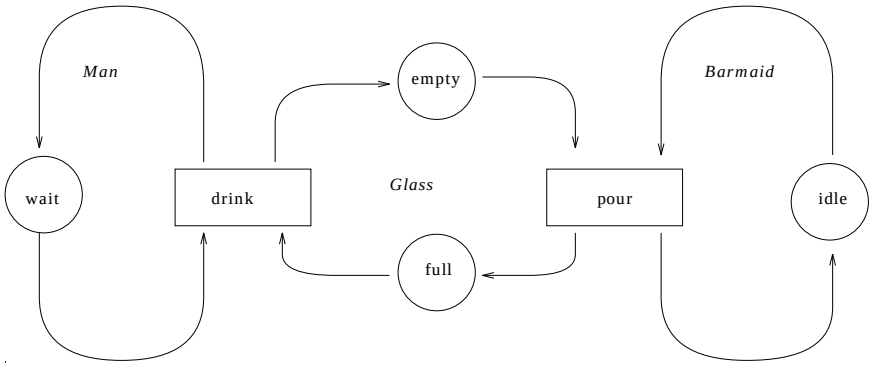


Figure 4.4: Activity Cycle Diagram for English Pub Model.

4.4.2 The simulation program generator approach

The main usage of ACDs is as a front-end for simulation *program generators*. A program generator is a program that *produces* another program in a high-level language from a simple input description [54]. The first program generator was the Programming by Questionnaire (PBQ) system developed at RAND [176, 177] which generated Job Shop simulations based on information provided by a modeler via machine-readable responses to a questionnaire.

A simulation program generator is an interactive software tool that translates the logic of a model described in a relatively general symbolism, usually ACDs, into the code of a simulation language and so enables a computer to mimic model behavior [143]. According to Mathewson [142], the steps in the use of a simulation program generator are to:

1. Prepare a symbolic description of the model.
2. Use the program generator to obtain a translation of the symbolic description into a simulation program.
3. Edit the simulation program to insert further detail whose representation is outside the scope of the symbolic logic.

Most of the work in simulation program generators has been conducted in Europe. Many of these generators, for example CAPS/ECSL [54], DRAFT [141], and GASSNOL [236], a simulation program generator based on the Network Oriented CAD Input Language (NOCADIL), are application specific and adopt the activity scan conceptual framework.

Table 4.3: Evaluation of Activity Cycle Diagrams as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	3
Permits model description to range from very high to very low level.	3
Permits model fidelity to range from very high to very low level.	2
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	1
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	2
Exhibits broad applicability.	3
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	3
Support provided for a broad array of model verification and validation techniques.	2
Facilitates component management and experiment design.	2

Program generators provide analysis at the program level; ACDs are expected only to provide gross aggregate depictions of model behavior. Direct analysis of ACDs requires the addition of timing, and variate distribution information to the graphs, and little attention has been paid to this process. Paul [188] notes that by their nature, ACDs provide a convenient means by which to recognize and prioritize simultaneous events at the specification level. However, no mechanism is described to accomplish this.

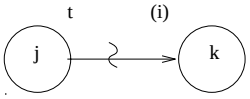
4.4.3 Evaluation

An evaluation of activity cycle diagrams, and the program generator approach, with regard to the identified requirements for a next-generation modeling framework appears in Table 4.3. The strongest advantage of these diagrams is that they are simple to work with. However, to fully support the simulation process, these diagrams must either be augmented, or the code generated from them must be edited. Methodological support for either of these approaches has not been demonstrated in the literature.

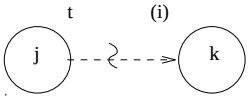
4.5 Event-Oriented Graphical Techniques

4.5.1 Event graphs

Observing that graphical modeling techniques had been developed for discrete event simulations adopting either an activity scan (activity cycle diagrams) or process interaction (GPSS block diagrams) view, but that no such tool was available for event scheduling models, Schruben [207] introduces a formalism dubbed the *event graph.*[10] Using Schruben's terminology, the crucial elements of a discrete event simulation are *state variables* that describe the state of the system, *events* that alter the values of state variables, and the *logical* and *temporal relationships* among events. An event graph is a directed graph that depicts the interrelation of the events in an event scheduling discrete event simulation. To construct an event graph, events are defined and numbered, and represented as vertices in the digraph. Event vertices are connected by directed edges that indicate how one event influences the occurrence of another event.[11] Two classes of edges are defined: a solid edge represents the scheduling of an event; a dashed edge represents an event cancellation. Thus,



indicates that t time units after the occurrence of event j, event k will be scheduled to occur provided that condition (i) holds at the time event j occurs. And,



indicates that t time units after the occurrence of event j, any currently scheduled occurrence of event k will be canceled provided condition (i) holds at the time event j occurs.[12]

Some additional properties of event graphs are: (1) two vertices may be joined by

[10] GPSS block diagrams (see [90]) are tailored to support the transaction flow conceptual framework of GPSS, and are not directly applicable for model development under the common process interaction world view (e.g. as supported by SIMULA). For this reason, GPSS block diagrams are considered implementation-language-dependent, and are therefore not included in this survey.

[11] In the usual parlence of graph theory (see [35]) vertices in an undirected graph are connected by *edges,* and vertices in a directed graph are connected by *arcs.* The terminology applied in this chapter adheres to that of the individual techniques, and not necessarily to the standards of graph theory.

[12] Schruben [207, p. 958] notes that event canceling is generally convenient in modeling but not necessary.

more than one edge, and loops are also permitted; (2) edges without condition labels are referred to as *unconditional* edges; (3) both edge delay times and condition labels may invoke random variates; (4) event vertices and condition labels may be *parameterized* to simplify the graph; (5) an event graph is not necessarily connected. Note that system time and the list of scheduled event occurrences are implicit in an event graph.

Example. The following Parts Model example is from [207]. In this example, parts arrive for processing by one of three identical machines. A machine is selected at random from the set, A, of available machines. Processing may be interrupted, and parts that have their processing interrupted will be finished once their machine resumes operation. We define:

t_a	=	random time between part arrivals
t_c	=	cycle time required for a machine to process a part
t_d	=	random duration processing interruption
t_i	=	random interval between machine interruptions
$T(j)$	=	processing time *remaining* for part currently on machine j $T(j) = 0$ if machine j is idle
$M(j)$	=	1 if machine j is available; 0 otherwise
p	=	number of parts waiting for processing
(i)	=	parts are waiting, $(p > 0)$
(ii)	=	at least one machine is available, $(A \neq \emptyset)$
τ_i	=	the time until the next currently scheduled occurrence of event i
event 1	=	{ *part arrival* } $p = p + 1$, randomly select $j \in A$, generate t_a
event $2(j)$	=	{ *begin processing on machine* j } $M(j) = 0, p = p - 1, T(j) = t_c - \text{MIN}(t_c, \tau_{4(j)})$
event $3(j)$	=	{ *end processing on machine* j } $M(j) = 1$
event $4(j)$	=	{ *interrupt machine* j } $M(j) = 0$, generate t_d
event $5(j)$	=	{ *machine* j *return to operation* } generate t_i

The event graph for this model is given in Figure 4.5.

Methodology and analysis. Schruben [207, p. 960] provides little guidance in terms of a methodology for graph construction, noting only that state variable definition, event definition, and edge conditioning usually proceed simultaneously in developing an event graph. Subsequent development yielded the Simulation Graphical Modeling and Analysis (SIGMA) environment. Written in C, and using the HOOPS object-oriented picture system,

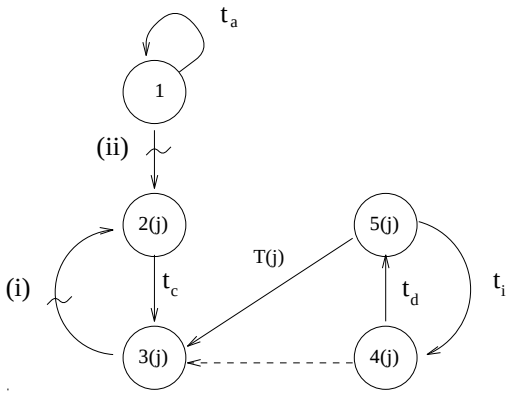


Figure 4.5: Event Graph for Parts Model.

SIGMA models – in the form of event graphs – are constructed and either directly executed or automatically transformed into standard C or Pascal code [208, 209, 210]. SIGMA is proposed as a learning environment rather than a commercial one. The environment is somewhat limited. For example, the first vertex created during the modeling process must always represent initialization, and editing of the source code and library routines is required to utilize multiple random number streams. A more significant limitation is the absence of methodological guidance in terms of defining and ordering the classes of decisions which need to be made during model development.

Diagnostic analysis of event graph models may aid in the following [207]:

- Identifying needed state variables.
- Determining a minimal set of events that must be scheduled at model initiation.
- Anticipating logic errors due to simultaneously scheduled events.
- Eliminating unnecessary event routines.

Schruben suggests heuristics for each of these, although no attempt is made to formalize the approach to model diagnosis.

Since 1983, several variations of event graphs have been proposed [104, 126, 189, 203], however the work of Schruben remains the most prominent. Schruben [209] illustrates how event graphs can be *marked* in a manner similar to Petri nets. In a marked event graph, the

number of tokens in an event vertex represents the number of outstanding instances of that event. Som and Sargent [219] formalize the analytic heuristics suggested by Schruben. Event execution order prioritization permits the generation of an *expanded event graph.* From this graph, *super events* are identified and used as a basis for computation, thereby reducing event list processing and fostering more efficient implementation of event scheduling models. Some questions exist regarding their approach, however. Yücesan [244, p. 34] gives an example graph for which these "event reduction" rules are invalid.

4.5.2 Simulation graphs and simulation graph models

Yücesan [244] demonstrates that event graphs of some simple queueing systems are planar, and shows that the *dual* of an event graph represents a model specification reflecting an activity scan world view (see [211]). These results illustrate the possible *generality* of event graphs; as a result, Yücesan [244] defines a *simulation graph,* which is a variant of event graph but intended as a world-view-independent representational mechanism. The discussion of simulation graphs given here is adapted from [246].

A simulation graph is defined as an ordered quadruple:

$$G = (V(G), E_s(G), E_c(G), \Psi_G)$$

where

$V(G)$	is the set of event vertices
$E_s(G)$	is the set of scheduling edges
$E_c(G)$	is the set of canceling edges
Ψ_G	is the incidence function

The data defined in the graph are given by the following indexed sets:

- $\mathcal{F} = \{f_v : \text{STATES} \rightarrow \text{STATES} \mid v \in V(G)\}$. The set of *state transition functions* associated with vertex v.
- $\mathcal{C} = \{C_e : \text{STATES} \rightarrow \{0, 1\} \mid e \in E_s(G) \cup E_c(G)\}$ The set of *edge conditions.*
- $\mathcal{T} = \{t_e : \text{STATES} \rightarrow \mathcal{R}^+ \mid e \in E_s(G)\}$ The set of *edge delay times.*
- $\Gamma = \{\gamma_e : \text{STATES} \rightarrow \mathcal{R}^+ \mid e \in E_s(G)\}$ The set of *event execution priorities.*

Where STATES is defined as in Zeigler's [250] development. A *simulation graph model* (SGM) is:

$$\mathcal{S} = (\mathcal{F}, \mathcal{C}, \mathcal{T}, \Gamma, G)$$

The first four sets in the above five-tuple define the entities in a model. The role played by a simulation graph, G, in the definition of a simulation graph model, $\mathcal{S}$, is analogous to the role of the incidence function, Ψ, in the definition of a directed graph: it organizes these sets of entities into a meaningful simulation model specification, i.e. G specifies the relationship between the elements in the sets $\mathcal{F}, \mathcal{C}, \mathcal{T}$ and Γ [212].

4.5.2.1 Equivalence analysis

Yücesan and Schruben [246] utilize simulation graphs as a basis for evaluating the equivalence of simulation model specifications. The objective is to identify when two simulation models can be used interchangeably without actually having to run both simulations under all possible experimental conditions and compare their output behavior. The authors' discussion is predicated on the following definitions. In an SGM, an edge condition is *simple* if it consists of two arithmetic expressions connected by a relational operator, i.e. a simple edge condition is a relation. An edge condition is *compound* if it consists of two or more relations joined by Boolean operators. A vertex is *simple* if there is at most one state variable change associated with it. Otherwise the vertex is *compound.* A vertex with no state variable changes is the *identity* vertex. An SGM is an *elementary simulation graph model* (ESGM) if it contains only simple vertices and simple edge conditions.

Given any SGM, an associated ESGM can always be constructed by *expansion* of the SGM. Expansion involves replacing all instances of single event vertices with m ($m \geq 1$) state variable changes, by m vertices in series, each with a single state variable change, and replacing all instances of edges with compound conditions by a group of identity vertices, each connected by edges with simple conditions. During this process, the logical structure of the original model is always preserved [246, p. 87]. Application of the expansion rules does not generate a unique ESGM. However, all ESGMs constructed in this manner are mutually isomorphic and therefore form an equivalence class. The isomorphism problem is intractable for general graphs, but efficient algorithms for planarity testing and determining isomorphism on planar graphs do exist [105, 106].

According to [246] SGMs $\mathcal{S}_1$ and $\mathcal{S}_2$ are *structurally equivalent* if they have ESGMs, $\mathcal{S}_1^E, \mathcal{S}_2^E$, respectively, which are isomorphic. A further result is that structural equivalence implies *behavioral* equivalence. This result is important since it means that we can *a priori* analyze two model specifications to determine their equivalence, without having to generate and run implementations of them. However, these analytic techniques have not been implemented in an environment, so their application to large-scale models remains the subject of future study.

Note that Overstreet [178] also shows that structural equivalence of a Condition Specification implies *external* equivalence. Furthermore, since digraphs utilized within the Condition Specification may not be planar, he argues that no polynomial-time algorithm exists to determine the structural equivalence of two CSs.

4.5.2.2 Complexity analysis

In [212] simulation graphs are used as a basis for analyzing model complexity. Their focus is on complexity measures that relate directly to the structural properties of simulation model specifications, with primary attention paid to predicting implementation and maintenance costs. They define three measures of *space complexity:*

$$C_1 = \mid V(G) \mid$$

C_1 relates complexity to the size of the specification.

$$C_2 = \frac{\mid E(G) \mid}{\mid V(G) \mid}$$

where $E(G) = E_s(G) \cup E_c(G)$. C_2 relates complexity to the number of possible component interactions.

$$C_3 = \sum_{v \in V(G)} C(v) + \sum_{v,w \in V(G)} I(v,w)$$

where $C(v)$ denotes some measure of the complexity of vertex v, and $I(v,w)$ denotes some measure of interaction between vertices v and w. C_3 represents the sum of the complexities of each "module" and the intermodular interaction. This metric is somewhat vague, however, since no clear choices for $C(v)$ and $I(v,w)$ exist.

Schruben and Yücesan [212] present a fourth complexity measure associated with the number of control paths through a graph. Based on McCabe's [146] work, the *cyclomatic*

number of a simulation graph, G, with n vertices, e edges, and p connected components is:

$$\eta(G) = e - n + p$$

The results of their analysis using the four complexity measures indicate that the complexity of individual events, measured as the number of modified state variables within that event, plays a principal role in determining the execution time of a single run. The branching structure, as measured by the cyclomatic complexity of the graph, has secondary influence [212].[13]

4.5.2.3 Theoretical limits of structural analysis

Yücesan and Jacobsen [245] discuss some theoretical limitations of structural analysis. Based on their experience with simulation graphs, the authors demonstrate that the following properties of discrete event simulation models are intractable (albeit decidable) decision problems:

- *Accessibility of states* - determining whether or not any given model state will occur during an execution of the model.
- *Ordering of events* - determining the existence of, or ruling out the possibility for, simultaneous events.
- *Ambiguity of model implementations* - determining whether the model implementation "satisfies" the model specification.
- *Execution stalling* - determining whether an execution can enter a state in which no determined events exist and the termination condition is not met.

They further argue that these properties hold for any model representation form.[14] Overstreet's [178] conclusions, based on Turing machine analysis of the CS, are slightly different. By reducing these issues to the Halting Problem, Turing analysis indicates that these problems are undecidable.

[13] The authors claim that this contradicts both Overstreet's and McCabe's assertions that complexity depends only on the decision structure (branching) of a program and not on the number of functional statements. However, Overstreet describes conceptual complexity, *not* run-time complexity.

[14] These results seem to contradict those of Yücesan and Schruben [246] that planar graph representations of simulation models do portend tractable analysis.

Table 4.4: Evaluation of Event-Oriented Approaches as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	2
Permits model description to range from very high to very low level.	3
Permits model fidelity to range from very high to very low level.	3
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	2
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	2
Exhibits broad applicability.	2
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	3
Support provided for a broad array of model verification and validation techniques.	3
Facilitates component management and experiment design.	3

4.5.3 Evaluation

Evaluation of event-oriented approaches based on the identified requirements for a next-generation modeling framework appears in Table 4.4. Event Graphs and Simulation Graphs have been well-exercised over the past ten years. While the notation seems expressive and extensible, no methodology for graph construction has been described. Experience with SIGMA may yield results in this area.

4.6 Petri Net Approaches

According to Peterson [190], a Petri net is an abstract formal model of information flow. Named for Carl Petri, the major use of Petri nets has been the modeling of systems which exhibit concurrency. This most common use is motivated by a desire to analyze this class of systems – by modeling them as Petri nets, and then manipulating the Petri nets to derive properties of the modeled systems. As a result, much study has gone into the development of techniques for analyzing Petri nets. One method of analysis is simulation. Petri nets

are also, themselves, a modeling tool. They have been suggested as a formalism to model general systems for the purpose of discrete event simulation. Petri nets are suitable for modeling systems that can be viewed as a set of *events* and a set of *conditions,* and the relationships among these sets [190, p. 288].

Thus the relationship between Petri nets and DES is somewhat symbiotic: Petri nets are used to develop DES models, and DES is used to simulate Petri nets when the limits of analytic techniques are exceeded. The use of Petri nets as a formalism for the development of discrete event simulation models of general systems is of primary interest here.

The presentation begins with a discussion of the basic, or *ordinary,* Petri net. Some common extensions to Petri nets are discussed subsequently.

4.6.1 Definitions

A Petri net is a directed bipartite graph. The graph contains two types of nodes: *places* – typically represented by circles, and *transitions* – typically represented by bars. An arc in the graph may exist only between places and transitions. In an ordinary Petri net, multiple arcs between any two nodes are not allowed.

If an arc from a place P to a transition T exists, then P is called an *input place* of transition T, and T is called an *output transition* of place P. Similar definitions hold for *output place* and *input transition.*

At any moment, a place may have 0 or more *tokens.* Tokens are represented by black dots in place nodes. A Petri net with tokens is called a *marked* Petri net. The distribution of (all) tokens (to places) in a marked Petri net is called its *marking.*

A Petri net for a single server queueing system is given in Figure 4.6. The graph contains three places and three transitions. The graph marking indicates that the server is idle and no customers are waiting. A valuable feature of Petri nets is their ability to model a system hierarchically. An entire net may be represented by a single place or transition for modeling at a more abstract level (abstraction), or places and transitions may be expanded into subnets to provide more detailed modeling (refinement). For example, the service transition in the Petri net given in Figure 4.6 could be expanded into a "service starts" transition, a "customer obtains service" place, and a "service ends" transition. Note that the graph of Figure 4.6 does not contain any timing information, and so is not directly suitable for

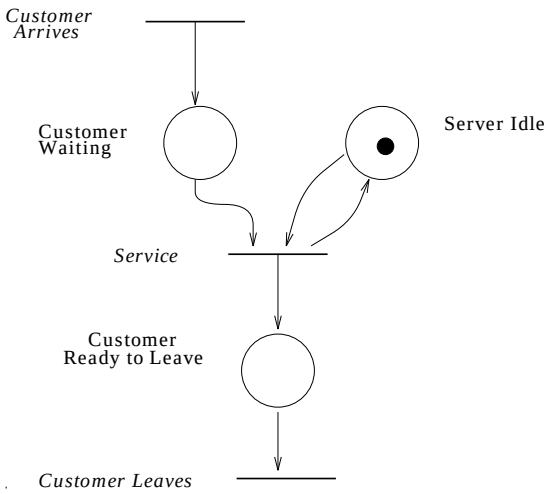


Figure 4.6: A Petri Net for a Single Server Queue. The marking indicates that the server is idle and no customers are waiting.

discrete event simulation, the incorporation of time within a Petri net is discussed below.

A transition node is said to be *ready* if and only if there exists at least one token in each of its input places. At any moment, 0 or more ready transitions are chosen (nondeterministically) to *fire*. When a transition fires, its associated input tokens are removed and new tokens are placed in each of its output places. In an ordinary Petri net, the firing of a transition is instantaneous. Two transitions are said to be *neighbors* if they share at least one input place.

While nondeterminism is potentially advantageous from a modeling point of view, it introduces complexity into the analysis of Petri nets. However, Peterson [190, p. 229] notes that if instantaneous firing of transitions, and a real-valued clock are assumed, the probability of simultaneous events (transitions) goes to zero.

A net is said to be *k-bounded* for some integer k if no more that k tokens can be in any place at the same time. A 1-bounded Petri net is called a *safe* net.

A Petri net is *conservative* if the number of tokens in the net is conserved.

A transition is *dead* in a marking if there is no sequence of transition firings that can enable it. A transition is *potentially firable* if there exists some sequence that enables it. A

transition is *live* if it is potentially firable in all *reachable* markings (defined below).

Petri net analysis. Almost all Petri net analytic techniques include the construction of a *reachability tree* [190, p. 240]. In a reachability tree the nodes represent markings of the Petri net and the arcs represent possible changes in state resulting from the firing of transitions. Tree construction is made finite (even though the reachability set may be infinite) through a parameterization process. Using this technique, one may determine if a marking, say, m' is *reachable* from some other marking, m.

Common Petri net analysis procedures include analysis for (1) boundedness, (2) conservation, (3) coverability, and (4) reachability. The reachability problem for Petri nets, however, has been shown to be decidable, but intractable [190, p. 249].

Petri nets that allow multiple arcs are often called *generalized* Petri nets. Addition of the provision for *inhibitor arcs* – arcs which indicate that a transition may fire only if the corresponding place has zero tokens in it – yields a formalism equivalent to a Turing machine [190, p. 246]. Commonly, most references to "Petri nets" refer to generalized Petri nets with inhibitor arcs. A discussion of some special extensions and applications of Petri nets follows.

4.6.2 Timed Petri nets

The basic Petri net definition contains no information regarding the temporal properties of the model behavior. Timing information may be added to an ordinary Petri net to produce a *Timed Petri net* in the following manner:

- Time may be associated with transitions. Each transition T has a time, δ, called the *execution time* of T. The usual interpretation of this construct is that if T begins firing at time t, the input token(s) are removed at t and the output token(s) appear at time $t + \delta$.
- Time may be associated with places. Each place P has an associated time, δ. In this case, if a token appears in in P at time t, then any associated output transition may not fire until time $t + \delta$.

Time may be associated with transitions only – the most common version of Timed Petri nets [173, 197, 233], places only [6, 57], or both transitions and places [123].

4.6.3 Stochastic Petri nets

Molloy [149] describes a *stochastic* Petri net (SPN) as a generalized Timed Petri net in which the time specifications are introduced by associating exponentially distributed firing times on transitions. Balbo and Chiola [14] present a tool, GreatSPN, which provides the facilities to build, analyze, execute and animate SPNs.

4.6.4 Simulation nets

Törn [233, 234] describes an approach to discrete event simulation known as the *simulation net.*[15] A simulation net is an extension to the ordinary Petri net which includes:

- generalized Petri net semantics
- inhibitor arcs
- general test arcs
- temporal properties for transitions
- a notation for representing queues

According to [233] the Petri net properties important for simulation are liveness and safeness. Törn [234] describes a tool, SimNet, which directly executes simulation net simulations. Implemented in SIMULA, SimNet provides, among other features, the automatic collection of common performance measures for queueing systems.

4.6.5 Petri nets and parallel simulation

Not surprisingly, due to the relationship between Petri nets and concurrent systems (see [197]), the use of Petri nets as a basis for parallel simulation has received significant attention.

Kumar and Harous [123] describe an approach for the parallel discrete event simulation of Timed Petri nets based on a conservative protocol in which deadlock avoidance is implemented through a variant of the null message scheme. Nicol and Roy [173] demonstrate a method for locating and exploiting "lookahead" in a conservative parallel simulation of Timed Petri nets. They describe an X-windows based graphical tool, pntool, which may

[15] Törn originally calls these structures *simulation graphs.*

Table 4.5: Evaluation of Petri Net-Based Approaches as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	1
Permits model description to range from very high to very low level.	1
Permits model fidelity to range from very high to very low level.	3
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	1
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	2
Exhibits broad applicability.	3
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	3
Support provided for a broad array of model verification and validation techniques.	3
Facilitates component management and experiment design.	1

be used to develop Timed Petri net models for the YAWNS simulation environment [174]. Another method, known as the *transition firing protocol* is described in [228].

4.6.6 Evaluation

Evaluation of Petri net-based approaches with respect to the identified requirements for a next-generation modeling framework appears in Table 4.5. Petri nets provide a simple mechanism for the representation of system behavior. However, the conceptual framework seems too restrictive, and no provisions have been demonstrated for model definitions, assumptions and objectives. Nor has a higher-level representation been identified. Very little work is evident regarding the use of Petri nets within the context of an end-to-end simulation study.

4.7 Logic-Based Approaches

Simulation model development approaches that provide a basis for formally *reasoning* about discrete event simulations (at the model specification level) are investigated in this section. Proof of correctness dates to [68], and a great deal of literature in exists in the area of computational logics: in artificial intelligence, software engineering, as well as philosophy. A body of research concerning the application of logic programming to discrete event simulation has evolved, but the focus of these efforts is mostly at the implementation level, and so are not examined in this survey. Perhaps the most extensive application of logics in computer science has been in the arena of real time systems (see [196] for a brief discussion). These real time, and temporal logics *may* be suitable for developing discrete event simulation models. However, the efforts along these lines are highly embryonic, and any potential benefits are speculative. For this reason, and for space considerations, a discussion of real time and temporal logics is considered beyond the scope of this survey.

4.7.1 Modal discrete event logic

By far the most developed effort in this area is due to Radiya and Sargent [195, 196]. According to [196, p. 4], Zeigler's systems theoretic work is the major theoretical foundation for discrete event modeling and simulation (DEMS). Radiya and Sargent suggest their own efforts, as well as Glynn's [87, 88] work in generalized semi-Markov processes as possible alternatives for a theoretical DEMS foundation [196, p. 4]. The authors identify the contributions of their work as follows:

- Identification of important *semantic concepts,* starting with the two fundamental concepts of *instantaneous propositions* (events) and *interim variables* (similar to piecewise constant state variables) and culminating in the central concept of *discrete event (DE) structure.*
- A *modal discrete event logic,* L_{DE}, for expressing discrete event models. The logic L_{DE} is defined, independent of its simulation procedures, by specifying its syntax and semantics with respect to DE structures. In L_{DE} a *model* of a system is a set of formulae. The purpose of the semantics is to specify conditions under which a DE structure can be said to "satisfy" a model in L_{DE}. A DE structure *satisfies* a model if the truth values of instantaneous propositions and changes in the values of interim variables at every instant of the DE structure are completely accounted for by the model.

- A *simulation procedure* for simulating models expressible in a sublogic of L_{DE}. *Simulation* is defined to be a process of finding a DE structure that satisfies a given model, and a *simulation procedure* is an algorithm that defines this process.

Semantic concepts. An *instantaneous proposition* is a proposition such that: (1) its truth (occurrence) can be claimed at any instant, and (2) over any bounded interval, the proposition true (occurs) only at finitely many instants. Used to represent events, this differs from Nance's [156] characterization. An *event,* as defined by Radiya, is not directly associated with instants or state changes. An *occurrence of an event* is associated with an instant but not necessarily a state change. In a queueing network example suggested by [196, p. 10], neither instants nor state changes are associated with an event "customer arrival," but its occurrence must be associated with an instant. Also certain occurrences of "customer arrival" may not be associated with state changes, e.g. when it coincides with "customer departure" the number of customers in the system does not change during that instant.

An *interim variable,* v, is a variable such that: (1) the claim that v has a value is meaningful at any instant, and (2) over any bounded interval I that is open on the left and closed on the right, the value of v changes only finitely many times. Further, every maximal subinterval of I over which v has the same value is open on the left and closed on the right.[16]

The values of propositions and variables at any particular instant are defined by *valuations* – one type for propositions and another for variables. A representation called the *discrete event trajectory* completely describes the behavior of a model by specifying the values of propositions and variables over all instants. The trajectory provides a basis for defining a *discrete event (DE) structure.* The discussion of DE structures as well as the description of the syntax and semantics of L_{DE} is quite lengthy and so is omitted here. The reader is referred to [196, pp. 12-31] for details.

Some other issues. The logic L_{DE} places no restrictions on the number of definable operators. The operators, **next, now, null, if, when, whenever, until, while, unless,**

[16]The restriction on the form of the interval is made to distinguish Boolean interim variables from instantaneous propositions.

some and **at** are defined in [196]. The provision for limitless operators is claimed as a strength of the approach, however, the authors concede that the model-theoretic semantics of L_{DE} are more complex than the semantics of the commonly used simulation languages, procedural programming languages, and mathematical logics such as first order predicate logic or the temporal logics [196, p. 23]. Further, construction of an L_{DE} model that is well defined by its semantics but cannot be simulated (because a simulation procedure for it may not be known) is possible [196, p. 42]. This occurs in practice when the L_{DE} operator, **unless,** is utilized in the model specification.

No proof system is defined for L_{DE}, although given the rigorous formal definition of its semantics it should be possible to do so. The value of the logical foundation provided by L_{DE} may best be as a methodology for designing discrete event simulation languages – by focusing on the capability to implement natural and powerful representations of system behavior. The authors view the ability to prove properties of model specifications as, potentially, a secondary contribution.

4.7.2 DMOD

Narain [166] describes an approach called DMOD in which a simulation model is viewed as a 7-tuple consisting of sets of events and timestamps, an initial event, as well as some ordering relations, *lt, eq, time* and *causes.* Using a phone system model, the author demonstrates a procedure for computing state trajectories and histories, as well as methods for programming in and formally reasoning about DMOD structures. The work described is in the very early stages of development, and no conclusions are drawn in the paper. No subsequent development in DMOD has appeared.

4.7.3 UNITY

Abrams et al. [2, 3] present a method for discrete event simulation based on the UNITY formalism defined by Chandy and Misra [48]. A methodology for developing simulation models is described, and the UNITY proof system is used to facilitate formal verification of model specifications. A discussion is given regarding the mapping of the UNITY programs to both sequential and parallel architectures. Similar to DMOD, the work described is in its early stages, and the methodology presented is burdensome to a modeler. The approach

Table 4.6: Evaluation of Logic-Based Approaches as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	1
Permits model description to range from very high to very low level.	2
Permits model fidelity to range from very high to very low level.	2
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	1
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	1
Exhibits broad applicability.	2
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	2
Support provided for a broad array of model verification and validation techniques.	2
Facilitates component management and experiment design.	1

also suffers from the lack of a provision for reasoning about temporal properties in UNITY.

4.7.4 Evaluation

Evaluation of logic-based approaches with respect to the identified requirements for a next-generation modeling framework appears in Table 4.6.

The logic-based approaches to discrete event simulation are on target in one very important area: they focus the effort on the *model.* In this manner, implementation details are less likely to interfere with the formal determination of model correctness. However, the existing approaches suffer greatly in terms of a methodology and automation. While automatic theorem provers are available, complex assertions must be formulated, in general, by hand. Furthermore, no provisions are made for a modeler to describe a model in "familiar" terms such as events, activities, or processes.

These logic-based approaches portend great strides in the development of correct models and programs, but until the models can be created and analyzed by modelers with limited, or even no experience in formalisms, these approaches provide little contribution to the

capabilities needed for realistic use of discrete event simulation.

4.8 Control Flow Graphs

Cota and Sargent [58, 59] introduce a mechanism called a *control flow graph* (CFG). Introduced as a conceptual tool for developing parallel simulation algorithms, CFGs are not proposed as a formalism for model description [59, p. 21]. However, CFGs have been sufficiently well defined to warrant their inclusion here.

A control flow graph is a directed graph that represents the behavior of an individual process, or class of processes, in a discrete event model. Each node in the CFG represents some possible state of the process – a *control state* or *synchronization point* – in which the process is waiting from some condition to become true or for some determinable period of time to pass. Each action that a process may take from a given state is represented by an edge exiting the node.

Processes described by CFGs communicate through message passing. Each process has associated with it, a set of state variables, and sets of input and output channels across which the process may send and receive messages. A process is said to be a *predecessor* of its input channels, and a *successor* of its output channels. Any number of channels may exist between two processes. A model that consists of a set of processes defined by CFGs and channels through which those processes communicate is called a *CFG model.*

In a CFG model, when a process sends a message across an output channel, that message immediately becomes available to the process that receives from that channel. Since the receiving process may not be ready to use the message, each channel may be regarded as a queue of messages waiting to be processed. When a process removes a message from an input queue, the process is said to have *received* that message. The receiving process decides when to receive the message, but messages must be processed in the order in which they were sent.

Each event that might take place when a process is in a particular control state is represented by a directed edge exiting the node that represents that state. Edges leaving a node are prioritized to break ties. Each edge in a CFG has associated with it an *event type,* which defines the action associated with that edge, and an *edge condition,* which defines the conditions under which the process takes that action. An edge condition is the conjunction

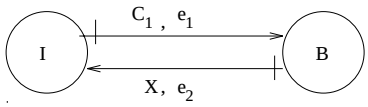


Figure 4.7: Control Flow Graph for a Single Server Queue.

of a *local condition,* which depends only only the state variables of the process, and a *global condition,* which can become true due to the arrival of messages from other processes or due to the passing of time. Each global condition is classified as one of the following:

- *Arrival condition.* An arrival condition becomes true when some specified input channel is non-empty. The arrival condition is said to *depend on* that input channel.
- *Time delay condition.* A time delay condition becomes true after some determinable (possibly random) period of time has elapsed.
- *Trivial condition.* A trivial condition is always true.

An event type is a procedure that can: (1) change the values of state variables belonging to a process, or (2) send or receive messages.

The behavior of a process described by a CFG may be viewed as a marker, called a *point of control,* traveling through a graph. The point of control waits at the *control node* until the earliest instant in simulated time at which an edge condition on an edge exiting that node is true. The event type associated with that edge is then carried out and the point of control enters the succeeding node by *traversing* the edge. Edge traversal is also referred to as an *event.* If the edge conditions of more than one edge exiting the control node become true simultaneously, then the edge with higher edge priority is traversed.

4.8.1 Examples

A CFG for a single server queueing system is illustrated in Figure 4.7. This example, as well as the succeeding one, is from [59]. The CFG contains two control states: (1) I – representing an idle server, and (2) B – representing a busy server. When in the idle state, the server waits for a message to arrive across input channel C_1 and then enters the busy state. From the busy state, the server waits for a random period of time, given by X, and

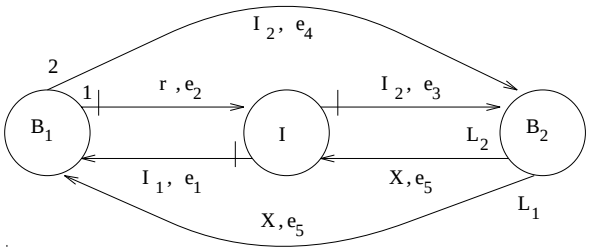


Figure 4.8: Control Flow Graph for a Single Server Queue with Preemption.

then enters the idle state. Two event types are defined: (1) e_1 – receive a message from C_1, and (2) e_2 – send a message to C_2. Note that the output channel, C_2, is not depicted in the graph. The lines through the edge tails indicate trivial local conditions.

A more complicated example can be made by the addition of preemption to the system. The graph for this is given in Figure 4.8. In this example, two classes of transactions are defined. We assume that service of class two transactions takes priority over service of class one transactions, and an interrupted transaction resumes at the point of interruption. The CFG contains three control states: (1) I – idle, (2) B_1 – busy, serving class one transaction, and (3) B_2 – busy, serving class two transaction. Two input channels, two output channels, and four state variables are defined. Class one (two) transactions arrive across input channel I_1 (I_2), and are sent across output channel O_1 (O_2). State variable, m_1 (m_2) is a message pointer that indicates the class one (two) transaction in service, or preemption, if any. State variable, r, contains the amount of service time required by a class one transaction. State variable, s, contains the time at which service on a class one transaction begins. The following event types are defined:

e_1 { *begin service of a class one transaction* } receive m_1 from I_1; compute the service time required and store in r; set s equal to the current clock.

e_2 { *complete service of a class one transaction* } send m_1 to O_1; set M_1 to null to indicate that no class one transaction is in service.

e_3 { *begin nonpreemptive service of a class two transaction* } receive m_2 from I_2.

e_4 { *preempt class one transaction* } let r equal $r -$ (current clock $- s$); receive m_2 from I_2.

Table 4.7: Evaluation of Control Flow Graphs as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	2
Permits model description to range from very high to very low level.	2
Permits model fidelity to range from very high to very low level.	2
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	2
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	2
Exhibits broad applicability.	2
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	2
Support provided for a broad array of model verification and validation techniques.	2
Facilitates component management and experiment design.	2

e_5 { *complete service of a class two transaction* } send m_2 to O_2.

Two edges have nontrivial local conditions: (1) L_1 is true iff m_1 is not null, (2) L_2 is true iff m_1 is null. Edge priorities are either 1 or 2, where 1 is considered the highest.

4.8.2 Evaluation

Evaluation of control flow graphs with respect to the identified requirements for a next-generation modeling framework appears in Table 4.7. The motivation for the development of control flow graphs is consistent with the philosophy described in Chapter 3. Sargent's goal is to provide an implementation-independent model representation. CFG development is fully grounded in the fundamentals of modeling methodology. However, the graphs are difficult to construct, and too much information is *implicit* in the representation. For example, no information concerning the queue of arrivals is conveyed in the representation shown in Figure 4.8. Further, the modified process interaction world view that these graphs support is restricting [61]. Research is ongoing, though, which may help alleviate some of these inadequacies [77].

4.9 Generalized Semi-Markov Processes

Applying theory of Markov processes to discrete event systems for the purposes of analysis predates the advent of digital computers. The vast majority of these efforts exist as an *alternative* to simulation. Recently, a paper by Glenn [87] suggests a variant of Markov processes, the *generalized semi-Markov process,* GSMP, as a formal basis for studying discrete event systems. Radiya and Sargent [196] indicate that GSMPs may provide a uniform formal basis for studying discrete event systems – both analytically and through simulation. The GSMP approach is briefly described here. For a more detailed treatment, see [31, 63, 87, 88].

Stochastic processes occurring in most "real-life" situations are such that for a discrete set of parameters $t_1, t_2, \ldots, t_n \in T$, the random variables $X(t_1), X(t_2), \ldots, X(t_n)$ exhibit some sort of dependence. The simplest type of dependence is the first-order dependence underlying the stochastic process. This *Markov-dependence* may be defined as follows: consider a finite (or countably infinite) set of points $(t_0, t_1, \ldots, t_n, t) \ni t_0 < t_1 < t_2 \cdots < t_n < t$ and $t, t_r \in T(r = 0, 1, \ldots, n)$ where T is the parameter space of the process $\{X(t)\}$. The dependence exhibited by the process $\{X(t), t \in T\}$ is called Markov-dependence if the conditional distribution of $X(t)$ for given values of $X(t_1), X(t_2), \ldots X(t_n)$ depends only on $X(t_n)$ which is the most recent known value of the process, i.e. if,

$$\begin{aligned} P[X(t) \leq x \mid X(t_n) &= x_n, X(t_{n-1}) = x_{n-1}, \ldots, X(t_0) = x_0] \\ &= P[X(t) \leq x \mid X(t_n) = x_n] \\ &= F(x_n, X; t_n, t) \end{aligned}$$

The stochastic process exhibiting this property is called a *Markov process.* In a Markov process, or a variant known as a Markov chain, if the state is known for any specific value of the time parameter, t, that information is sufficient to predict the behavior of the process beyond that point [31].

The formulation of GSMPs allows the distribution of an event to depend on the event itself, the current and previous states, and the event which triggered the last transition. According to [63, p. 323], the basic building blocks of GSMPs are the probability distributions of the event lifetimes and the routing probabilities. Also central to a GSMP are its set of *states* and set of *events.* When an event triggers a transition, the GSMP moves from its current state to some other state with a certain routing probability. It then stays in this

new state for a certain length of time, until another transition is triggered by some event, and so on.

The state space S of the GSMP is countable in the general theory, but is often assumed to be finite. The event set, E, is finite.

A GI/G/1 queue can be modeled as a GSMP with state space $S = \{0, 1, 2, \ldots\}$ where the current state represents the number of customers in the system.[17] When no customer is present in the system ($s = 0$), the only possible next-event is the arrival of a customer. When one or more customers are in the system ($s \geq 1$), the possible events are an arrival or an end of service. If the next event is an arrival (end of service) the GSMP moves from state s to state $s + 1$ ($s - 1$) with probability one. The interarrival times and service times are distributed according to their respective cumulative distribution functions.

Embedded in the GSMP is a general state-space discrete time Markov chain, $\{X_n = (s_n, c_n) : n \geq 0\}$, where s_n is the state occupied immediately following the nth transition [63, p. 324]. If $N(t)$ is the number of transitions by time t_1 the GSMP will be at that time in state $Q(t) = S_n(t)$. The component c_n of the embedded Markov chain is actually a vector $\mid E \mid +1$ "clocks." Clock 0 indicates the elapsed time between transitions $n - 1$ and n. All other clocks are associated with an event: if event i is active at time t_n, where t_n is the epoch of the nth transition, its corresponding clock reading c_i, n indicates the elapsed time since it was generated last.[18]

The level of formalism demanded to utilize GSMP is seen in the following. The development is due to [63] where the parametric inference process for GSMPs is examined. Assume the distribution of event j depends only on the event itself and an unknown parameter. Denote the distribution $F_j(\cdot; \theta)$. Let $\overline{F}_j(\cdot; \theta) \equiv 1 - F_j(\cdot; \theta)$ be the residual lifetime distribution of event j. Further, assume that the support of the distributions is $(0, \infty)$. This also implies that the supports of the event distributions do not depend on the unknown parameter. Also assume that the distribution function $F_j(\cdot; \theta)$ of an event j admits a density, $f_j(\cdot; \theta)$.

Let $E(s)$ be the set of active events in state s, and $N(s', s, i), O(s', s, i)$ represent the set of new and old events respectively. In state s' when it is event i which just triggered the transition from state s.

[17] Note that S is not finite here.

[18] Clocks may run backwards or forwards; both conventions have been used in the literature.

The transition density function $h(x, x'; \theta)$ of the embedded Markov chain is given by:

$$\begin{aligned} h(x=(s,c), x'=(s',c');\theta) \quad = \quad & \sum_{i \in E(s)} \{p(s';s,i;\theta) \frac{F_i(c_i + c'_o;\theta)}{\overline{F}_i(c_i;\theta)} \\ & \cdot \prod_{j \in O(s',s,i)} \frac{\overline{F}_j(c'_j;\theta)}{\overline{F}_j(c_j;\theta)} I[c'_j = c_j + c'_o] \\ & \cdot \prod_{j \in N(s',s,i)} I[c'_j = 0] \prod_{j \notin E(s)} I[c'_j = -1]\} \end{aligned}$$

Where $I[\cdot]$ denotes the indicator function, and appear for consistency.

The modeling power of GSMP may be suitable to capture any discrete event system. In [94] GSMP and stochastic Petri nets are shown to have equivalent modeling power. However, provisions for an unobtrusive conceptual framework, higher-level descriptions, life cycle and methodological support remain to be defined. The GSMP evaluation appears in the summary (Table 4.8).

4.10 Some Other Modeling Concepts

4.10.1 Hierarchy

As noted in Section 4.3, a basic principle of general systems theory, and its realization in DEVS-based approaches, is the concept of *hierarchy.* Recently, a great deal of interest in the simulation community has been focused on the issue of *hierarchical modeling.* At first glance, it would appear that hierarchical modeling and DEVS-based, general systems theoretic approaches are one-and-the-same. And while these approaches clearly dominate the realm of hierarchical modeling, several existing approaches such as the RESearch Queueing Package Modeling Environment (RESQME) provide hierarchical modeling in a fashion that is divorced of general systems theory [91]. Nance's Conical Methodology (see Chapter 5) also stresses the importance of hierarchical model development. In this section, ongoing attempts to formally characterize hierarchical modeling are reviewed.

In a panel session conducted at the *1993 Winter Simulation Conference*, three basic approaches to hierarchical modeling were identified [206]:

- *Closure under coupling.* In this approach models are coupled together to form larger models. DEVS is an example of this approach.

- *Metamodels.* According to [204], a metamodel is a polynomial (mathematical) model that relates the I/O behavior of the simulation as a black box. A metamodel is often a least squares regression model that only contains the input variables necessary to describe the output behavior of the simulation model over the experimental region. This approach is not yet viewed as feasible [206, p. 570].

- *Specific software frame.* Also known as the *backbone* or *base model* approach, this technique allows "plug compatible" submodels to plug into or communicate by passing messages.

Luna [140] attempts to find a precise characterization of hierarchical modeling. He points out that of primary importance is the characterization of what constitutes a *model.* Luna suggests that discrimination must be made between viewing a model as:

- An *abstract concept.* This model exists in the mind and has no documented representation.

- A *diagram.* This type of graphical model provides a view of the static properties of the model, but often model behavior must be inferred.

- A *mathematical representation.* This type of model may be suitable for describing model dynamics, but often fails to communicate a "picture" of the system.

- An *implementation.* This is the source, or object, code.

These aspects (of what a model is) can be divided into four categories:

- *System aspect.* This corresponds to the perceived (conceptual) model of the system.

- *Representation aspect.* This concerns the expression of the model in some form (graphical, mathematical, or both).

- *Implementation aspect.* Source code level; the typical level at which users work.

- *Organization aspect.* This concerns the organization of the model implementation.

Based on the above, Luna identifies four types of model hierarchies:

- *Representation.* Here, the higher level does not have its own being per se, but is a representation of the lower level. For example, the U.S. Government may be viewed as illustrated in Figure 4.9. The government is hierarchically one level above the individual branches, but the government has no existence separate from the branches.

- *Composition.* Here, the higher level has its own being and employs the lower level in its behavior. A typical example of this relation is a system-subsystem relationship.

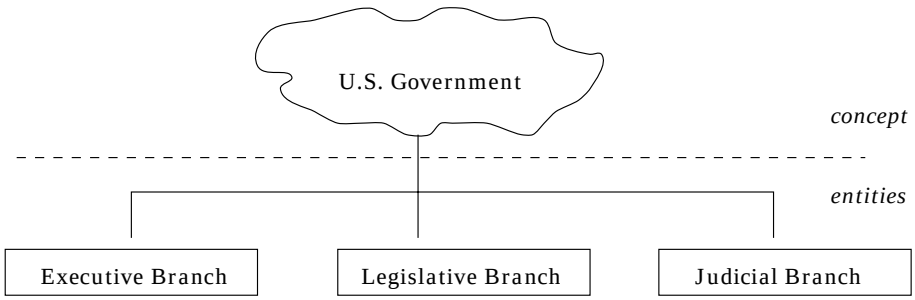


Figure 4.9: Hierarchical Modeling – The Representation Relation.

- *Substitution.* The substitution for the lower level by the higher level in a given model. This relation encompasses both abstraction by reduction and morphic reduction as a means of simplifying the model. The basic idea here is to simplify the model with respect to some measure of complexity.
- *Specification.* The higher level and lower level are related by type and the lower level is a more specific type than the higher level. Inheritance mechanisms in object-oriented design typify this type of relation. For example, an object class *car* may be defined in terms of a higher level object class, *vehicle.* Similarly, an object class *motorcycle* may also be defined as a more specific occurrence of the *vehicle* class.

Luna concludes that the claim that a model is hierarchical needs to be evaluated with respect to both the model aspect and the hierarchical relation applied. In particular, the hierarchical relations of representation and composition apply to the representation model aspect; the relations of specification, composition, and substitution apply to the organization model aspect, and the composition relation applies to the implementation aspect.

Miller and Fishwick [148] describe the *hybrid model theory* and the *heterogeneous hierarchical modeling* methodology. The methodology is designed to allow a modeler to utilize multiple formalisms and organize these formalisms hierarchically. The authors identify two categories of model hierarchies:

- *Type-of.* This category relates to object-oriented models and is usually the focus of the software engineering, artificial intelligence and simulation communities. Here the emphasis is on categorization of entities based on the generalization of static properties. SES is a type-of hierarchy.
- *Part-of.* This category can describe either static or dynamic properties and emphasize the categorization of physical or conceptual composition. DEVS is a part-of hierarchy.

The hybrid model theory, which descends from the *multimodel methodology* proposed by Fishwick and Zeigler [74], is a specialized construct defined in terms of general systems theory and permits a single model to be hierarchically constructed either by intermodel or intramodel coordination from five formalisms: (1) Petri nets, (2) Markov systems, (3) queueing networks, (4) state machines, and (5) block models.

The hierarchy is based on the composition of a system (part-of hierarchy) rather than the classification of entities as typical in object-oriented simulation: state formalisms (state machines, Markov systems) model the transition of a system from one discrete event to another; selective formalisms (queueing networks, Petri nets) model events based on resource allocation; functional formalisms (block models) model continuous signal-based systems.

4.10.2 Abstraction

The process of *abstraction* has received much attention in many areas of computer science. In the context of discrete event simulation modeling, when two models represent the same reality at different levels of detail, or fidelity, the less detailed model is said to be the more *abstract* model.

According to Sevinc [214], model abstraction serves two purposes: (1) it increases our understanding of models and model behavior, and (2) it may provide us with computationally more efficient models of the systems we study. He asserts that a *theory of model abstraction* is a well-defined formal expression of the relationship between any two models. It does not attempt identifying ways of abstracting models, but given any two models, the theory should tell whether they are related via this abstraction mechanism or not. Sevinc proposes a weakened version of Zeigler's homomorphisms (see [139]) as a basis for model abstraction.

Fishwick [73] proposes a number of methods for abstracting processes. These methods combined with definitions of a process at different levels is suggested to form a partially ordered graph called an "abstraction network" which in turn is used to study the model behavior at different levels of detail. A simulation environment, HIRES, is developed to support this process.

4.11 Summary

A set of requirements for a next-generation modeling framework is given in Chapter 3. These criteria are applied to the existing approaches to discrete event simulation modeling in this chapter. The evaluation is summarized in Table 4.8.

The survey indicates that no existing approach fully satisfies the requirements for a next-generation modeling framework. The systems theoretic approaches score the highest with a 2.7, while the generalized semi-Markov process approach score of 1.4 is the lowest for the approaches surveyed. Four observations are made from the data:

1. An average score below 2.0 indicates that an approach is significantly flawed due to an incognizance of one or more of the identified requirements. Lack of concept recognition fundamentally limits the viability of the approach.

2. For the ten requirements identified, "model representation independence" scores highest at 3.0. Since each approach surveyed is independent of an SPL or other programming language, this result is not surprising. However, no approach receives a 4 in this category since none has conclusively demonstrated architecture independence.

3. For the ten requirements identified, "unobtrusive conceptual framework" scores lowest at 1.375. One way to interpret this result is to observe that the ten requirements generally fall in one of two categories: (1) representation, or (2) methodology. The unobtrusive CF requirement is essentially where "the rubber meets the road" in this set of criteria. It represents the synergism of methodology and representation. The approaches surveyed tend to support one or the other, and a few have strengths in both areas. But where methodology meets representation – at the conceptual framework – the interface is ill-defined.

4. The evaluation treats each of the ten criteria as equally important. A biased evaluation may be preferred in situations where a set of objectives stipulates that some of the criteria are more relevant than others. The precedence for such an evaluative approach is given in [9].

The framework described in Chapter 3 may help to ameliorate the situation given by number (3) above. Since the framework is based upon a hierarchy of representations, any methodology adopted should tend to *explicitly* support the representation process. Further, the methodology must define the transformations among representations. Using the holistic view of discrete event simulation provided by this (or a similarly defined) framework, the situation that has developed with extant approaches may be less likely to occur.

Table 4.8: Evaluation Summary. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated. Methods: CC - Change Calculus; GST - General Systems Theory; ACD - Activity Cycle Diagrams; EvGr - Event-Oriented Graphs; PN - Petri Nets; LB - Logic-Based; CFG - Control Flow Graphs; GSMP - Generalized Semi-Markov Process.

Requirement	*Level of Support*							
	CC	GST	ACD	EvGr	PN	LB	CFG	GSMP
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	2	2	3	2	1	1	2	1
Permits model description to range from very high to very low level.	2	2	3	3	1	1	2	1
Permits model description to range from very high to very low level.	1	2	2	3	3	2	2	1
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	2	1	1	2	1	1	2	1
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	2	3	2	2	2	1	2	1
Exhibits broad applicability.	2	4	3	2	3	2	2	3
Model representation is independent of implementing language and architecture.	3	3	3	3	3	3	3	3
Encourages automation and defines environment support.	2	3	3	3	3	2	2	1
Support provided for a broad array of model verification and validation techniques.	2	3	2	3	3	2	2	1
Facilitates component management and experiment design.	1	4	2	3	1	1	2	1
AVERAGE	1.9	2.7	2.4	2.6	2.1	1.7	2.1	1.4

Chapter 5

FOUNDATIONS

Let us ... restrict ourselves to simple structures whenever possible and avoid in all intellectual modesty "clever constructions" like the plague.

Edsger Dijkstra, *Notes on Structured Programming*

In Chapter 3, a philosophy of simulation model development is presented, and an environment, based upon this philosophy, is described. The Conical Methodology and the Condition Specification - two pivotal aspects of the environment and its development as a prototype – provide the foundations for this research effort as well, and are described here.

5.1 The Conical Methodology

The earliest attempts to define a methodology for discrete event simulation can be traced to the 1960s in the work of Tocher [229, 230, 232], Lackner [124, 125] (see Chapter 4), and Kiviat [120, 121, 122]. While most of the simulation community concerned itself with the programming-related aspects of simulation, these efforts brought focus to the *fundamental* issues confronting simulation as a model-centered problem solving technique. The subsequent decade witnessed the definition of the first comprehensive and well-defined modeling methodologies designed to provide support throughout the life cycle. Of significance are the efforts of Zeigler [250], who proposes a framework for discrete event simulation based upon general systems theory (see Chapter 4), and Nance, who describes the Conical Methodology [155, 158, 160].

5.1.1 Conical Methodology philosophy and objectives

The Conical Methodology (CM) is a model development approach that is intended to provide neither abstract nor concrete definitions for general systems [155, p. 22]. The CM adopts the view that model development leads potentially to myriad evolutionary representations, but that the *mental perception* is the initial representation for every model, and that assistance in the area of mental perception, or *conceptualization*, is (should be) a critical aspect of any modeling methodology.

Within the CM, model development begins with a set of definitions. These definitions should permit an accurate, unambiguous, and complete description of the system consonant with the objectives of the simulation study. The CM further stipulates the requirement for a structure by which parts of a model can be related, i.e. model development tools should provide a discipline for both model composition and model decomposition. The methodology also asserts that the development task should provide a large part of the model documentation and that diagnostic assistance to the modeler should be available throughout the model development process. Specifically, the following objectives for the CM are identified [155, p. 22]:

1. Assist the modeler in structuring and organizing the conceptual model.
2. Impose an axiomatic development within an apparently free and unrestrictive model creation system.
3. Utilize model diagnosis to assess measures such as completeness and consistency for verification purposes and relative model complexity for planning purposes.
4. Produce major model documentation throughout model development as an essential byproduct of definition and specification but permitting the modeler to expand the descriptions as deemed necessary.
5. Promote an organized experimental design and monitor the realization of that design in the experimental model.

The methodology reflects influences of the object-oriented (see [239]), entity-relation-attribute (see [51]) and automation-based (see [24]) paradigms, and has been demonstrated to support the larger principles of software engineering – specifically fostering the objectives of model correctness, testability, adaptability, reusability and maintainability [9].

Concepts in the Conical Methodology conform to the definitions of Chapter 2. The CM structures the modeling process by identifying two stages of model development: a top down

model decomposition – the *model definition phase*, and a bottom-up model synthesis – the *model specification phase*. The phases in the methodology provide a pedagogical separation of the modeling process, but are neither intended to be executed independently nor without iteration. The methodology encourages model development as a cycling through the two stages, and places no restrictions on a modeler other than the requirement that object definition precede object specification for a given object.

5.1.2 Model definition phase

During the model definition phase, a modeler decomposes a model into objects and subobjects, then names and types the attributes of these objects. This decomposition can be visualized as a tree with the root of the tree being the model itself (also an object) and the leaves representing the subobjects at the most detailed level. Thus, a modeler may view a model through any perspective of object-level granularity by focusing on a particular level of the development tree. During the model definition phase, the modeler describes the *static* aspects of a model.

The Conical Methodology encourages explicit typing; explicit and strong typing permits analysis of specifications to a greater extent than where typing information is absent [178]. The methodology prescribes that typing be associated with attributes, rather than objects. This attribute typing follows the taxonomy illustrated in Figure 5.1, and summarized below.

Indicative attributes describe an aspect of an object.

> *Permanent* attributes are assigned a value only once during model execution.
>
> *Transitional* attributes receive multiple value assignments.
>
> > *Temporal* attributes are assigned values that represent system time.
> >
> > *Status* attributes assume values from a finite set of possibilities.[1]

Relational attributes relate an object to one or more objects.

> *Hierarchical* attributes establish the subordination of one object to another implying that all characteristics of the subordinate object are descriptive of the superior object.
>
> *Coordinate* attributes establish a bond or commonality between two objects.

[1] This stipulation does not mean to preclude the use of real-valued attributes. However, a finite range *must* be identified. Essentially, status transitional attributes encompass all indicative attributes whose values are not functions of system time.

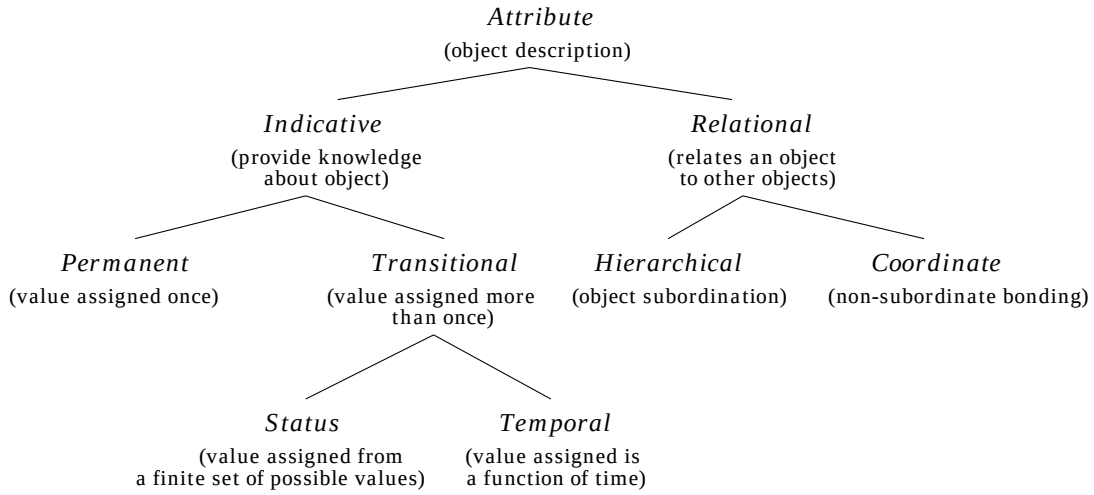


Figure 5.1: Conical Methodology Types.

In addition to typing, the dimensionality and range of an attribute should also be provided during model definition, and the methodology does not preclude an attribute from having multiple types. At least one attribute is associated with every model: the model indexing attribute. Typically this attribute is *system time*, although Nance notes that the use of a spatial indexing variable is also plausible [155, p. 30].

Very often, relations among objects are described by modelers through the use of *sets* [155, p. 28]. Within the CM, a set is an object that can be classified as either a *primitive set* or a *defined set*. In a primitive set (p-set) all member objects must have identically the same attributes. A defined set (d-set) is an object representing a collection of objects, not necessarily having the same attributes, defined by an expression evaluation occurring during model execution. Thus, membership in a p-set is static and can be defined prior to model execution, whereas membership in a d-set is dynamic. The CM views set relationships as instances of the general classification scheme noted above. For example, a coordinate attribute would describe the relation among set members, and the relationship between the set object and any member would be hierarchical. Set creation defines a set object (referred to as a set *header* in [155]) having one or more relational attributes that provide access to the attribute values of all member objects. Likewise, set deletion removes

Table 5.1: CM Object Definition for M/M/1 Queue.

Object	*Attribute*	*Type*	*Range*
`M/M/1`	*arrival_mean*	permanent indicative	positive real
	service_mean	permanent indicative	positive real
	system_time	temporal transitional indicative	nonneg real
	arrival	temporal transitional indicative	nonneg real
`server`	*server_status*	status transitional indicative	(idle, busy)
	queue_size	status transitional indicative	nonnegative integer
	num_served	status transitional indicative	nonnegative integer
	max_served	permanent indicative	positive integer
	end_of_service	temporal transitional indicative	nonneg real

the relationship established by at least one relational attribute.

5.1.3 Model definition example

As an example of the CM provisions for model definition, consider the CM definition for a classical M/M/1 queueing model illustrated in Table 5.1.[2] Two objects are defined: the model itself (`M/M/1`), and the object `server`. The attributes of the top-level model are the indexing attribute, *system_time* and attributes for the mean interarrival and service times, as well as an attribute representing the time of the next arrival. The object `server` has attributes indicating its status, the number in its queue, the number served so far, the maximum number of customers to serve, and the time of the next end-of-service.

5.1.3.1 Meaningful model definitions

Note that associating attributes to objects in a "meaningful" way is outside the influence of the methodology. Indeed, it may make more "sense" to associate the arrival time with the server object than with top-level model – especially in light of the association of end service time with the server object. In defining the Conical Methodology, Nance adopts the view that *over-constraining* the model development process potentially more deleterious within the context of the simulation life cycle than providing too much freedom to the modeler. A

[2]This example does not detail the important contribution of the Conical Methodology in terms of generating model documentation and identifying model definitions, objectives and assumptions. In deference to brevity, we only illustrate the CM provisions for object definition here.

modeling methodology could provide a more comprehensive set of rules for conceptualizing a system. However, systems exist which confound the constraints of any methodology. And the "work-around" required in a highly constrained methodology often results in a very confusing, and unnatural, model.

Nance views the methodology as but one piece – albeit a piece of primary importance – in a larger puzzle. Many issues that contribute to the development of "meaningful" models necessarily fall within the domain of the simulation model specification and documentation languages (SMSDLs, see Chapter 3) utilized within the simulation support environment. These issues can also be specific to a particular application domain or target implementation. Thus, the CM purposefully delineates a set of principles in very broad terms. To go further would risk defining a rigid approach that is unyielding to new techniques and ever-changing objectives.

5.1.3.2 Relationship between definitions and objectives

Also worthy of note in the example of Table 5.1 is the relationship of the model definition to the model objectives. The model defined in the figure could potentially satisfy most questions of interest, such as the utilization of the server, mean time in service, and mean time in the queue. But could the total time in the system of the third customer be reported? The model definition alone does not provide an answer. Whether or not model attributes must be *explicitly* defined to facilitate the gathering and reporting of statistical information, is appropriately relegated to the domain of the SMSDL. The methodology itself, permits either approach.

5.1.4 Model specification phase

The CM advocates a bottom-up specification process. A modeler starts at the leaves of the model decomposition tree and describes what effect attributes of one object, by their value changes, have on attributes of other model objects – thereby describing model behavior. During the model specification phase, a modeler identifies the *dynamic* aspects of a model.

The methodology enunciates the need for a simulation model specification and documentation language but does not prescribe its form. The CM stipulates that the SMSDL

should:

1. Exhibit independence of the specification from implementational constraints of simulation programming languages.
2. Allow expression of static and dynamic model properties.
3. Facilitate model validation and verification.
4. Produce documentation as a by-product.

A specification language fulfilling these requirements is described in Section 5.2.

In the M/M/1 example, the partial specification of the attribute *status* of the object `server` may take the form: "*status* of `server` equals *idle* when *end_of_service* is true and *queue_size* is zero." This partial specification details the state change of the object `server` by indicating how one of its status transitional indicative attributes, *status*, changes value from *busy* to *idle*. Barger [25] observes that status transitional indicative attributes may provide the key to model specification under the Conical Methodology; Page [182, p. 42] echoes this assertion.

5.2 The Condition Specification

In his dissertation, Overstreet defines a formalism for simulation model specification in which the description of model behavior has several useful and desirable properties [178, p. 40]:

1. The formalism is independent of traditional simulation world views.
2. A specification can be analyzed to identify natural components that measure complexity and identify potential problems with the specification.
3. A specification can be transformed to produce additional representations that conform to traditional simulation world views.
4. Some aspects of a model can be left unspecified without hindering the analyses and transformations identified above.
5. A model is defined in terms that do not prescribe any particular implementation techniques, such as the time flow mechanism.

The goal of this formalism, the Condition Specification (CS), is to provide a world-view-independent model representation that is expressive enough to represent any model and

concise enough to facilitate automated diagnosis of the model representation. An important contribution of the CS in this regard, is the precise and explicit delineation of time and state within a model representation. Thus, given a CS, all model dynamics are easily identifiable as time-based, state-based or a mixture of the two. In light of the objectives for the CS development, when the requirements for model diagnosis conflict with flexibility in model description and syntax, Overstreet favors model diagnosis. As a result, the CS is not generally intended to function as a language with which the modeler *directly* works when constructing a model – although its syntax is no more constraining than a typical simulation programming language. Several efforts have addressed techniques for extracting a CS from a modeler via dialog-driven model generators [25, 96, 182]. In these approaches, the model generator provides a buffer between the modeler and the low-level syntax of the CS. Still, as indicated in Chapter 3, the precise nature of the conceptual framework for the model generator in the SMDE is an unresolved issue [22].

5.2.1 Modeling concepts

Overstreet's development focuses on discrete event simulation modeling. For purposes of discussion he considers a *simulation model* to be a model that uses the technique of progressing through a series of changes in a time ordered fashion [178, p. 45]. The representation of time (or some indexing attribute used as a surrogate) is considered fundamental to the simulation *technique.* In essence, the term simulation refers to a technique; a simulation model is a model which employs the simulation technique. A simulation model is defined as a *discrete event model* if all object attributes, other than system time, are represented as changing value only a countable number of times during any simulation run, under the assumption that the termination condition is met eventually [178, p. 51].

Overstreet defines a *simulation run* as the act of using a simulation model to provide data about the behavior of the model, whereas a collection of simulation runs designed to generate a set of data about the model behavior is considered a *simulation experiment* [178, p. 46].

Fundamental to Overstreet's approach is the characterization of: (1) a simulation model specification and (2) a simulation model implementation.

5.2.1.1 Model specification

A *model specification* (MS) is a quintuple: $\langle \Phi, \Omega, \Gamma, \tau, \Theta \rangle$ where:

Φ is the *input specification.* The input specification provides a description of the information the model receives from its environment.

Ω is the *output specification.* The output specification provides a description of the information the environment receives from the model.[3] Attributes used in the output specification serve two functions:

1. If the model is part of a larger model, they provide information needed to coordinate model components.
2. Reporting of model behavior (a) to support the model objective(s), and (b) to support model validation. Attributes doing the former may affect model behavior, attributes accomplishing the latter do not.

Γ is the *object definition set.*[4] An object definition is an ordered pair, $\langle O, A(O) \rangle$, where O is the object and $A(O)$ is the object's *attribute set.* During a simulation run, several *instances* of the same object "type" may exist. However they are at all times distinguishable by the value of at least one of their attributes.[5]

A *model attribute set,* $A(M,t)$ is the union of all object attribute sets for a model M that exists at system time t. This set is not time invariant. It is based not only on a particular simulation run for the model, but for a point in time for that run. (Note, $A(O)$ is time invariant for the lifetime of O.)

The *state of an object,* $S(O,t)$ at system time t for and object O is defined by the values of all its attributes. Likewise, the *state of the model,* $S(M,t)$ is defined by the values of the attributes in $A(M,t)$. A change in the value of an attribute constitutes a *state change* both in the model and the object with which the attribute is associated.

A model attribute set cannot be assumed to provide a basis for a set of state variables [178, p. 52]:

> A set of variables for a system form a *state set* if the set, together with future system inputs, contain enough information to completely determine system behavior.

In order to establish a set of state variables, the model attribute set must be augmented with "system variables" such as those required to implement scheduling statements, list management, and so on.

[3] The input specification and the output specification can be combined to form a boundary specification. Either way, the communication requirements between a model and its environment must be completely defined.

[4] Overstreet assumes an object-based view when specifying a model. As noted in Chapter 2, while the identification of objects is not *essential* to model specification, the object-based perspective is highly expedient. Nonetheless, attributes (or variables) *must* be defined in any model specification.

[5] Overstreet [178, p. 49] notes that his teatment of object specification is abbreviated. For instance, no mechanism for considering "sets" of objects is defined.

τ is the *indexing attribute.* Commonly this attribute is referred to as *system time.* While not mandatory, system time is usually one of the model inputs and if so, the model does not describe how it changes value. The indexing attribute, τ, provides a partial ordering of the changes that occur within the model during any simulation run.

Θ is the *transition function.* The transition function for a simulation model specification contains each of the following:

1. An *initial state* for the model. The initial state defines values for all attributes of objects that exist at initiation (model "start up") including an initial value for system time. It must also include the scheduling of at least one determined event.
2. A *termination condition.*
3. A definition of the dynamic behavior of the model, describing the effect each model component has on other components, the model response to inputs, and how outputs are generated. The nature of this specification depends on the language used. Any form may be used as long as it *unambiguously* defines model behavior.

The MS describes how a model behaves over time, but the MS itself is time invariant.

5.2.1.2 Model implementation

Let $A(M, t)$ be the model attribute set for a model specification M at time t. A model specification is a *model implementation* if,

1. For any value of system time t, $A(M, t)$ contains a set of state variables.
2. The transition function describes all value changes of those attributes.

Thus, if "system variables" have been added to the object specification set so that $A(M, t)$ will always contain a state set, then the transition description also contains a complete description of how these additional attributes change value.

Since $A(M, t)$ typically does not contain a set of state variables, a primary function of a simulation programming language (SPL) is to augment the attributes of the model specification as necessary to create a state set. The SPL must also augment the transition function as necessary to accommodate the additional attributes. Thus, the nature of the implementation of a simulation model varies according to the representational mechanism.

A model implementation provides the basis for a *model execution* – which is the instantiation of the actions described by the model implementation on some suitable device, typically a digital computer.

5.2.2 Condition Specification components

A Condition Specification of a model consists of two basic elements: a description of the communication interface for the model and a specification of model dynamics [178, p. 86]. The specification of model dynamics can be further divided into an object specification and a transition specification. The CS also identifies a report specification designed to provide details about statistical reporting of simulation results. These four components of the CS are briefly outlined in this section. Some of the CS provisions for model analysis are detailed in Section 5.2.3.

5.2.2.1 System interface specification

The system interface specification identifies input and output attributes by name, data type and communication type (input or output). Overstreet assumes that the communication interface description can be derived from the internal dynamics of the model and can be system generated. Any CS must have at least one output attribute [179].

5.2.2.2 Object specification

The object specification contains a list of all model objects and their attributes. The CS enforces typing for each attribute similar to those types used in Pascal: integer, real, Boolean, or list values (enumerated typing). An additional type, time-based signal, is provided which enables the *scheduling* of attribute value changes, thus providing the means to relate simulation time to model state.

5.2.2.3 Transition specification

A transition specification consists of a set of ordered pairs called *condition-action pairs.* Each pair includes a condition and an associated action. A *condition* is a Boolean expression composed of model attributes and the CS sequencing primitives, WHEN ALARM and AFTER ALARM. Model *actions* come in five classes: (1) a value change description, (2) a time sequencing action, (3) object generation (or destruction), (4) environment communication (input or output), or (5) a simulation run termination statement. The transition specification can be augmented by a list of functions (function specification) utilized by

a modeler to simplify the representation of model behavior, although Overstreet does not prescribe a form for the specification of functions.

Condition-action pairs (CAPs) with equivalent conditions are brought together to form *action clusters.* Action clusters (ACs) represent all actions which are to be taken in a model whenever the associated condition is true.

Besides WHEN ALARM and AFTER ALARM, the CS provides several other primitives: SET ALARM, and CANCEL which manipulate the values of attributes typed as time-based signals, CREATE and DESTROY which provide instance manipulation for "temporary" objects, and INPUT and OUTPUT which provide communication with the model environment. Two conditions appear in every CS: *initialization* and *termination.* Initialization is true only at the start of a model instantiation (before the first change in value of system time). The expression for termination is model dependent and may be time-based, state-based, or a combination of time- and state-based.

5.2.2.4 Report specification

The syntax for report generation is undefined. Overstreet separates the report specification from the Condition Specification noting that this is not mandatory, but often desirable since typically many "computations" are required to gather and report statistics that in-and-of-themselves do not prescribe model behavior [178].

5.2.2.5 CS syntax and example

The syntax for the CS primitives is given in Table 5.2. Table 5.3 and Figures 5.2 through 5.4 contain a CS description of an M/M/1 queueing model.

5.2.3 Model analysis in the Condition Specification

A key issue for model analysis is the notion of *model specification equivalence.* Overstreet [178] offers definitions for model specification equivalence, noting that what is intuitively easy to understand is somewhat difficult to define mathematically. Intuitively, we accept that two model specifications are equivalent if and only if they can be used interchangeably. Certainly two model specifications can be used interchangeably if they produce identical output when presented with identical input. But two model specifications may also

Table 5.2: Condition Specification Syntax.

Name	*Syntax*	*Function*
Value Change Description	*<objectName>.attribute := newValueExpression*	Assign attribute values.
Set Alarm	SET ALARM(*alarmName, alarmTime <, argList>*)	Schedule an alarm.
When Alarm	WHEN ALARM(*alarmName*)	Time sequencing condition.
After Alarm	AFTER ALARM(*alarmName & boolExpr <, argList>*)	Time sequencing condition.
Cancel	CANCEL(*alarmName <, alarmId>*)	Cancel previously scheduled alarm.
Create	CREATE(*objectName<[instanceId]>*)	Create new model object.
Destroy	DESTROY(*objectName<[instanceId]>*)	Eliminate a model object.
Input	INPUT(*attribList*)	Receive input from model environment.
Output	OUTPUT(*attribList*)	Produce output to model environment.
Stop	STOP	Terminate simulation run.

Input attributes:

arrival_mean	- positive real
service_mean	- positive real
max_served	- positive integer

Output attribute:

server utilization	- positive real

Figure 5.2: M/M/1 System Interface Specification.

Table 5.3: M/M/1 Object Specification.

Object	*Attribute*	*Type*	*Range*
`Environment`	*arrival_mean*	positive real	
	service_mean	positive real	
	system_time	real	
	arrival	time-based signal	
`server`	*server_status*	ennumerated	(idle, busy)
	queue_size	nonnegative integer	
	num_served	nonnegative integer	
	max_served	nonnegative integer	
	end_of_service	time-based signal	

{*Initialization*}
initialization:
    INPUT(arrival_mean, service_mean, max_served)
    CREATE(server)
    queue_size := 0
    server_status := idle
    num_served := 0
    SET ALARM(arrival, 0)

{*Arrival* }
WHEN ALARM(arrival):
    queue_size := queue_size + 1
    SET ALARM(arrival, negexp(arrival_mean))

{*Begin Service*}
queue_size $>$ 0 and server_status = idle:
    queue_size := queue_size - 1
    server_status := busy
    SET ALARM(end_of_service, negexp(service_mean))

{*End Service*}
WHEN ALARM(end_of_service):
    server_status := idle
    num_served := num_served + 1

{*Termination*}
num_served $\geq$ max_served:
    STOP
    PRINT REPORT

Figure 5.3: M/M/1 Transition Specification.

Part I

```
whenever server_status changes
    Report(system_time, server_status)

at start of simulation
    Report(system_time, server_status)

at end of simulation
    Report(system_time, server_status)
```

Part II

```
program compute_server_utilization

    var   former_time      : real
          server_status    : {busy, idle}
          system_time      : real;
          total_busy_time  : real

    total_busy_time := 0.0
    read(system_time, server_status)
    former_time := system_time

    while not eof do
          read(system_time, server_status)
          if server_status = busy then
                total_busy_time := total_busy_time + (system_time - former_time)
          former_time := system_time
    end while

    write("server utilization: ",total_busy_time / system_time)

end program
```

Figure 5.4: M/M/1 Report Specification.

be used interchangeably if both satisfy the model objectives – even if their external behaviors differ. Equivalence under model objectives is an extremely difficult thing to establish; while one model may "do more" than another, if both accomplish the study objectives then the two may be used interchangeably. This is an issue of significance, in that, for reasons of enhanced software quality (lower maintenance costs, etc.) we desire models that *exactly* solve our problems – although we want these models to be readily extensible should the problems we wish to solve using the model change in some way. This "general" problem of model specification equivalence is obviously NP-complete [178, p. 269]. Overstreet's examination, however, focuses on the (slightly more tractable) issue of specification transformations as they affect specification equivalence.

Definitions for specification equivalence can have either an analytic or statistical basis. Using a statistical approach, a probability statement with the equivalence of two (or more) specifications is generated based on the output of implementations of each. Alternatively, analytic methods can be used to determine if different specifications imply "equivalent" model actions under "equivalent" circumstances [178, p. 117].

Two types of equivalence are identified in [178]:

Structural equivalence. Two model specifications are structurally equivalent with respect to a set of model attributes if (1) the condition sets are equivalent with respect to those attributes, and (2) identical model actions (if stochastic, variates must be from the same distribution) affecting the set of model attributes are specified for corresponding conditions.

External equivalence. Two model specifications are externally equivalent with respect to a set of model attributes if they specify identical output for those attributes when provided identical input.

5.2.3.1 Condition Specification model decompositions

For any given model, the set of condition-action pairs may be very large, and although the CS is designed to be a form for automated model diagnosis, many "interesting" questions cannot be automatically answered. Thus, the CS must provide forms which are accessible – in some sense – to the human analyst.

The most obvious way of organizing CAPs is by grouping them into action clusters as described in the previous section. Still, an AC-oriented CS may have on the order of hundreds or thousands of ACs – too many independent pieces to deal with effectively.

In addition to the action cluster aggregation, Overstreet defines several "decompositions" which provide varying levels of model description by couching the same information – the relationship among model conditions and model actions – in a variety of ways. These decompositions are briefly discussed here. The following taxonomic description of attributes within CAPs provides the basis for much of the subsequent discussion [178, p. 120]:

Control attributes. Attributes that provide the information needed to determine when the action should occur. These are the attributes that occur in the condition expression. All CAPs (except those used for model initialization) have control attributes.

Input attributes. Attributes that provide the data to be used to set new values for output attributes or schedule future actions. Not all CAPs have input attributes.

Output attributes. Attributes that change value due to the action. Not all CAPs have output attributes. (Those that have none cannot influence subsequent model behavior.)

Object decomposition. One approach to defining the behavior of a model is to define individually the behavior of each object "class" in the model. Assuming a CS as a basis, the attributes in each CAP can be used to associate the CAP with one or more model objects. Thus, the CAPs associated with an object describe the object's behavior. This object-based description may be realized in two ways: (1) all model actions affecting an object (passive object), or (2) all model actions performed by the object (active object). Overstreet's presentation adopts the latter approach.

An object specification may be constructed by identifying for every model object, O, two types of CAPs: all CAPs with a control attribute of O, and all initialization CAPs with an output attribute of O. This structure has the advantage that it decomposes a model specification into a collection of smaller, more manageable units, but has the disadvantage that much of the information is redundant (the same CAPs appearing in many object specifications), and any notion of sequencing in model actions is difficult to detect.

Cutset decomposition. Another means of decomposing a model specification is in the identification of "minimally connected" submodels, where minimally connected refers to some measure of the interactions between groups of action clusters. Since action cluster interaction occurs through the use of model attributes, this type of decomposition involves developing an *action cluster interaction graph* which is a directed graph in which the action clusters in the model are the nodes and the attributes that "connect" them are the arcs.

The model may then be decomposed into two (or more) minimally interactive submodels by partitioning the graph into nonempty subgraphs with minimal arcs connecting them. This technique, however, is sensitive only to the *number* of potential links among action clusters and not to the possible *frequency* of communications. Further details of the graph representations of a CS are given in Section 5.2.3.2.

Traditional world-view decompositions. Since the CS captures explicit descriptions of all model actions as having a time-base, a state-base or both, and associates attributes with model objects, a CS may be translated into representations adopting the *locality* [178, p. 164] of traditional world views. To produce an *event scheduling* orientation of a CS, the CAPs are organized around WHEN ALARMS – by generating a set of subgraphs from the *action cluster incidence graph* (ACIG) representation (defined subsequently) which contain a single time-based action cluster and all the state-based action clusters reachable from it without passing through another time-based action cluster – thus describing a model exhibiting a *locality of time.* Similarly, an *activity scanning* approach may be captured by creating subgraphs oriented around the state-based ACs in an ACIG (providing a *locality of state*), and a *process interaction* orientation may be generated by creating subgraphs of the ACIG that are actions as they relate to objects within the specification (*locality of object*). Overstreet demonstrates that any CS may be automatically translated into an equivalent event scheduling, activity scanning, or process interaction model description, thus exhibiting the independence of the CS from these traditional conceptual frameworks [178].

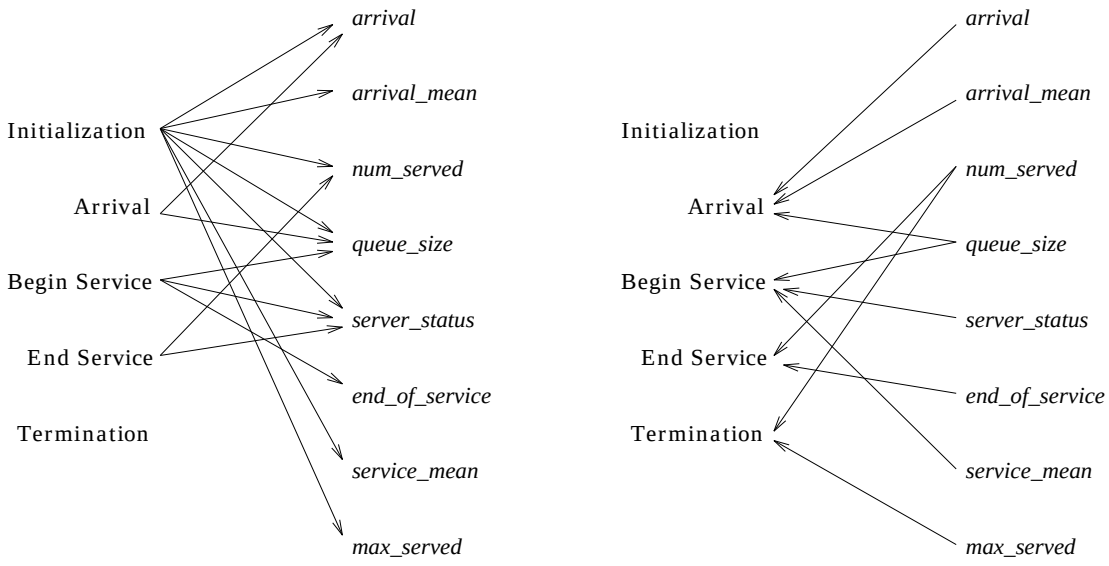
5.2.3.2 Graph-based model diagnosis

Much of the analysis provided by the CS is defined on graph representations of the model specification (and the matrix equivalents of the graphs). The most useful graph forms are described below. For further details see [163, 164, 194, 238]. A summary of the analyses defined for these representations is given in Table 5.4 (adapted from [164]).

Action cluster attribute graph. We define the *action cluster-attribute graph* (ACAG) as follows. Given a Condition Specification with k time-based signals, m other attributes, and n action clusters, then G, a directed graph with $k + m + n$ nodes is constructed as

Table 5.4: Summary of Diagnostic Assistance in the Condition Specification.

Category of Diagnostic Assistance	*Properties, Measures, or Techniques Applied to the Condition Specification*	*Basis for Diagnosis*
Analytical: Determination of the existence of a property of a model representation.	*Attribute Utilization*: No attribute is defined that does not effect the value of another unless it serves a statistical (reporting) function.	ACAG
	Attribute Initialization: All requirements for initial value assignment to attributes are met.	ACAG
	Action Cluster Completeness: Required state changes within an action cluster are possible.	ACAG
	Attribute Consistency: Attribute typing during model definition is consistent with attribute usage in model specification.	ACAG
	Connectedness: No action cluster is isolated.	ACIG
	Accessibility: Only the initialization action cluster is unaffected by other action clusters.	ACIG
	Out-complete: Only the termination action action cluster exerts no influence on other action clusters.	ACIG
	Revision Consistency: Refinements of a model specification are consistent with the previous version.	ACIG
Comparative: Measures of differences among multiple model representations.	*Attribute Cohesion*: The degree to which attribute values are mutually influenced.	AIM
	Action Cluster Cohesion: The degree to which action clusters are mutually influenced.	ACIM
	Complexity: A relative measure for the comparison of a CS to reveal differences in specification (clarity, maintainability, etc.) or implementation (run-time) criteria.	ACIG
Informative: Characteristics extracted or derived from model representations	*Attribute Classification*: Identification of the function of each attribute (e.g. input, output, control, etc.).	ACAG
	Precedence Structure: Recognition of sequential relationships among action clusters.	ACIG
	Decomposition: Depiction of coordinate or subordinate relationships among components of a CS.	ACIG



(a) influence of action clusters on attributes (b) influence of attributes on action clusters

Figure 5.5: The Action Cluster Attribute Graph for the M/M/1 Model.

follows:[6]

> G has a directed, labeled edge from node i to node j if
> (1) node i is a control or input attribute for node j, an AC,
> (2) node j is an output attribute for node i, an AC.

The ACAG represents the interactions between action clusters and attributes in the CS; specifically, the potential for actions of one AC to change the value of an attribute and the influence of an attribute on the execution of an AC are shown in the ACAG. The ACAG for the M/M/1 specification given in the previous section is illustrated in Figure 5.5.

Since the ACAG is a bipartite graph, it may be represented using two Boolean ma-

[6]Overstreet [178] differentiates interactions in the ACAG. He depicts the interactions among ACs and time-based signals (as output attributes) with dashed edges, to denote a time-delayed interaction. However, the fact that this distinction is not made in the matrix forms for the ACAG raises questions regarding its value. The characterization of time-delayed interactions in an ACAG is omitted here. Interactions between an AC and its output attributes are considered instantaneous irrespective of attribute type. Time-delayed interactions are important to recognize, and *do occur,* but only *between* action clusters (see ACIG).

trices: the *attribute-action cluster matrix* (AACM) and the *action cluster-attribute matrix* (ACAM). For a CS with m action clusters $(ac_1, ac_2, ..., ac_m)$, and n attributes $(a_1, a_2, ..., a_n)$ The AACM is an n by m Boolean matrix in which:

$$b(i,j) = \begin{array}{ll} 1 & \text{if edge}(a_i, ac_j) \text{ exists in the ACAG} \\ 0 & \text{otherwise} \end{array}$$

And the ACAM is an m by n Boolean matrix where:

$$b(i,j) = \begin{array}{ll} 1 & \text{if edge}(ac_i, a_j) \text{ exists in the ACAG} \\ 0 & \text{otherwise} \end{array}$$

From these two matrices, two other matrices may be formed, the *attribute interaction matrix* (AIM),

$$\text{AIM} = \text{AACM} \times \text{ACAM}$$

and the *action cluster interaction matrix* (ACIM),

$$\text{ACIM} = \text{ACAM} \times \text{AACM}$$

Action cluster incidence graph. An *action cluster incidence graph* (ACIG) is a directed graph in which each node corresponds to an AC in the CS. If, during the course of any given implementation of the CS modeled, the actions in one action cluster, AC_i, cause the condition for another action cluster, AC_j, to become true (at either the same simulation time at which AC_i is executed or at some future time by setting an alarm) then there is a directed arc from the node representing AC_i to AC_j. By convention this arc is depicted as a dotted line if AC_i sets an alarm that is used in the condition for AC_j, otherwise the arc is depicted as a solid line. If the condition on AC_j is a WHEN ALARM then AC_j is referred to as a *time-based successor* of AC_i. If the condition on AC_j is an AFTER ALARM then AC_j is referred to as a *mixed successor* of AC_i. Otherwise AC_j is referred to as a *state-based successor* of AC_i.

Formally, one may construct an ACIG for a CS consisting of a set of ACs $ac_1, ac_2, \ldots, ac_n$ according to the algorithm in Figure 5.6. Note that this algorithm generates an ACIG that completely depicts the potential sphere of influence of each AC in the specification, that is when an output attribute of an action cluster is a (state-based or time-based) control

For each $1 \leq i \leq n$, let node i represent ac_i
For each ac_i, partition the attributes into 3 sets:
    $T_i = \{$control attributes that are time-based signals$\}$
    $C_i = \{$all other control attributes$\}$
    $O_i = \{$output attributes$\}$
For each $1 \leq i \leq n$,
    For each $1 \leq j \leq n$,
        Construct a solid edge from node i to node j if $O_i \cap C_j \neq \emptyset$
        Construct a dashed edge from node i to node j if $O_i \cap T_j \neq \emptyset$

Figure 5.6: Algorithm for Constructing an Action Cluster Incidence Graph.

attribute of another (not necessarily distinct) action cluster. However, in the general case, many of these "interactions" may never occur. For instance if AC_i has an output attribute that is involved in the Boolean expression on the condition, denoted p, for AC_j, then there is a solid arc in the ACIG from AC_i to AC_j. However, if the *postcondition* for AC_i (the values of model attributes following the "execution" of AC_i) implies $\neg p$, then the execution of AC_i can never cause the execution of AC_j and the arc can safely be removed from the graph. Overstreet shows that no algorithm can be described to completely simplify an ACIG [178, p. 271]. However, Puthoff [194] describes an expert system approach to this type of precondition/postcondition analysis for ACIG simplification, noting near-optimal results for the model specifications considered. The simplified ACIG for the M/M/1 model is given in Figure 5.7.

5.2.4 Theoretical limits of model analysis

The following are brief descriptions of some important results from [178, Ch. 8]. We include them here due to their relevance to subsequent development (Chapters 6 through 9). For complete details refer to [178].

Definitions.

- Two sequences of model actions in two implementations of a model specification are *equivalent* if execution of either at a particular instant in an instantiation will produce

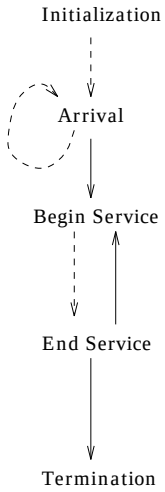


Figure 5.7: The Simplified Action Cluster Incidence Graph for the M/M/1 Model.

identical results.

- Two action sequences, A and B, are *order independent* if the execution of action sequence A followed immediately by the execution of action sequence B is equivalent to the execution of action sequence B followed immediately by the execution of action sequence A.
- A CS is *trivial* if the termination condition must be met at the same instant as the initialization of the model.

Properties.

- A CS is *finite* if in any instantiation of it, when given valid input data, only a finite number of action instances occur before the termination condition is met.
- If any actions of a CS are subject to stochastic influences, then the executions of two implementations need not produce identical output. But if two implementations of a CS are possible in which the output of their executions would differ, even if the stochastic behaviors of the implementations were identical and the executions used identical input, then the CS is *ambiguous.*
- A CS is *complete* if, at each instant in any instantiation of it, either the termination condition is met or at least one additional action instance is pending.
- A CS is *accessible* if each action prescribed in the specification can occur for some instantiation of the CS.

- A CS is *connected* if the completely simplified ACIG with the initialization node removed is connected.

Results.

- Any finite model specification is complete.
- Any Turing Machine specification can be transformed into a Condition Specification.
- No algorithm exists to determine if a CS is finite.
- No algorithm exists to determine if two model actions are order independent.
- No algorithm exists to determine if a CS is ambiguous.

The actions of two contingent action clusters should be order independent if their conditions can be simultaneously true in any instantiation of the CS. If this property of order independence is not satisfied, the CS is said to have the property of *state ambiguity.*

If two determined action clusters can be scheduled to occur at the same instant in some simulation run, then either they should be order independent or sufficient ordering information must be provided in the CS to establish priority. If this is not true, the CS is said to have the property of *time ambiguity.*

- No algorithm exists to determine if a CS has the properties of state or time ambiguity.
- No algorithm exists to determine if a CS is complete.
- No algorithm exists to determine if a CS is accessible.
- Connectivity implies accessibility.
- Let X be a CS containing only the accessible action clusters of a CS Y. X is equivalent to Y with respect to all attributes of X.
- For any finite CS, each contingent action instance (other than initialization) is caused, directly or indirectly, either by initialization or by a determined action instance coincident in time with the contingent action instance.
- Any nontrivial finite CS contains at least one attribute that is a time-based signal.
- No algorithm exists to determine if two Condition Specifications are externally equivalent.
- No algorithm exists to determine if two conditions can be simultaneously true in any simulation run based on the CS.
- No algorithm exists to transform a CAP-based CS into an AC-based CS with a minimum number of ACs.

Table 5.5: Evaluation of the CM/CS Approach as a Next-Generation Modeling Framework. Level of Support is given as: 1 - Not Recognized; 2 - Recognized, but Not Demonstrated; 3 - Demonstrated; 4 - Conclusively Demonstrated.

Requirement	*Level of Support*
Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.	3
Permits model description to range from very high to very low level.	2
Permits model fidelity to range from very high to very low level.	3
Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.	2
Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.	3
Exhibits broad applicability.	3
Model representation is independent of implementing language and architecture.	3
Encourages automation and defines environment support.	3
Support provided for a broad array of model verification and validation techniques.	4
Facilitates component management and experiment design.	3

- No algorithm exists to generate a completely simplified ACIG.
- No algorithm exists to determine the actual successors of an action cluster in a CS.
- No algorithm exists to determine if a CS is connected.
- Structural equivalence implies external equivalence.

5.3 Evaluation

We denote the model development approach given by the Conical Methodology in conjunction with the Condition Specification as its model specification form, as the CM/CS approach. The CM/CS approach is evaluated with respect to the requirements for a next-generation modeling framework (identified in Chapter 3) in Table 5.5.

The CM/CS approach compares favorably with the approaches surveyed in Chapter 4. However, the CM/CS is still far from fully demonstrative of all the criteria. Much of the remainder of this research describes a *widening* of the CS *spectrum* in an effort to strengthen the CM/CS approach as a next-generation modeling framework.

Chapter 6

MODEL REPRESENTATION

In the interest of clearness, it appeared to me inevitable that I should repeat myself frequently, without paying the slightest attention to the elegance of the presentation.

Albert Einstein, *Relativity*

In Chapter 3, a philosophy of simulation model development is described and a model development abstraction consistent with this philosophy is proposed. The abstraction stipulates a hierarchy of representations managed by a single, coherent, underlying methodology. The argument is made that this abstraction may enable the realization of a next-generation modeling framework where emerging technologies and system-level requirements can be cost-effectively incorporated into the simulation life cycle. In this chapter, and those that succeed it, the feasibility of this argument is demonstrated utilizing Nance's Conical Methodology. The approach taken regarding model representation within the hierarchy is neither top-down nor bottom-up. Investigation regarding the nature of the highest-level form(s) has persisted within the context of the SMDE research effort since its inception, and continues to occupy a prominent position (see [66]). The facilities and capabilities of general purpose languages (GPLs) and simulation programming languages (SPLs) are also well-studied. The approach taken here may best be described as inside-out. Overstreet's Condition Specification is assessed as most suited to occupy a mid-level position within the hierarchy indicated by the framework – specifically as a form for model analysis. Its relationship to both the envisaged higher-level and lower-level forms is addressed in Chapters 6 through 9. By undertaking this investigation in an inside-out manner, the goal is to facilitate a proper recognition of, and reconciliation between, the requirements of the

highest-level forms (as dictated primarily by the theories of modeling methodology) and those of the lowest-level forms (as dictated primarily by system-level constraints).

6.1 Preface: Evaluating the Condition Specification

Overstreet never intends the CS as a modeler-level language. The program-like syntax demands *at least* some buffering mechanism between the CS and a modeler. Similarly, the statistical and reporting capabilities of the CS are not completely defined; nor are mechanisms for list processing and time-flow described. These facilities, required for model implementation, are correctly viewed as too low-level for a *specification* language. Accordingly, the CS is most suited to a mid-level position in the transformational hierarchy, primarily serving as a target form for automated model diagnosis. This being established, several issues must be addressed.

1. If a narrow-spectrum approach is adopted, a mid-level representation must exhibit congruence with both the higher-level and lower-level representations. What can be established regarding the CS in this area?
2. Can the CS be adapted to provide wide-spectrum support?
3. What is the nature of the highest-level (modeler generated) representation(s)?
4. What is the nature of the underlying target implementations?
5. Can the CS be adapted – in either a narrow-spectrum or wide-spectrum approach – without sacrificing the analysis provided by the language?

In the following sections, the CS is evaluated through its application to a set of examples. The language evaluation is such that the conclusions are applicable in the context of either a narrow-spectrum or wide-spectrum approach, although the primary focus of the remainder of this research is on widening the spectrum of the CS. The narrative is structured as a tutorial, explicating the model development process under the Conical Methodology without an explicit description of the highest-level representation form(s). For each example, observations are made regarding both model definition and model specification. This enables some evaluation and discussion of the Conical Methodology, in addition to that involving the CS. This seems appropriate given the observation from Chapter 4 that the relationship between methodology and representation is a symbiotic one. Relevant adaptations and suggestions regarding the CS accompany the examples.

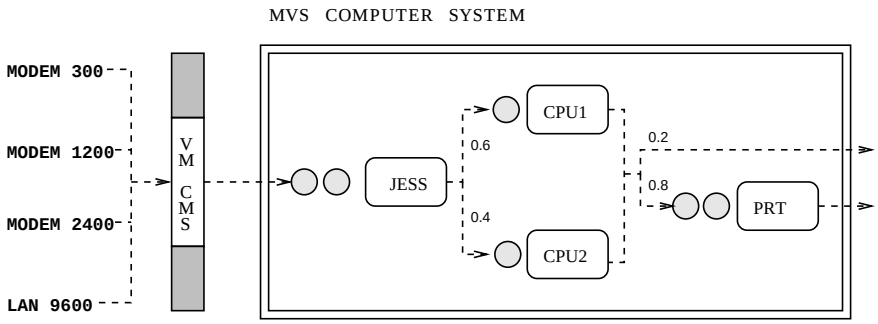


Figure 6.1: MVS System.

Table 6.1: MVS Interarrival Times.

Type of User	*Interarrival Times*	*Mean*
Modem 300 User	Exponential	3200 Seconds
Modem 1200 User	Exponential	640 Seconds
Modem 2400 User	Exponential	1600 Seconds
LAN 9600 User	Exponential	266.67 Seconds

6.2 Example: Multiple Virtual Storage Model

Balci [19] presents an example involving a multiple virtual storage (MVS) batch computer system. The MVS operates with two central processing units (CPUs). Users submit batch programs to the MVS by using the *submit* command on an interactive virtual memory (VM) computer system running under the CMS operating system. As shown in Figure 6.1, the users of MVS via VM/CMS are classified into four categories: (1) users dialed in by using a modem with 300 baud rate, (2) users dialed in by using a modem with 1200 baud rate, (3) users dialed in by using a modem with 2400 baud rate, and (4) users connected to the local area network (LAN) with 9600 baud rate. Each user develops the batch program on the VM/CMS computer system and submits it to the MVS for processing. Based on collected data, assume that the interarrival times of batch programs to the MVS with respect to each user type are determined to have an exponential probability distribution with corresponding means as shown in Table 6.1.

A batch program submitted first goes to the job entry subsystem (JES) of MVS. The

Table 6.2: MVS Processing Times.

Facility	*Processing Times*	*Mean*
JESS	Exponential	112 Seconds
CPU1	Exponential	226.67 Seconds
CPU2	Exponential	300 Seconds
PRT	Exponential	160 Seconds

JES scheduler (JESS) assigns the program to processor 1 (CPU1) with a probability of 0.6 or to processor 2 (CPU2) with a probability of 0.4. At the completion of program execution on a CPU, the output of the program is sent to the user's virtual reader on the VM/CMS with a probability of 0.2 or to the printer (PRT) with a probability of 0.8. Assume that all queues in the MVS system are first-come-first-served and each facility processes one program at a time. The probability distribution of the processing times for programs by each facility is given in Table 6.2.

Assuming that the simulation model reaches steady state after 3,000 programs, simulate the system for 15,000 programs in steady state and construct confidence intervals for the following performance measures (known values given in parentheses):

1. Utilization of the JESS ($\rho_{JESS} = 0.70$).
2. Utilization of CPU1 ($\rho_{CPU1} = 0.85$).
3. Utilization of CPU2 ($\rho_{CPU2} = 0.75$).
4. Utilization of the PRT ($\rho_{PRT} = 0.80$).
5. Average time spent by a batch program in the MVS computer system ($W = 2400$ seconds).
6. Average number of batch programs in the MVS computer system ($L = 15$).

6.2.1 MVS model definition

The model definition for the MVS under the CM is given in Table 6.3. A discussion of the derivation of the model is warranted. In defining the model, we attempt to portray a modeler whose expertise is in the application domain and *not* in any particular area of modeling or analysis or computer science (more about this later). The idea is to describe the system in a "natural" way, i.e. in a way that is as close as possible to the model of the

Table 6.3: CM Object Definition for MVS Model.

Object	*Attribute*	*Type*	*Range*
MVS	*system_time*	temporal transitional indicative	nonneg real
	num_served	status transitional indicative	0..18000
	max_served	permanent indicative	18000
User	*type*	permanent indicative	(m300,m1200,m2400,l9600)
	arrival	temporal transitional indicative	nonneg real
	arrival_mean	permanent indicative	(266.67,640,1600,3200)
Job	*enter_time*	permanent indicative	nonneg real
Jess	*end_service*	temporal transitional indicative	nonneg real
	status	status transitional indicative	(busy,idle)
	service_mean	permanent indicative	112
	cpu1_prob	permanent indicative	0.6
Cpu1	*end_service*	temporal transitional indicative	nonneg real
	status	status transitional indicative	(busy,idle)
	service_mean	permanent indicative	226.67
	prt_prob	permanent indicative	0.8
Cpu2	*end_service*	temporal transitional indicative	nonneg real
	status	status transitional indicative	(busy,idle)
	service_mean	permanent indicative	300
	prt_prob	permanent indicative	0.8
Prt	*end_service*	temporal transitional indicative	nonneg real
	status	status transitional indicative	(busy,idle)

Set	*Type*	*Member Type*	*Description*
JessQ	d-set	Job objects	provide FIFO queue capabilities
Cpu1Q	d-set	Job objects	provide FIFO queue capabilities
Cpu2Q	d-set	Job objects	provide FIFO queue capabilities
PrtQ	d-set	Job objects	provide FIFO queue capabilities

system that tends to naturally exist in the mind of the modeler. Where useful for clarity, the convention is adopted to set object names in `typewriter` font and attribute names in *italics.*

6.2.1.1 Objects

The first object is mandated by the methodology: the top-level object. We give it a name, `MVS` and associate the model indexing attribute with it. Attributes for number served and maximum number served are also defined.

Next, four user objects are described – one for each of the possible sources of jobs. This can be effected two ways in the methodology: by defining four separate objects, e.g. `m300User, m1200User,` etc., or by defining a single object, `User`, which has attributes indicating its type, arrival mean and time of next arrival. In this manner, the *instantiation,* as handled by the specification language, must assign the correct attribute values. These two approaches yield externally equivalent models (see Chapter 5). The latter approach is adopted here.

Since the user object is viewed as creating jobs which enter the system,[1] an object `Job` is defined and given an attribute *enter_time* (to represent the time in which the job entered the system). Realizing that a job, once created, will be sent to the JESS, the need is recognized for an object representing the JESS.

The object `Jess` is defined to have attributes representing its service mean and the time at which the next end-of-service occurs. Also defined are an attribute indicating its status and an attribute giving the probability with which a job leaving the JESS will travel to CPU1. This leads naturally to the definition of the object `Cpu1` and subsequently `Cpu2` and then `Prt`. However, at this point a recognition may be made that jobs routed to these "facilities" may need to be *stored* (in first-come-first-served order) for processing.

We elect to make use of the CM provisions for sets to represent the queues for each of the facilities. The sets are typed as d-sets, since set membership must be determined during execution. The members are identified as being job objects. The CM doesn't describe set

[1]Note, the derivation of the user and job objects to some extent hinges upon the modeler's perception of model dynamics. Specifically, the user is envisioned as creating jobs, according to a particular rate, that are sent to the JESS. This illustrates that model definition and model specification are not completely independent processes, even though they produce artifacts that may be considered independent.

implementation, i.e. no "default" attributes or operations are defined. The set is described as providing "FIFO queue capabilities." At this point in the model definition process, it may be sufficient to assume the attributes and operations are available to determine queue size, provide insertion and deletion, and so on.

An interesting observation is that the CM, unlike some simulation programming languages, e.g. SIMSCRIPT, doesn't provide "ownership" among objects. That is, in a SIMSCRIPT description, the Cpu object might be declared as owning a queue (or FIFO set). Access would be provided in a manner such as:

REMOVE FIRST Job FROM queue(Cpu)

as long as the context provides the identification of the Cpu. Under the CM (assuming use of the CS) the CPUs and queues, in a manner similar to the previously described definition of the user object, could be defined and specified three ways:

1. As independent objects, `Cpu1, Cpu2, Cpu1Q, Cpu2Q.`
2. As a single object with an *a priori* determined number of "instances," e.g. `Cpu[1..2], CpuQ[1..2].`
3. As a single object with an undetermined number of possible "instances."

Methods (1) and (2) provide a convenient means by which to exploit the relationship between a cpu and its queue. Method (3) provides the requisite information, but the access mechanism may be somewhat clumsy. In this case, each object requires an attribute (e.g. *id*) to uniquely identify it within the set. And the condition that gives the begin service for a cpu must be expressed in terms such as:

$$\text{not empty}(\texttt{CpuQ}) \text{ and } (\texttt{Cpu}.\mathit{status} = \text{idle}) \text{ and } (\texttt{Cpu}.\mathit{id} = \texttt{CpuQ}.\mathit{id})$$

Suitable, perhaps, to express behavior at a low level, but higher-level representations must permit more elegant descriptions.

6.2.1.2 Activity sequences

Since the definition provided by the CM is object-based it might lead naturally, for a given modeler, to an object-based (process) visualization of model behavior. In this context, the model is viewed very broadly as follows.

```
1. Schedule the "arrival" of the next job.
2. Wait for arrival time.
3. Create Job and record enter time.
4. Place Job in JessQ.
5. Return to 1.
```

Figure 6.2: Activity Sequence for User.

```
1. Whenever the JessQ is not empty and status of Jess is idle:
2.      Remove first Job in JessQ.
3.      Set status to busy.
4.      Wait for end-of-service.
5.      Determine route for Job.
6.      If route is to Cpu1, put Job in Cpu1Q.
7.      Else put job in Cpu2Q.
8.      Set status to idle.
9.      Return to 1.
```

Figure 6.3: Activity Sequence for Jess.

Four user objects are *instantiated* (one for each type: m300, m1200, m2400 and l9600). The appropriate arrival mean is assigned, and the user proceeds according to the activity sequence given in Figure 6.2. The behaviors of the JESS, the CPUs and the printer are given in Figures 6.3, 6.4 and 6.5 respectively.

Notice that, in this model, the job is depicted as having no "active" lifetime. Another, equally valid, model of this system could describe the job as an active object. Such an approach might define the lifetime of a job as given in Figure 6.6. Either definition may conform to a given modeler's "natural" view of the underlying system. The key methodological issue is the permission of either description in an unconstrained fashion. The Conical Methodology provides this.

```
1. Whenever the Cpu queue is not empty and status of Cpu is idle:
2.      Remove first Job in Cpu queue.
3.      Set status to busy.
4.      Wait for end-of-service.
5.      Determine route for job.
6.      If route is to Prt, put job in PrtQ.
7.      Else calculate total time in system for job.
8.      Set status to idle.
9.      Return to 1.
```

Figure 6.4: Activity Sequence for Cpu.

```
1. Whenever the PrtQ is not empty and status of Prt is idle:
2.      Remove first Job in PrtQ.
3.      Set status to busy.
4.      Wait for end-of-service.
5.      Calculate total time in system for Job.
6.      Delete Job.
7.      Set status to idle.
8.      Return to 1.
```

Figure 6.5: Activity Sequence for Printer.

```
1. Enter system.
2. Wait for Jess.
3. Use Jess.
4. Determine route from Jess.
5. If route is to Cpu1:
6.      Wait until Cpu1 is available.
7.      Use Cpu1.
8.      Determine route from Cpu1.
9. Else:
10.     Wait until Cpu2 is available.
11.     Use Cpu2.
12.     Determine route from Cpu2.
13. If route is to Prt:
14.     Wait until Prt is available.
15      Use Prt.
16. Record total time in system.
17. Exit system.
```

Figure 6.6: Alternate Approach: Activity Sequence for Job.

6.2.1.3 Flexibility in model representation

Of course, in the MVS model the need for all the objects defined in Table 6.3 is questionable. In fact, someone knowledgeable in queueing theory, or an SPL such as GPSS, could construct a program for this system with fewer objects and very few lines of code. This program would doubtless be totally comprehensible to the modeler, and could in all likelihood be explained to a decision maker, who may be a novice to many of these concepts. However, the model is constructed in this fashion to make an important point:

> *An evolving tenet of modeling methodology is that as systems being modeled grow more and more complex, the need will become ever greater to allow people with the domain knowledge to create the models.*

The reasoning behind this position is as follows. The current paradigm requires that a domain expert "communicate," often in an unstructured and ad hoc fashion, with a modeling expert, or expert tool user. For complex systems this leads to *many* levels of uncertainty. The modeler is never quite sure that he understands the domain and likewise the domain expert seldom has 100 percent faith in the produced model. This approach requires the extensive use of prototype models, which are successively refined in an attempt to remove these "gray areas." However, this may not always be the most cost-effective means of producing a model. The modeling effort typically does not cease with the first "production" form. Many models represent a large investment, and therefore have lengthy lifetimes, during which the model evolves considerably. Keeping a modeling consultant on contract for this potentially lengthy period is a costly proposition. Also, the potential exists that the original modeler may no longer be available subsequent to the original development; thus model maintenance means re-communicating the domain knowledge to a new modeler.

Hence, a belief is evolving that the methodology and environment should permit the *domain expert* to describe the model and, to as great an extent as possible, do so in his or her own terms. This seems the best way to foster the development of a *correct* model – a critical factor to the provision of decision support (see Chapter 3).

In summary, the modeling methodology must be *flexible.* It should provide the guidelines and constraints that foster time-proven techniques that encompass *good modeling* practice. But the flexibility *must* remain with the modeler to allow the description of novel systems. The CM achieves this very well.

6.2.1.4 Support for statistics gathering

The description of behavior given in the model lifetimes does not include the computations required to gather statistics, nor are all the necessary attributes defined to accomplish it. The question is, should they be? Consider these facts:

1. The CM stipulates that the objectives (in terms of the performance measures) be explicitly stated.
2. Existing SPLs like GPSS and SIMSCRIPT provide a great deal of statistical information "automatically," without requiring anything on the part of the programmer, except to ask for the information collected.

If the objectives are stated in terms of CM-defined objects and attributes then the statistical calculations, since these are mathematically well-defined, need not be required from the modeler when describing a model or its behavior.[2]

These issues primarily impact the representational forms. Note, however, that if this approach is adopted for the MVS model, the attribute *enter_time* for the object `Job` would not need to be defined. Simply stating the objective of calculating the mean time in the system for jobs would be sufficient. This leads to the production of an object seemingly having no attributes. Can the object be deleted? The methodology indicates yes, since an object is only defined in terms of its attributes (and their values). But, the object *does* in fact have attributes. The attributes are those required to facilitate statistics gathering and reporting, based on the stated model objectives, and one of these attributes must represent the time at which the object entered the system. These attributes could, in fact, be seen in some *augmented* object definition.

As illustrated previously with its handling of sets, the CM does not advocate any particular *implementation* of concepts. As long as the "things" being described have a well-defined meaning (and this can perhaps only be determined in the context of the representational forms and supporting environment), the CM should, and does, permit flexibility. Descriptions of model behavior should be permitted without stipulating, for instance, the implementation of set mechanisms. Similarly, it should be permissible to define an object and

[2]For analytical purposes, a representation that explicitly captures these definitions and computations may be desirable. But this can be automatically generated from the underlying model specification and the properly formulated description of model objectives.

not define *explicitly* any attributes for it – if the only interest in the object is a set of statistical observations regarding its behavior and no other attributes are needed to realize the behavior. The realization of statistical behavior could perhaps be determined by examining an *augmented* object definition and specification. If the object has no attributes in the augmented definition, then the object has no function in the model. Therefore, we adopt the view that the situation described above is acceptable, especially in light of the alternative: forcing the modeler to explicitly define and specify statistics gathering for *every* model developed. Since these things *can* be automated, in accordance with the automation-based paradigm that influences the CM, they *should* be automated.

6.2.2 MVS model specification

In this section, the Condition Specification is examined with regard to the MVS model defined in the previous section. The MVS transition specification resulting from this development is given in Appendix D.

6.2.2.1 Specification of sets in the CS

Through its provisions for set definition, the Conical Methodology provides a convenient means by which to utilize a common mechanism in simulation: the queue. A queue may be viewed as a set with some ordering properties that dictate the set insertion and deletion operations. The Condition Specification does not explicitly support the concept of sets. Sets used within the CM definition, however, *can* be described using the extant CS syntax. However, the encumbrance to the description is significant. An object that may belong to an ordered set (or queue), as in the case of the job object from the MVS example, must be given attributes that describe both its location and the time it entered that location. Selection of the first object in the queue could be accomplished by quantification over all existing jobs with a given location, e.g. "in waiting queue for Jess," and selecting the one with the smallest enter time. Since the CS is not envisioned as a modeler-level language, this places no undue inconvenience on the modeler in terms of the description of model behavior. The CS representations are envisaged as being automatically generated from higher forms. However, a couple of observations can be made at this point:

1. A high-level representation will likely provide convenient mechanism for appealing to sets (and queues).

Table 6.4: Set Operations for the Extended Condition Specification. Operations may be qualified with well-formed expressions of model attributes as well as keywords such as FIRST, LAST, ALL, and UNIQUE.

Name	*Call*	*Returns*	*Description*
Insert	INSERT(*object, set <, qualifier >*)	–	Insert object into set.
Remove	REMOVE(*set <, qualifier >*)	Object	Remove object from set.
Empty	EMPTY(*set*)	Boolean	True if set has no members.
Member	MEMBER(*object, set*)	Boolean	True if object in set.
Find	FIND(*set, qualifier*)	Set, Object	Find object or subset based on qualifier.

2. As noted previously, interesting model-based questions exist that cannot be answered automatically. For these instances, the CS may need to be viewed by an analyst.

These observations beg the question, should the concept of sets, and operations on sets, as provided by the CM, be added to the CS? If so, can sets be added without hampering the analytic capabilities of the CS? Another interesting question involves the specification of sets versus their implementation: can a model translator determine efficient mechanisms for implementing sets according to their usage? For example, a queue may be used at the highest levels of description when a counter or other simple variable is sufficient at the execution level. A modeler may choose to represent a set of failed machines (in the machine interference problem described subsequently) and choose a machine for repair by finding the first failed from that set. This could be implemented by two attributes *status* and *time-of-failure,* and avoid the overhead associated with an actual implementation of a set. Capabilities such as these must be defined to permit truly implementation-independent model development, but these types of problems are essentially the same as those that have confronted optimized compilation for years.

The general capabilities for defining and using sets are recommended for the Condition Specification. The syntax for the set operations, INSERT, REMOVE, EMPTY, MEMBER and FIND is given in Table 6.4.[3]

[3]Note that specialized queue operations, e.g. ENQUEUE and DEQUEUE, could be defined based on the general operations INSERT and REMOVE.

6.2.2.2 Object typing

A modeling approach may permit typing of objects. SIMSCRIPT provides a mechanism through which entities may be classified as *permanent* or *temporary.* In GPSS, objects are viewed as *dynamic* (transactions) or *static* (facilities). In the parlance of the CS, designating an object as temporary or permanent could be used to indicate whether or not a DESTROY operation is permissible on the object. Designating an object as dynamic or static could provide an indication of its proper use with regard to model sets, i.e. an ENQUEUE operation should perhaps be illegal on a static object.

However, since the CM stipulates that attributes, not objects, are typed, no mechanism for object typing is described for the CS.

6.2.2.3 Parameterization of alarms

Overstreet provides the facility to parameterize alarms. Alarm parameterization would seem unnecessary and unadvised for the following reason: use of parameters permits the separation of the object from the alarm by using a single alarm for many objects. For example, WHEN ALARM(failure,i). This seems bad conceptually, and in a software engineering sense, increases the coupling of the specification. A better specification for this would be, FOR SOME i:1..N:: WHEN ALARM(machine[i].failure).

In the former case, the use of alarm parameters may indicate a poorly designed model. Model analysis should perhaps be defined to detect this type of situation. However, alarm parameters are useful not only to identify the object to which the alarm belongs, but also in a general sense to allow an expression in terms of model attributes to be evaluated when the alarm is set, and then used when the alarm goes off. To disallow this facility may cause a modeler to resort to the creation of extra, artificial, attributes, to store values for this same purpose. For this reason, the parameterization of alarms remains a part of the representation provided in the Condition Specification. Nontheless, how this facility manifests itself in the higher-level representational forms is unclear.

6.2.2.4 On the relationship of action clusters and events

Consider the situation described in Figure 6.7. The illustration represents, essentially, an "event" description of an end-of-service at the JESS. Certainly, a high-level representation

```
Whenever Jess.end_service
        Jess.status := idle
        Job := REMOVE(JessQ)
        if (random() < Jess.cpu1_prob)
                INSERT(Job,Cpu1Q)
        else
                INSERT(Job,Cpu2Q)
```

Figure 6.7: Event Description for JESS End-of-Service.

would permit the model to be described in similar terms. The question is: how is this represented in the CS, where each action must be under the domain of a single, explicitly defined condition? One possible solution is illustrated in Figure 6.8. In this case, the event is decomposed into the three action clusters pictured. The condition for the first AC is the condition on the occurrence of the event. The two remaining conditions represent the conjunction of the event condition with a condition relating to the value of the random variate.[4] This process requires the creation of two Boolean variables. Within the CM, these may be defined as attributes of the top-level model object. However, the model, as defined by the modeler, will not have these attributes defined – since the specification mechanism will be at a much higher level than the CS. We observe,

> *these are attributes needed to* implement *the higher-level representation using the CS syntax.*

This type of phenomenon may commonly occur throughout the hierarchy. Management of these additional attributes is an issue of concern for a modeling methodology and environment supporting model evolution through transformations. However, the interest of this research effort, with respect to the CS, is primarily at the action cluster level; the management problem for these variables isn't addressed further. However, this type of problem has been addressed within the development of compiler theory. Appeal to these results is

[4] As shown in Chapter 8, this type of augmentation is required only when each AC must be considered independently. The knowledge that the event (WHEN ALARM) condition must always be accompanied by one of the two remaining ACs, as can be depicted in the ACIG, permits the simplification of the AC conditions and obviates the need for "dummy" variables.

```
WHEN ALARM(Jess.end_service):
        Boolean1 := true
        Boolean2 := random() < Jess.cpu1_prob

Boolean1 AND Boolean2:
        Jess.status := idle
        Job := REMOVE(JessQ)
        INSERT(Job,Cpu1Q)
        Boolean1 := false

Boolean1 AND NOT Boolean2:
        Jess.status := idle
        Job := REMOVE(JessQ)
        INSERT(Job,Cpu2Q)
        Boolean1 := false
```

Figure 6.8: Action Clusters Corresponding to Event Description for JESS End-of-Service.

made to resolve any variable management issues not detailed specifically herein. For the context of this effort, the convention for naming these attributes follows the form, B$1, B$2, etc. These are considered attributes of the top-level object, but are not listed in the object definition.

6.2.2.5 The report specification

Overstreet does not prescribe a specific form for the report specification, but instead indicates how the interface between the report specification and the transition specification might be formed using a program designed to compute statistics (see Figure 5.4). An alternative form for the report specification is proposed. The specification is comprised of statements taking the form:

REPORT *expression* AS "*title*"

The expression may be given in terms of model objects and attributes and common, well-defined statistical measurements (so that the calculations needed to gather statistics can be automatically generated from the information provided in the object definitions and

```
REPORT TIME IN STATE Jess.status = busy OVER STEADY STATE DURATION AS "Utilization of Jess"
REPORT TIME IN STATE Cpu1.status = busy OVER STEADY STATE DURATION AS "Utilization of Cpu1"
REPORT TIME IN STATE Cpu2.status = busy OVER STEADY STATE DURATION AS "Utilization of Cpu2"
REPORT TIME IN STATE Prt.status = busy OVER STEADY STATE DURATION AS "Utilization of Prt"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Job AS "Average time of job in system"
REPORT TIME WEIGHTED MEAN NUMBER IN SYSTEM FOR OBJECT Job AS "Average number of jobs in system"
```

Figure 6.9: MVS Report Specification.

transition specification). The report specification for the MVS model is given in Figure 6.9.

6.2.2.6 On automating statistics gathering

When seeking to *automatically* generate the attributes and actions necessary to accomplish the statistics gathering specified by the report specification, the problem may be addressed in two ways:

1. Generate the necessary attributes and actions to collect and calculate the statistical information as the simulation is running.
2. Generate the necessary actions to write the appropriate value changes to "logs" which can be post-processed to gather the requisite statistical information.

The first approach is adopted by many extant SPLs. The second method is often utilized in distributed and parallel discrete event simulation to prevent the statistical gathering routines from becoming either a source of nondeterminism or a performance bottleneck. The appropriateness of either approach depends upon the characteristics of the target implementation as well as the language in which the executable model is represented.

Clearly, both approaches are automatable. The later approach is the simplest, requiring only that a set of OUTPUT actions be added as appropriate within a transition specification, and that a post-processor be provided to generate the statistical values from the logs. The feasibility of the former approach merits further discussion. We consider the approach in terms of augmenting an existing object and transition specification.

Augmented object specification. To produce an augmented object specification that facilitates "on-the-fly" statistics gathering, some mechanism must automatically generate attributes to accomplish the tasks specified by the report specification. This augmenting mechanism requires some well-defined naming scheme to provide general assurance against creating any compilation problems by having conflicts arise between the "baseline" (modeler-generated) and augmented attribute naming. As before, the details of this approach are beyond the scope of this work, but for purposes of this example we use the following scheme.[5] For a report specification containing,

REPORT TIME IN STATE object.attrib = value OVER STEADY STATE DURATION AS "..."

we define the following attributes:

- *timeInState$attribValue* for the object. This attribute contains the accumulated simulation time in steady state (if defined) for which the attribute has the corresponding value.
- *timeInState$attribValueStart* for the object. This attribute contains the simulation time at which the object last assumed the value.

For a report specification containing,

REPORT MEAN TIME IN SYSTEM FOR OBJECT object AS "..."

we define the following attributes:

- *enterTime$system* (or enterTime$setname) for the object. This attribute contains the entry time for the object instance into the system (or set).
- *timeInSys$object* for the system object (or timeInSetname for a set). This attribute contains the accumulated time in steady state (if defined) for all the instances of the given class of object in the system (or set). (The time is given by the difference between object creation and destruction – for the system, or by insert and remove operations – for a set.)

For a report specification containing,

REPORT TIME WEIGHTED MEAN NUMBER IN SYSTEM FOR OBJECT object AS "..."

we define the following attributes:

[5] Assume that the dollar symbol ($) is not permitted in modeler-level attribute naming. Attributes containing the $ are recognized as being system generated.

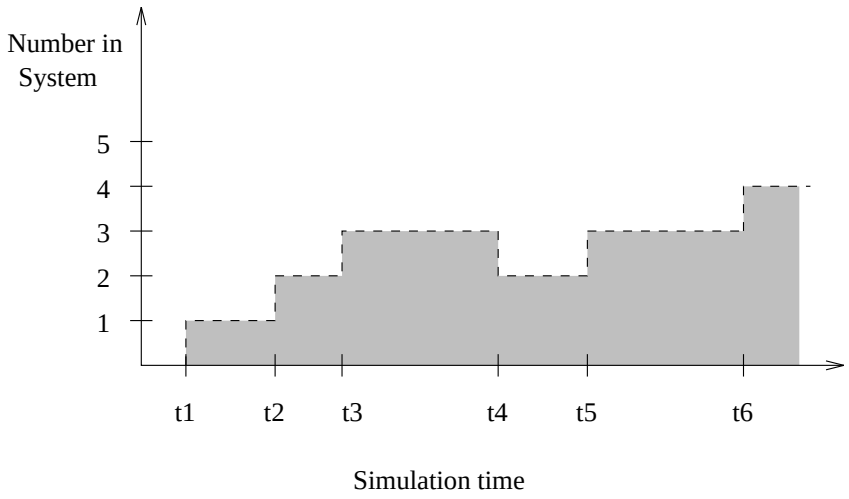


Figure 6.10: Calculating a Time-Weighted Average for Number in System. Average number in system is given by the total area divided by the duration time of the simulation.

- *numInSys$object* for the system object (or numInSetname for a set). This attribute contains the current number of object instances of the given class inside the system (or set).
- *numInSysTime$object* for the system object (or numInSetnameTime for a set). This attribute contains the simulation time at which the number of object instances of the given class inside the system (or set) was last set.
- *numInSysArea$object* for the system object (or numInSetnameArea for a set). This attribute contains the accumulated area in steady state (if defined) of object instances of the given class inside the system (or set). This concept is illustrated in Figure 6.10.

The following are candidate system-generated attributes (belonging to the system object – a $ symbol could be added for consistency):

- *systemTime.* Contains the current value of simulation time.
- *steadyState.* A Boolean indicating whether or not steady state has been reached for a given model execution.
- *steadyStateStartTime.* Contains the value of simulation time when system steady state was achieved.

A comprehensive set of statistical reporting attributes (and computations) has not been defined here. A wide variety of statistical functionality can be automatically supported

similar to that provided by most simulation programming languages. This presentation is simply intended to give the *flavor* of how attribute monitoring in an augmented object specification may be defined.

Augmented transition specification. In order to provide monitoring of "baseline" attributes, the system must generate a description of the assignments to augmented attributes that accompany any change in value of a monitored baseline attribute. For example, given a report specification containing,

REPORT TIME IN STATE obj.attrib = value OVER STEADY STATE DURATION AS "..."

we define the following calculations:

Baseline Action	*Augmented Actions*
obj.attrib := value	obj.attrib := value obj.timeInState$attribValueStart := systemTime

obj.attrib := value′	if ((obj.attrib = value) and (steadyState))
	  obj.timeInState$attribValue := obj.timeInState$attribValue +
	  (systemTime - obj.timeInState$attribValueStart)
	obj.attrib := value′

For a report specification containing,

REPORT MEAN TIME IN SYSTEM FOR OBJECT obj AS "..."

we define the following calculations:

Baseline Action	*Augmented Actions*
CREATE(obj)	CREATE(obj) obj.enterTime$system := systemTime

DESTROY(obj)	if (steadyState)
	  sysobj.timeInSys$obj := sysobj.timeInSys$obj +
	  (systemTime - obj.enterTime$system)
	DESTROY(obj)

For a report specification containing,

REPORT TIME WEIGHTED MEAN NUMBER IN SYSTEM FOR OBJECT obj AS "..."

we define the following calculations:

Baseline Action	*Augmented Actions*

CREATE(obj)	CREATE(obj)
	if (steadyState)
	  sysobj.numInSysArea$obj := sysobj.numInSysArea$obj +
	  sysobj.numInSys$obj * (systemTime - sysobj.numInSysTime$obj)
	sysobj.numInSys$obj := sysobj.numInSys$obj + 1
	sysobj.numInSysTime$obj := systemTime

DESTROY(obj)	if (steadyState)
	  sysobj.numInSysArea$obj := sysobj.numInSysArea$obj +
	  sysobj.numInSys$obj * (systemTime - sysobj.numInSysTime$obj)
	sysobj.numInSys$obj := sysobj.numInSys$obj - 1
	sysobj.numInSysTime$obj := systemTime
	DESTROY(obj)

Can augmented calculations be added as ACs? The most direct approach to augmenting a CS would be to adopt a stratified approach in which any additional calculations generated to facilitate statistics gathering are incorporated within the existing CAP/AC paradigm underlying the CS. But, whenever a monitored attribute is referenced in the baseline specification, the attendant statistical calculations need to be atomic with the reference. Consider the following fragment from the MVS example,

```
{ Jess Begin Service }
Jess.status = idle AND NOT EMPTY(JessQ):
        Jess.status := busy
        SET ALARM(Jess.end_service, exp(Jess.service_mean))

{ Jess End Service Route Cpu1 }
B$1 AND B$2:
        Jess.status := idle
        Job := REMOVE(JessQ)
        INSERT(Job,Cpu1Q)
        B$1 := false
```

At end service the total busy time is accumulated, using the calculation:

```
jess.timeInState$statusBusy := jess.timeInState$statusBusy +
                               (systemTime - jess.timeInState$statusBusyStart)
```

If this action is incorporated into a state-based successor of the end service AC, the possibility for race conditions will have been introduced between the new statistical AC – which reads the value of jess.timeInState$statusBusyStart, and the begin service AC – which sets the value of jess.timeInState$statusBusyStart. In order to prevent race conditions, the

condition for begin service might have to be conjoined with a condition indicating the completion of the new statistical AC. This approach could quickly become unattractive. An alternative approach would be to relax the CAP/AC paradigm in the augmented specification, permitting the conditions on statistics gathering to appear as *sub-conditions* in an AC. In light of these two alternatives, the method of statistics gathering through logs seems superior in this context.

6.2.2.7 The experiment specification

To facilitate the experimentation process, the following information must typically be provided by a modeler:

1. Condition for start of model's steady state.
2. Random number seeds.
3. Number of replications to perform.
4. Name(s) of input/output files.

Many other details may also be provided. For example, the choice of architecture may be specified (or perhaps a best choice can be provided by the model analyzer – given some global objective like "find most efficient implementation").

To the extent that the information involved in model experimentation can be utilized for analysis, it may be desirable to capture it at the CS level. We propose an *experiment specification* for the CS, but do not prescribe its form.

6.3 Example: Traffic Intersection

A simulation model of the traffic intersection (TI) at Prices Fork Road and West Campus Drive in Blacksburg, Virginia may adopt the structure illustrated in Figure 6.11. A single traffic light with north, south, east and west directions controls vehicular movement within each of the nine lanes of the intersection. The intersection itself is conceptually divided into twenty-five blocks through which vehicles travel; while the location of a vehicle moving through the actual intersection is a continuous function, the blocks provide a convenient means of approximating a traffic flow pattern (with reasonable fidelity) within a discrete event simulation of the system.

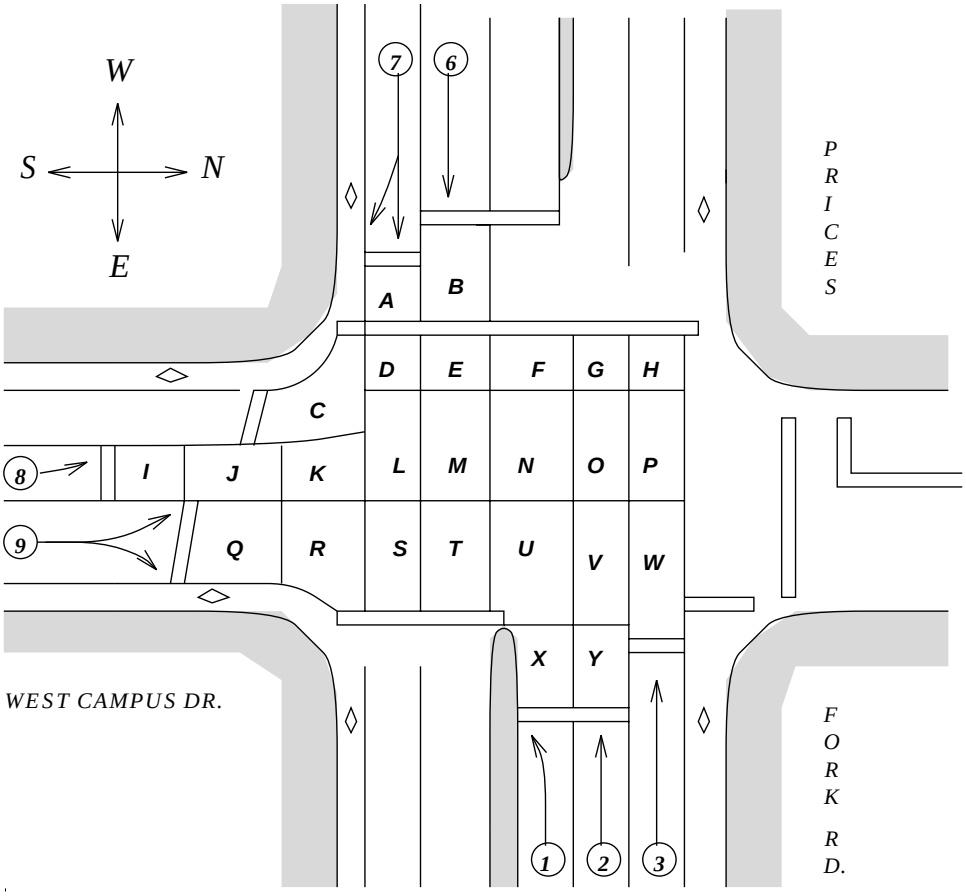


Figure 6.11: The Intersection of Prices Fork Road and West Campus Drive.

Table 6.5: Traffic Intersection Interarrival Times.

Lane	*Interarrival Distribution*	*Mean*
1	Exponential	20.61 Seconds
2	Unknown	8.52 Seconds
3	Unknown	6.21 Seconds
6	Unknown	8.53 Seconds
7	Unknown	5.52 Seconds
8	Unknown	3.77 Seconds
9	Unknown	5.63 Seconds

The objective of the simulation is to provide a light timing sequence which improves the throughput for the intersection. The following definitions are used to describe the model,

1. N = number of lanes in the intersection.
2. m = number of vehicles departing from lane $j : j = 1, 2, \ldots, N$
3. *Arrival Time* = the time at which a vehicle joins the end of the waiting line or the time at which the front end of the vehicle moves across the first white line in the lane (if no waiting line exists).
4. *Departure Time* = the time at which the rear end of the vehicle clears the last white line in the travel path.
5. IAT_{ij} = interarrival time of the ith $(i = 1, 2, \ldots, m)$ vehicle in lane $j : j = 1, 2, \ldots, N$.
6. *Vehicle Waiting Time* = departure time - arrival time
7. W_{ij} = waiting time of the ith vehicle in lane j $(i = 1, 2, \ldots, m; j = 1, 2, \ldots, N)$.
8. WT_j = waiting time of all vehicles in lane $j : j = 1, 2, \ldots, N = \frac{1}{m} \sum_{i=1}^{m} W_{ij}$
9. $E(W_j)$ = expected waiting time of vehicles in lane $j : j = 1, 2, \ldots, N = \frac{1}{m} \sum_{i=1}^{m} W_{ij} = \frac{1}{m} WT_j$

Vehicle interarrival times and travel times are presented in Tables 6.5 and 6.6.[6] During the observation period, traffic flow in the north-south, north-east, and north-west directions was negligible. Therefore the model contains no information about traffic from lanes 4 and 5. Also, the effects of pedestrian traffic (as provided by a pedestrian light control) within the intersection are not present in the model. According to the observed system, the probability

[6]The values presented are based on observations of the system taken during "rush hour" conditions in May 1987 by the CS 4150 simulation class at Virginia Tech.

Table 6.6: Traffic Intersection Travel Times.

Lane	*Travel Time Distribution*	*Mean*
1	Uniform	4.87 Seconds
2	Uniform	2.70 Seconds
3	Uniform	1.85 Seconds
6	Uniform	2.67 Seconds
7	Uniform	4.30 Seconds
7(r)	Uniform	2.43 Seconds
8	Uniform	4.32 Seconds
9(l)	Uniform	4.75 Seconds
9(r)	Uniform	1.84 Seconds

of a right turn by a vehicle traveling in lane 7 is 0.524 and the probability of a right turn from lane 9 is 0.494. The model allows right turn on red for these lanes.

The light timing sequence is illustrated in Figure 6.12. The light follows a cycle of 40 seconds of green for south-north traffic (while other directions in red), followed by 3 seconds where all directions are under red (for intersection clearance), followed by a 62 second green period for east-west traffic. During this 62 second span, south-north lanes are under red for the entire time, while west-east lanes get a green after 22 seconds.

6.3.1 TI model definition

The CM model definition for the TI is prefaced with some remarks regarding system behavior.

6.3.1.1 Vehicular behavior

Traffic through the intersection is governed by the following assumptions. A vehicle arrives at the intersection and waits until it reaches the head of the line. In general, if the light is green and the block immediately ahead in the path of the vehicle is available, the vehicle moves into that block and travels a time proportional to the total travel time for a vehicle in the given lane. Provisions are made to ensure that the first vehicle entering the intersection on a new green waits until the intersection has cleared before proceeding. Subsequent vehicles entering the intersection during the same green do not check this clearance. Only vehicles making specified right turns may proceed under red, i.e. all vehicles in

Figure 6.12: Light Timing Sequence Diagram.

the model follow the established rules of the road.

Figure 6.13 illustrates the movement of a vehicle in lane 1. A vehicle traveling through the intersection in lane 1 does so by moving through blocks X,U,M,L, and C in that order. The first vehicle entering the intersection through lane 1 after a new east-west green must wait for the intersection to clear from the previous green (which was for the south-north traffic in lanes 8 and 9). This means determining that blocks I, J, K, L, M, N, T, and U are clear. Note that the clearance of blocks Q, R and S should not be part of this criterion since these are the blocks involved in a right turn from lane 9 which is permitted under south-north red. The blocks Q, R and S can safely be ignored by the clearance check for lane 1 due to the 3 second delay in which all lanes are under red following the south-north green.[7]

Each vehicle traveling through lane 1, however, must check clearance for blocks A, B,

[7]This is true since the travel time for vehicles going south-to-west in lane 9 through blocks Q, R and S is 2.23 seconds. Further, if the intersection is full when the south-north green ends, traffic backup cannot cause the delay to exceed the 2.23 seconds to clear blocks Q,R and S for the last vehicle through.

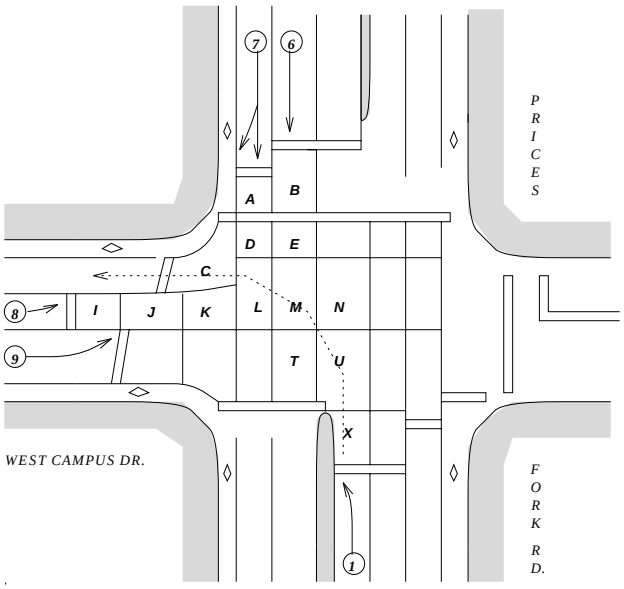


Figure 6.13: Traffic Flow Diagram for Lane 1 with Clearance Lanes Indicated.

D, E, L, and M before proceeding from block U to block M since traffic may be flowing simultaneously in lanes 6 and 7. In order to prevent vehicles in lane 7 that are turning right under a red light from blocking lane 1 traffic, a vehicle in lane 7 turning right on red during a green light for east-west traffic (lanes 1,2,3), may only enter block A if block U is unoccupied.[8] Traffic Flow Diagrams for the remaining lanes are given in Figures 6.14 and 6.15.

6.3.1.2 Objects

The CM object definitions for the TI model are given in Tables 6.7 through 6.12. The first object defined is for the traffic signal. The `light` is given attributes indicating the status of each of its signals, *sn, ew, we,* which assume the value green or red and thereby dictate traffic flow through the intersection. The hold times for each of the states as well as

[8]The logic defined for this model may produce a somewhat crude approximation of the behavior of the actual system. Particularly since driver behavior, erratic and difficult to predict in the actual system, is idealized in the model. We assume, for purposes of this example however, that this approximation is within the tolerance levels prescribed for the simulation study.

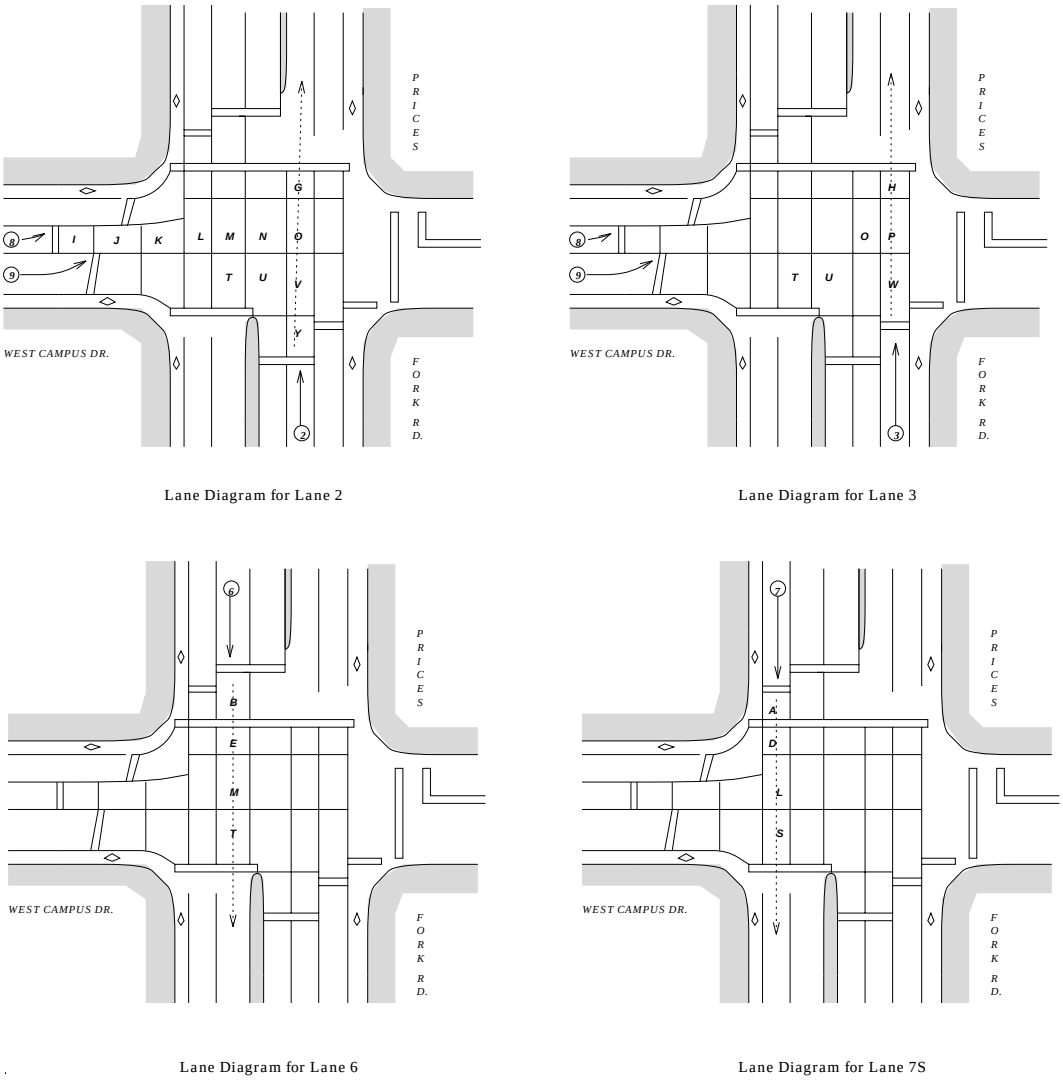
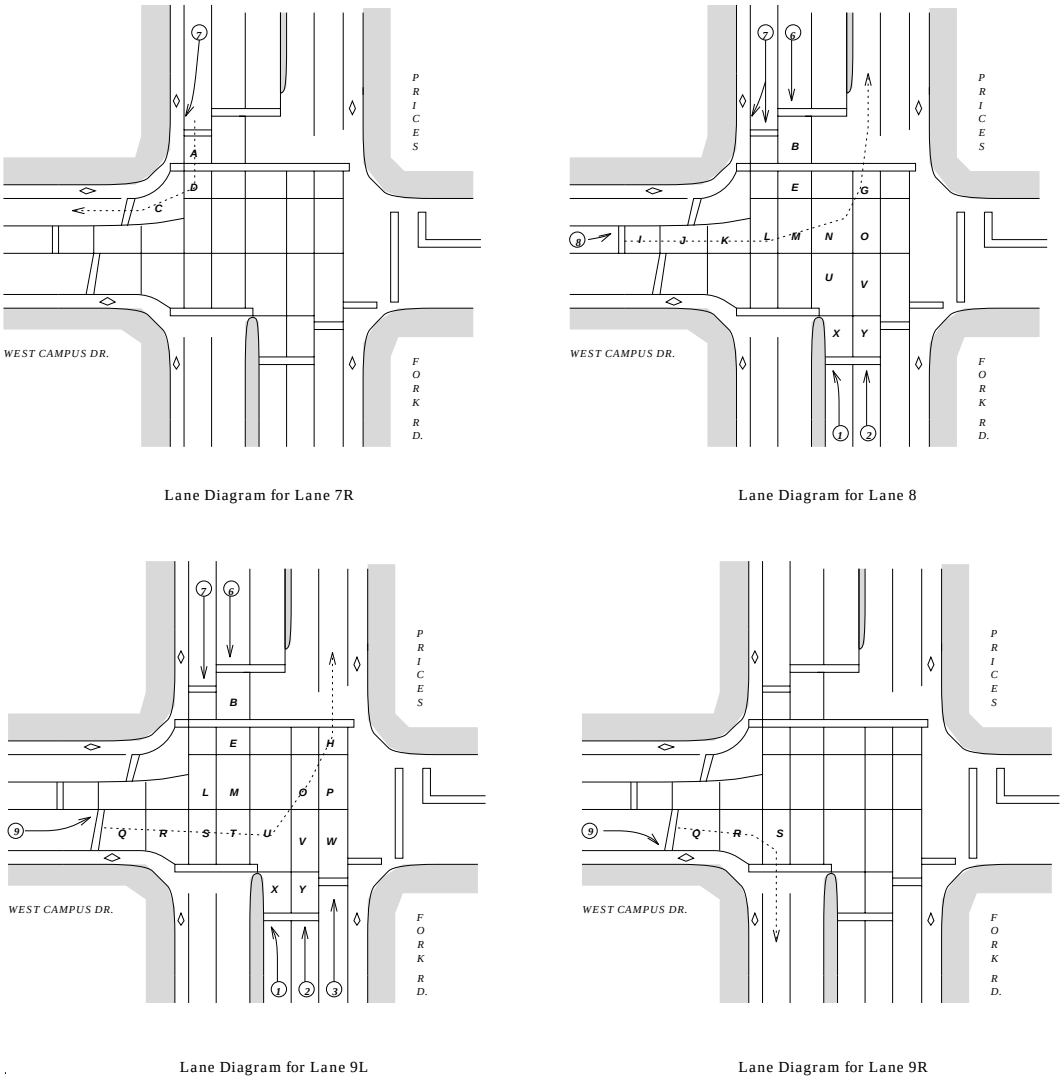


Figure 6.14: Traffic Flow Diagrams for Lanes 2, 3, 6 and 7S with Clearance Lanes Indicated.



Lane Diagram for Lane 7R

Lane Diagram for Lane 8

Lane Diagram for Lane 9L

Lane Diagram for Lane 9R

Figure 6.15: Traffic Flow Diagrams for Lanes 7R, 8, 9L and 9R with Clearance Lanes Indicated.

Table 6.7: CM Object Definition for Top-Level Object and Traffic Signal

Object	*Attribute*	*Type*	*Range*
`ti`	*numCars*	status transitional indicative	nonneg int
	maxCars	permanent indicative	18600
`light`	*sn*	status transitional indicative	(green,red)
	ew	status transitional indicative	(green,red)
	we	status transitional indicative	(green,red)
	snGreen	temporal transitional indicative	nonneg real
	snRed	temporal transitional indicative	nonneg real
	ewGreen	temporal transitional indicative	nonneg real
	weGreen	temporal transitional indicative	nonneg real
	snGreenTime	permanent indicative	40.00 seconds
	snClearTime	permanent indicative	3.00 seconds
	ewGreenTime	permanent indicative	22.00 seconds
	weGreenTime	permanent indicative	40.00 seconds

Table 6.8: CM Object Definition for Lanes

Object	*Attribute*	*Type*	*Range*
`lane[1..9]`	*arrival*	temporal transitional indicative	nonneg real
	arrival_mean	permanent indicative	positive real
	probTurn	permanent indicative	positive real
	newGreen	status transitional indicative	(true,false)

the time at which the next state change will occur are also provided as attributes for the `light`.

An object for each lane is defined as shown in Table 6.8. Within the CM, when the number of object instances is *a priori* determinable, an object may be defined using "array notation" to indicate that number. In this case, `light[1..9]` is used for notational convenience. Of course, since lanes 4 and 5 are not represented in the model, the definition could be, `lane[i: i=1,2,3,6,7,8,9]`. The details of the definitional syntax are not elements of the methodology crucial within the scope of this effort. Of primary concern is that the "meaning" of a given definition or specification be unambiguously conveyed.

We represent the topology of the intersection by creating an object, `block` for each of the twenty-five blocks pictured in Figure 6.11. Each block has an attribute, *status,* indicating by busy or idle, whether or not the block is occupied by a vehicle.

Table 6.9: CM Object Definition for Blocks.

Object	*Attribute*	*Type*	*Range*
`block[A..Y]`	*status*	status transitional indicative	(busy,idle)

Table 6.10: CM Object Definition for Lane Waiting Lines.

Set	*Type*	*Member Type*	*Description*
`laneQ[1..9]`	d-set	Lane*x*Car objects	provide FIFO queue capabilities

Since cars arrive at the intersection and potentially are made to join a waiting line prior to actually entering the intersection proper, we appeal to the CM provisions for set definition (as in the previous example) to provide a queue for each lane.

Finally, objects representing vehicular traffic are defined. We define one object "class" for each of the paths through the intersection, i.e. an object for vehicles in lane 1, one for vehicles in lane 2, one for vehicles in lane 7 turning right, etc. Each object has attributes that dictate its path through the intersection proper and holding times for each of the blocks in the path.

6.3.2 TI model specification

Since, in the actual system, the vehicles provide the activity of interest, a natural means of describing model dynamics is to depict the lifetimes of vehicles traveling in the various lanes. These lifetimes are depicted in the activity sequences of Figures 6.16 through 6.24. The "implementations" of these lifetimes in the CS are given in the transition specification for the TI model in Appendix E. The report specification is presented in Figure 6.25.

6.3.2.1 Using functions in the Condition Specification

Overstreet identifies a function specification in which a modeler may describe functions. These functions may be invoked within the transition specification to aid in the description of model behavior. Overstreet places no restrictions on the use of functions. Given the perceived need to provide flexibility to a modeler, this stance is appropriate. However, since functions are exempt from the analysis defined by the CS, perhaps their use should be lim-

Table 6.11: CM Object Definition for Vehicles (Part I).

Object	*Attribute*	*Type*	*Range*
`lane1Car`	*getBlockU*	temporal transitional indicative	nonneg real
	getBlockM	temporal transitional indicative	nonneg real
	getBlockL	temporal transitional indicative	nonneg real
	getBlockC	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockXTime	permanent indicative	1.12 seconds
	blockUTime	permanent indicative	1.02 seconds
	blockMTime	permanent indicative	0.87 seconds
	blockLTime	permanent indicative	0.61 seconds
	blockCTime	permanent indicative	1.25 seconds
`lane2Car`	*getBlockV*	temporal transitional indicative	nonneg real
	getBlockO	temporal transitional indicative	nonneg real
	getBlockG	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockYTime	permanent indicative	0.68 seconds
	blockVTime	permanent indicative	0.68 seconds
	blockOTime	permanent indicative	0.67 seconds
	blockGTime	permanent indicative	0.67 seconds
`lane3Car`	*getBlockP*	temporal transitional indicative	nonneg real
	getBlockH	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockWTime	permanent indicative	0.63 seconds
	blockPTime	permanent indicative	0.62 seconds
	blockHTime	permanent indicative	0.60 seconds
`lane6Car`	*getBlockE*	temporal transitional indicative	nonneg real
	getBlockM	temporal transitional indicative	nonneg real
	getBlockT	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockBTime	permanent indicative	0.73 seconds
	blockETime	permanent indicative	0.69 seconds
	blockMTime	permanent indicative	0.64 seconds
	blockTTime	permanent indicative	0.61 seconds
`lane7SCar`	*getBlockD*	temporal transitional indicative	nonneg real
	getBlockL	temporal transitional indicative	nonneg real
	getBlockS	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockATime	permanent indicative	0.52 seconds
	blockDTime	permanent indicative	0.84 seconds
	blockLTime	permanent indicative	0.80 seconds
	blockSTime	permanent indicative	0.78 seconds

Table 6.12: CM Object Definition for Vehicles (Part II).

Object	*Attribute*	*Type*	*Range*
`lane7RCar`	*getBlockD*	temporal transitional indicative	nonneg real
	getBlockC	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockATime	permanent indicative	0.46 seconds
	blockDTime	permanent indicative	0.91 seconds
	blockCTime	permanent indicative	1.06 seconds
`lane8Car`	*getBlockJ*	temporal transitional indicative	nonneg real
	getBlockK	temporal transitional indicative	nonneg real
	getBlockL	temporal transitional indicative	nonneg real
	getBlockM	temporal transitional indicative	nonneg real
	getBlockN	temporal transitional indicative	nonneg real
	getBlockG	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockITime	permanent indicative	0.45 seconds
	blockJTime	permanent indicative	0.86 seconds
	blockKTime	permanent indicative	0.82 seconds
	blockLTime	permanent indicative	0.40 seconds
	blockMTime	permanent indicative	0.39 seconds
	blockNTime	permanent indicative	0.72 seconds
	blockGTime	permanent indicative	0.68 seconds
`lane9LCar`	*getBlockR*	temporal transitional indicative	nonneg real
	getBlockS	temporal transitional indicative	nonneg real
	getBlockT	temporal transitional indicative	nonneg real
	getBlockU	temporal transitional indicative	nonneg real
	getBlockO	temporal transitional indicative	nonneg real
	getBlockH	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockQTime	permanent indicative	0.94 seconds
	blockRTime	permanent indicative	0.86 seconds
	blockSTime	permanent indicative	0.43 seconds
	blockTTime	permanent indicative	0.42 seconds
	blockUTime	permanent indicative	0.58 seconds
	blockOTime	permanent indicative	0.76 seconds
	blockHTime	permanent indicative	0.76 seconds
`lane9RCar`	*getBlockR*	temporal transitional indicative	nonneg real
	getBlockS	temporal transitional indicative	nonneg real
	exit	temporal transitional indicative	nonneg real
	blockQTime	permanent indicative	0.73 seconds
	blockRTime	permanent indicative	0.74 seconds
	blockSTime	permanent indicative	0.37 seconds

1. Enter intersection.
2. Wait until first in line.
3. Wait until light is green.
4. If first through - wait for clearance: Blocks I,J,K,L,M,N,T,U,X.
5. Get Block X.
6. Hold 1.12 seconds.
7. Get Block U.
8. Release Block X.
9. Hold 1.02 seconds.
10. Wait for clearance: Blocks A,B,D,E,L,M.
11. Get Block M.
12. Release Block U.
13. Hold 0.87 seconds.
14. Get Block L.
15. Hold 0.61 seconds.
16. Get Block C.
17. Release Block M.
18. Release Block L.
19. Hold 1.25 seconds.
20. Release Block C.
21. Exit.

Figure 6.16: Activity Sequence for Lane 1 Vehicle.

1. Enter intersection.
2. Wait until first in line.
3. Wait until light is green.
4. If first through - wait for clearance: Blocks I,J,K,L,M,N,T,U,Y.
5. Get Block Y.
6. Hold 0.68 seconds.
7. Get Block V.
8. Release Block Y.
9. Hold 0.68 seconds.
10. Get Block O.
11. Release Block V.
12. Hold 0.67 seconds.
13. Get Block G.
14. Release Block O.
15. Hold 0.67 seconds.
16. Release Block G.
17. Exit.

Figure 6.17: Activity Sequence for Lane 2 Vehicle.

1. Enter intersection.
2. Wait until first in line.
3. Wait until light is green.
4. If first through - wait for clearance: Blocks O,T,U,W.
5. Get Block W.
6. Hold 0.63 seconds.
7. Get Block P.
8. Release Block W.
9. Hold 0.62 seconds.
10. Get Block H.
11. Release Block P.
12. Hold 0.60 seconds.
13. Release Block H.
14. Exit.

Figure 6.18: Activity Sequence for Lane 3 Vehicle.

1. Enter intersection.
2. Wait until first in line.
3. Wait until light is green.
4. Get Block B.
5. Hold 0.73 seconds.
6. Get Block E.
7. Release Block B.
8. Hold 0.69 seconds.
9. Get Block M.
10. Release Block E.
11. Hold 0.64 seconds.
12. Get Block T.
13. Release Block M.
14. Hold 0.61 seconds.
15. Release Block T.
16. Exit.

Figure 6.19: Activity Sequence for Lane 6 Vehicle.

1. Enter intersection.
2. Wait until first in line.
3. Wait until light is green.
4. Get Block A.
5. Hold 0.52 seconds.
6. Get Block D.
7. Release Block A.
8. Hold 0.84 seconds.
9. Get Block L.
10. Release Block D.
11. Hold 0.80 seconds.
12. Get Block S.
13. Release Block L.
14. Hold 0.78 seconds.
15. Release Block S.
16. Exit.

Figure 6.20: Activity Sequence for East-Bound Lane 7 Vehicle.

```
1. Enter intersection.
2. Wait until first in line.
3. If light is red and east-west is green- wait for clearance: Blocks L,M.
4. Get Block A.
5.      Hold 0.46 seconds.
6. Get Block D.
7. Release Block A.
8.      Hold 0.91 seconds.
9. Get Block C.
10. Release Block D.
11.     Hold 1.06 seconds.
12. Release Block C.
13. Exit.
```

Figure 6.21: Activity Sequence for South-Bound Lane 7 Vehicle.

ited to non-model-specific activity, such as the generation of random numbers and random variates? Regardless, *functions should have no unanalyzable effects on model attributes.* In the absence of the highest-level representations, however, further guidance on the use of functions in the CS is impracticable.

6.3.2.2 Another set operation

Developing the transition specification for the TI model identifies the need for another set operation. Here, the need arises since d-sets are defined (the lane queues) which may have different "classes" of objects as members. For example, the set `laneQ[9]` may have `lane9RCar` objects and `lane9LCar` objects. Model behavior varys according to which class of object is removed. Specifically, a car turning right in lane 9 enters the intersection and holds block Q for 0.73 seconds, whereas a car turning left holds block Q for 0.94 seconds. Furthermore, the left-turning car must establish a different set of clearances than the right turning car. We define the set operator, CLASS, which interrogates an object within a set and returns the value of its class, i.e. the object name that appears in the CM definition. The operator must be passed the set name and a pointer to the object. A typical use of

1. Enter intersection.
2. Wait until first in line.
3. Wait until light is green.
4. If first through - wait for clearance: Blocks B,E,I,L,M,X,U,Y,V,O.
5. Get Block I.
6. Hold 0.45 seconds.
7. Get Block J.
8. Release Block I.
9. Hold 0.86 seconds.
10. Get Block K.
11. Release Block J.
12. Hold 0.82 seconds.
13. Get Block L.
14. Hold 0.40 seconds.
15. Get Block M.
16. Release Block K.
17. Hold 0.39 seconds.
18. Get Block N.
19. Release Block L.
20. Release Block M.
21. Hold 0.72 seconds.
22. Get Block G.
23. Release Block N.
24. Hold 0.68 seconds.
25. Release Block G.
26. Exit.

Figure 6.22: Activity Sequence for Lane 8 Vehicle.

1. Enter intersection.
2. Wait until first in line.
3. Wait until light is green.
4. If first through - wait for clearance: Blocks B,E,L,M,X,U,Y,V,O,W,P,H.
5. Get Block Q.
6. Hold 0.94 seconds.
7. Get Block R.
8. Release Block Q.
9. Hold 0.86 seconds.
10. Get Block S.
11 Hold 0.43 seconds.
12. Get Block T.
13. Release Block R.
14. Hold 0.42 seconds.
15. Get Block U.
16. Release Block S.
17. Release Block T.
18. Hold 0.58 seconds.
19. Get Block O.
20. Release Block U.
21. Hold 0.76 seconds.
22. Get Block H.
23. Release Block O.
24. Hold 0.76 seconds.
25. Release Block H.
26. Exit.

Figure 6.23: Activity Sequence for West-Bound Lane 9 Vehicle.

```
1. Enter intersection.
2. Wait until first in line.
4. If light is red - wait for clearance: Blocks D,L,S,Q.
5. Get Block Q.
6.      Hold 0.73 seconds.
7. Get Block R.
8. Release Block Q.
9.      Hold 0.74 seconds.
10. Get Block S.
11      Hold 0.37 seconds.
12. Release Block R.
13. Release Block S.
14. Exit.
```

Figure 6.24: Activity Sequence for East-Bound Lane 9 Vehicle.

```
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane1Car AS "Average travel time of vehicles in Lane 1"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane2Car AS "Average travel time of vehicles in Lane 2"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane3Car AS "Average travel time of vehicles in Lane 3"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane6Car AS "Average travel time of vehicles in Lane 6"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane7SCar AS "Average travel time of east-bound vehicles in Lane 7"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane7RCar AS "Average travel time of south-bound vehicles in Lane 7"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane8Car AS "Average travel time of vehicles in Lane 8"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane9LCar AS "Average travel time of west-bound vehicles in Lane 9"
REPORT MEAN TIME IN SYSTEM FOR OBJECT Lane9RCar AS "Average travel time of east-bound vehicles in Lane 9"
```

Figure 6.25: TI Report Specification.

this operation may be a Boolean test of the form:

$$\text{CLASS}(\text{laneQ}[9],\text{FIRST}) = \text{Lane9LCar}$$

where the modifier FIRST indicates the object at the head of an ordered set.

6.3.3 Object-based versus object-oriented

This section concludes with some thoughts regarding the CM as an *object-based* approach to model development as contrasted with *object-oriented* approaches.

For purposes of this discussion, the following are considered characteristic of the object-oriented paradigm (OOP):[9]

1. Association of objects in a system to objects in a model.
2. Class descriptions.
3. Inheritance structure.
4. Object behavior encapsulated within methods.
5. Object instantiation.
6. Object "communication" through message passing.

A long-running debate in Computer Science raises the question, is object-oriented a superior approach? Certainly, the OOP has advantages over traditional programming languages from a general software engineering perspective. Still, overuse of features like multiple inheritance can lead to code that is nearly impossible to comprehend. Our question has a slightly different focus: from the point of view of *discrete event simulation* model development, is OOP superior to the object-based perspective of the CM? We assert that the answer to this question is emphatically no. First of all, the CM provides (1), (2), (3) and (5) from the list above. The CM has no notion of "method" and places no restrictions on the manner in which objects read and write the values of attributes. These issues fall within the domain of the model representation form(s). Certainly an SMSDL could encapsulate model dynamics in such a manner, and enforce "communication" through a message passing

[9]Many may argue that other features such as polymorphism and operator overloading are also integral to the OOP. We consider these traits to be more an aspect of object-oriented programming languages than the OOP itself.

structure, but at what cost? As argued in the previous section, an important characteristic of any methodology for simulation model development is providing flexibility to the modeler – specifically, not forcing a single restrictive conceptual framework on every problem. The constraints of the object-oriented paradigm can cause a modeler to define a system in a very unnatural way. Take, for instance, the TI model presented in this section. An OOP characterization would allow the blocks of the intersection proper to be defined as objects (just as done with the CM), but a vehicle object is forced to send a message to a block object to determine the status of the block. Communication among model objects, when it occurs, should be expressible (at the highest, modeler-end, level) in a *natural* manner. One may view a pilot and a co-pilot in an aviation simulation as communicating through passed messages, but describing driver behavior as passing messages to – and receiving them from – asphalt, is another matter altogether.

6.4 Example: Colliding Pucks

The *Colliding Pucks* problem, hereafter referred to as pucks, is based on the pool ball systems described by Goldberg [89]. In the basic pucks model, rigid disks move along a flat surface and collide with surface boundaries and other disks. The kinematics of the pucks system are detailed below.

6.4.1 Kinematics of pucks

A pucks system can be viewed as illustrated in Figure 6.26. A large variety of models are possible for pucks based on the myriad physical assumptions that can be made about the system. For this example, the following system characteristics are assumed:

1. The surface is a rectangular table aligned with the x-y origin.
2. The table is frictionless.
3. Table boundaries have infinite mass.
4. All pucks are of equal mass.
5. Collisions are elastic and total system energy is conserved.

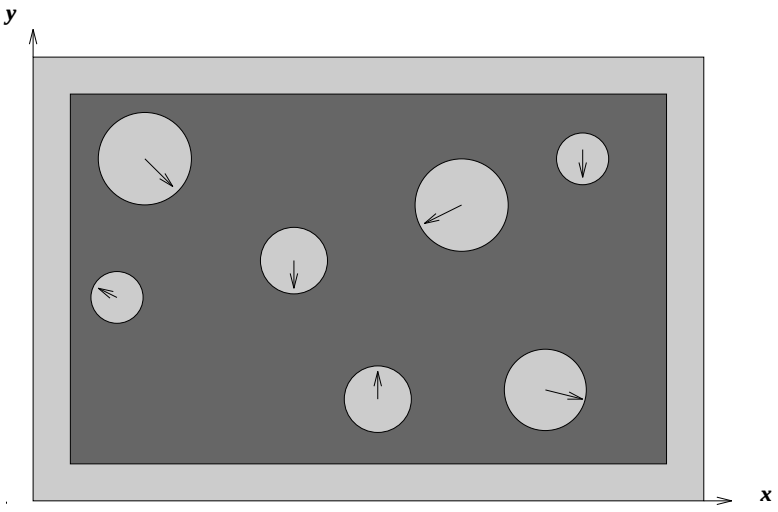


Figure 6.26: Colliding Pucks System.

Each puck has a position (x, y), velocity vector $\mathcal{V} = (\nu_x, \nu_y)$, and radius, r. The table boundaries are defined by the equations:

$$x = 0,\ x = n,\ y = 0,\ y = m \tag{6.1}$$

Two types of collisions occur in the system: (1) puck-boundary collisions, and (2) interpuck collisions. For each type of collision a simulation must provide both collision prediction (or detection) and collision resolution.

6.4.1.1 Pucks and boundaries: collision prediction

At any given point in simulation time, we can calculate the time until the next boundary collision for any puck in the system. This calculation is a function of the puck's position and velocity, and is a *prediction,* not a guarantee.[10] Times to boundary collisions are given

[10]Subsequent to the calculation of the boundary collision time and prior to the collision itself, the puck may be involved in an interpuck collision, potentially causing the predicted boundary collision time to be incorrect.

by:

$$t_x = \begin{cases} t_{right} \equiv \frac{n-(x+r)}{\nu_x} & \text{if } \nu_x > 0 \\ t_{left} \equiv \frac{x-r}{-\nu_x} & \text{if } \nu_x < 0 \\ \infty & \text{if } \nu_x = 0 \end{cases} \tag{6.2}$$

$$t_y = \begin{cases} t_{top} \equiv \frac{m-(y+r)}{\nu_y} & \text{if } \nu_y > 0 \\ t_{bottom} \equiv \frac{y-r}{-\nu_y} & \text{if } \nu_y < 0 \\ \infty & \text{if } \nu_y = 0 \end{cases} \tag{6.3}$$

For any puck, the time until the most imminent predicted boundary collision is:

$$t_{collision} = \min(t_x, t_y) \tag{6.4}$$

6.4.1.2 Pucks and boundaries: collision resolution

To resolve a puck-boundary collision we update the puck's position and velocity. If the position and velocity of the puck are given by (x, y) and (ν_x, ν_y) respectively, and $t_{collision} = \tau$, then the position of the puck (at the time of the collision) is:

$$x' = x + \nu_x \tau \tag{6.5}$$

$$y' = y + \nu_y \tau \tag{6.6}$$

And the new velocity is:

$$\mathcal{V} = \begin{cases} (-\nu_x, -\nu_y) & \text{if } t_x = t_y \\ (-\nu_x, \nu_y) & \text{if } t_x < t_y \\ (\nu_x, -\nu_y) & \text{if } t_y < t_x \end{cases} \tag{6.7}$$

6.4.1.3 Pucks and pucks: collision prediction

To determine the time until a collision between any two pucks, we solve the quadratic equation that results from the interpretation of the distance squared between the centers of the two pucks as a function of time. Given two pucks `A` and `B` with positions, velocities, and radii $(x_A, y_A), (\nu_{x_A}, \nu_{y_A}), r_A$ and $(x_B, y_B), (\nu_{x_B}, \nu_{y_B}), r_B$ respectively then the distance squared between pucks is given by:

$$d^2 = (x_B - x_A)^2 + (y_B - y_A)^2 \tag{6.8}$$

To determine when the AB collision occurs (if one occurs), we evaluate the equation:

$$d^2(t) = (r_A + r_B)^2 \tag{6.9}$$

To solve for t in Equation 6.9 we let $d^2(t) = at^2 + bt + c - (r_A + r_B)^2$. The coefficients are given by:

$$a = (\nu_{x_B} - \nu_{x_A})^2 + (\nu_{y_B} - \nu_{y_A})^2 \tag{6.10}$$

$$b = 2[(x_B - x_A)(\nu_{x_B} - \nu_{x_A}) + (y_B - y_A)(\nu_{y_B} - \nu_{y_A})] \tag{6.11}$$

$$c = (x_B - x_A)^2 + (y_B - y_A)^2 - (r_A + r_B)^2 \tag{6.12}$$

Solve for t by evaluating:

$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{6.13}$$

If the quadratic equation yields two positive real roots, then the collision time, $t_{collision}$, is taken as the minimum of the two roots from Equation (6.13) (the larger value represents the time at which the trailing edges of the pucks will be touching i.e. the pucks will have passed through one another). Two negative real roots or a negative discriminant indicate that the pucks are moving away from one another or the pucks are on parallel courses and no future collision is possible. When two pucks are traveling in the same direction and at the same speed then a (Equation (6.10)) is zero.[11]

6.4.1.4 Pucks and pucks: collision resolution

Resolving interpuck collisions requires: (1) updating the puck positions to those at the time of the collision, and (2) updating the puck velocities.

Puck positions are updated as in the puck-boundary case by Equations (6.5) and (6.6). Updating the velocities involves: (1) establishing the normal and tangential component velocities of the collision (and thereby creating a t-n coordinate system), (2) updating the puck velocities relative to the t-n system, and (3) translating these updated velocities back into the x-y coordinate system. Figure 6.27 illustrates a collision between two pucks and shows their component velocities.

[11] An implementation of the system must check for this to avoid division by zero errors.

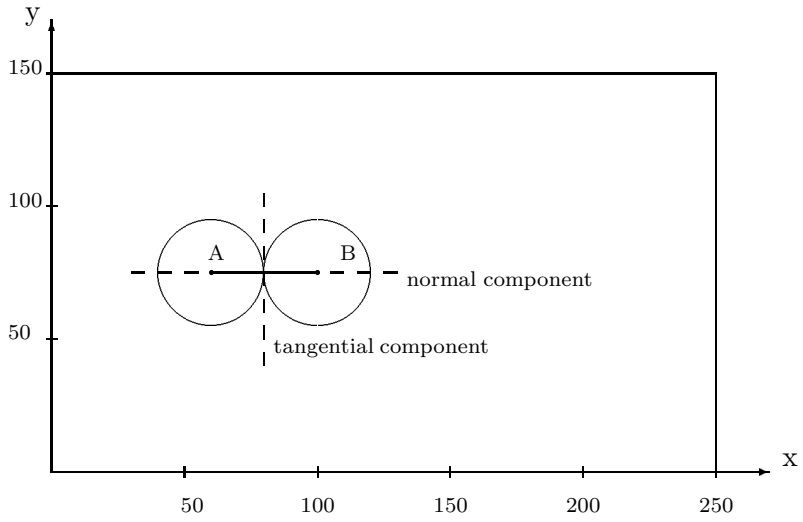


Figure 6.27: Component Velocities of an Interpuck Collision.

We establish the normal component as a vector between the positions of the two pucks:

$$\mathcal{N} = (x_n, y_n) \begin{cases} x_n & = \frac{x_B - x_A}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}} \\ y_n & = \frac{y_B - y_A}{\sqrt{(x_B - x_A)^2 + (y_B - y_A)^2}} \end{cases} \tag{6.14}$$

The tangential component is perpendicular to the normal and can be established by rotating the normal vector ninety degrees:

$$\mathcal{T} = (-y_n, x_n) \tag{6.15}$$

To update the velocities of the two pucks, relative to the t-n system, we swap the velocities in the normal component and leave the velocities in the tangential component unchanged.

$$\mathcal{V}'_A = (\mathcal{V}_B \cdot \mathcal{N}, \mathcal{V}_A \cdot \mathcal{T}) \tag{6.16}$$

$$\mathcal{V}'_B = (\mathcal{V}_A \cdot \mathcal{N}, \mathcal{V}_B \cdot \mathcal{T}) \tag{6.17}$$

With the new velocities calculated in the t-n system, we must translate the velocities back into x-y coordinates. Let $\mathcal{U}_x$ and $\mathcal{U}_y$ be the unit vectors of x and y respectively. And let $\mathcal{R}_x$ and $\mathcal{R}_y$ be vectors defined as:

$$\mathcal{R}_x = (\mathcal{U}_x \cdot \mathcal{N}, \mathcal{U}_x \cdot \mathcal{T}) \tag{6.18}$$

$$\mathcal{R}_y = (\mathcal{U}_y \cdot \mathcal{N}, \mathcal{U}_y \cdot \mathcal{T}) \tag{6.19}$$

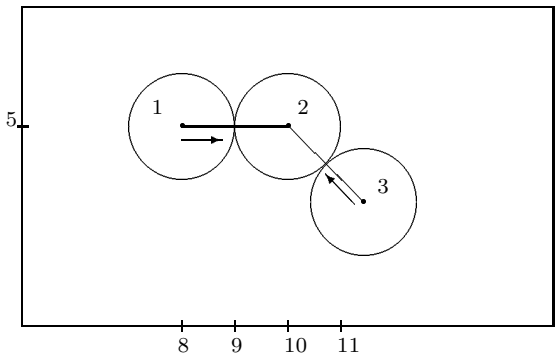


Figure 6.28: A Collision Among Three Pucks.

Then the velocities of the pucks `A` and `B` in the x-y coordinate system are given by:

$$\mathcal{V}''_A = (\mathcal{V}'_A \cdot \mathcal{R}_x, \mathcal{V}'_A \cdot \mathcal{R}_y) \quad (6.20)$$

$$\mathcal{V}''_B = (\mathcal{V}'_B \cdot \mathcal{R}_x, \mathcal{V}'_B \cdot \mathcal{R}_y) \quad (6.21)$$

6.4.1.5 Collisions involving multiple pucks

The collision resolution scheme described above generates updated velocities for two pucks involved in a collision. When several pucks collide simultaneously, the algorithm must pairwise resolve the collisions.[12] In some cases, the resultant velocities of an *N*-disk collision are *not* strictly independent of the serial order of resolution using this scheme. One such case is presented in Figure 6.28. In the Figure, Puck 1 is at (8,5) and $\mathcal{V}_1$ is (1,0); Puck 2 is stationary at position (10,5); and Puck 3 is at $(10+\sqrt{2}, 5-\sqrt{2})$ with $\mathcal{V}_3 = (-1, 1)$. Thus we see that Puck 1 is striking Puck 2 head on while at the same time Puck 3 collides with Puck 2 at an angle of forty-five degrees. We have two choices for pairwise collision resolution: resolve collision (1,2) then collision (2,3) or resolve collision (2,3) then collision (1,2). Table 6.13 shows the velocity changes, and the differing resultant trajectories

[12]Since no general closed form solution exists for the *N*-body problem of colliding disks, the mathematics described is only partially correct. We assume that these approximations are acceptable within the tolerance levels prescribed for the simulation study.

Table 6.13: Order of Resolution Dependence in Multiple Puck Collisions.

	CASE I			*CASE II*		
	Initially	Coll(1,2)	Coll(2,3)	Initially	Coll(2,3)	Coll(1,2)
$\mathcal{V}_1$	(1,0)	(0,0)	(0,0)	(1,0)	(1,0)	(-1,0)
$\mathcal{V}_2$	(0,0)	(1,0)	$(-\frac{1}{2}, \frac{3}{2})$	(0,0)	(-1,1)	(1,1)
$\mathcal{V}_3$	(-1,1)	(-1,1)	$(\frac{1}{2}, -\frac{1}{2})$	(-1,1)	(0,0)	(0,0)

for both cases.[13]

Using the pairwise collision resolution scheme we must assure that the system *always* processes the same multiple puck collision in the same pairwise order – to provide reproducibility of simulation results. We may achieve this by simply requiring that in any multiple puck collision the collision involving the puck with the smallest identifier is processed first, then the collision involving the remaining disk with the smallest identifier, and so on.[14]

6.4.2 A literature review of pucks solutions

The pucks model was developed specifically as a benchmark for parallel discrete event simulation protocols [29, p. 56]. The nature of pucks – a system where the level of inherent parallelism seems high, but for which few assumptions can be made regarding both the times and frequencies of interactions among system objects – makes it interesting in this respect. On the other hand, the model formulation clearly indicates a misperception of the fundamental nature of discrete event simulation; a misperception that seems to permeate much of PDES. For pucks, *no modeling objectives are defined.* The PDES view would seem to be that if a program approximates reality in some sense, then that program must be, by definition, a simulation. The development of Chapter 3 clearly contradicts this view. A simulation is, first-and-foremost, a tool for decision support. Fundamental to decision support is the formulation of a modeling objective. As stated in Chapter 2, only through the modeling objective can meaning be assigned to a model or its results. This fact cannot be overstated.

A brief review of pucks-related literature further illustrates this significant misappre-

[13]For Case I, a third collision will occur – between Puck 1 and Puck 2 – in which the final x-component velocities given in the Table are switched.

[14]This scheme is utilized in [29, 52, 89, 103, 138].

hension of the nature of discrete event simulation.

6.4.2.1 Goldberg's model

In his thesis, Goldberg [89] originally defines the pucks system for an object-oriented simulation of pool ball motion.

Time flow. Goldberg discusses the pool ball simulation as implemented using two time flow mechanisms, fixed-time increment (FTI) and time of next event (TNE).[15] He observes a significant problem with an FTI implementation of the simulation is a tradeoff between speed and accuracy, noting that accuracy of the simulation is compromised using FTI since a collision cannot be simulated exactly at the time it occurs. At each time step the simulation must determine if two balls have collided by determining if the balls overlap. The smaller the time step, the greater the accuracy of the simulation; but larger time steps are viewed as more desirable to reduce the amount of computation within the simulation. Goldberg concludes that no good heuristics exist that indicate the optimum selection of time step size [89, p. 6].

According to Goldberg, an event-based implementation does not suffer from the accuracy problem of the FTI approach. In Goldberg's TNE algorithm, all possible future collisions are scheduled, i.e. each ball calculates the most imminent collision between itself and every other ball and any cushions. When a ball undergoes a collision and updates its velocity, it cancels all scheduled collisions and schedules new ones based on its new trajectory. Goldberg claims that the TNE approach is computationally more efficient than the FTI approach in typical cases (e.g. when the average number of collisions per time step is less than $n/\log n$, where n is the number of pool balls in the simulation). Algorithms for the object-oriented solution are given in Appendix C. (Note: Figures C.1 and C.2 illustrate the behavior for balls and cushions. The behaviors for corners and pockets are similar to cushion behavior and are not illustrated.) The logic of the object-oriented implementation is similar to that defined for the pure TNE implementation except that the event list is "distributed" as objects schedule events via message passing (given the three message types: NewVelocity,

[15] Goldberg [89, p. 3] refers to these as the "two major temporal simulation methods: *time step* simulation and *discrete event simulation*."

Collision, and Cancel).

Implications of an object-oriented solution. The object-oriented simulation execution paradigm utilized by Goldberg requires that for any value of simulation time an object may execute (process outstanding messages) *at most once* (running an object more than once for any value of simulation time can lead to incorrect results since the object may behave differently than if allowed to process all messages at once). This causes difficulty in modeling systems with zero time delay or, using Goldberg's terminology, "instantaneous" events. To illustrate this, consider the following scenario: Ball-1, resting against a cushion, is being struck by another ball, Ball-2. Three things happen simultaneously: Ball-2 knocks Ball-1 into the cushion, Ball-1 bounces off the cushion, Ball-1 collides with Ball-2 sending Ball-2 back into the table. Suppose the simulation executive schedules the object execution in the order: Ball-1, Ball-2, Cushion.[16] Ball-1 receives a Collision message from Ball-2 and sends a NewVelocity message to the Cushion then terminates. Ball-2 processes the Collision message it sent to itself, sends a NewVelocity message to the Cushion and terminates. The Cushion processes the NewVelocity messages. The NewVelocity message from Ball-1 causes the Cushion to send a Collision message to Ball-1. But Ball-1 has already executed for this value of simulation time. Further, we see that any ordering of object processing leads to a similar conclusion. To circumvent this inherent problem of the scheduling policy Goldberg allows the second collision to be processed after a small delay.

Sectored model. Since the complexity of the object-oriented pool ball model is dominated by the number of messages, Goldberg proposes a sectorized model to cut down on the number of messages required for the average case. In a sectored model, a ball determines if it will collide only with the other balls in its sector, not all the balls on the table. However, the addition of sectors is not without its costs: new messages for entering and leaving sectors are required as well as mechanisms for dealing with collisions on and around sector boundaries. Goldberg's algorithms for ball and sector behaviors are given in Appendix C.

The sectored algorithm contains five types of messages, which can be categorized into two groups. First, the VelocityChange and NewVelocity messages convey information about

[16] During execution each object in turn is allowed to process all messages it has received whose timestamps are equal to the simulation time.

a ball's change in velocity. Second, the Collision, SectorEntry and SectorDeparture messages schedule future events, involving two balls or a ball and a sector, based on the ball's new velocity.[17]

In detail, the algorithm behaves as follows. When a ball changes velocity it sends a VelocityChange message to each sector it occupies. Unless the ball is stationary, each occupied sector schedules a SectorDepart for the ball. Involved sectors send NewVelocity messages to all adjacent sectors and to all balls within the sectors themselves. If the ball's trajectory intercepts an adjacent sector's perimeter, the sector schedules a sector entry by sending a SectorEntry message to the ball and one to itself.

A NewVelocity message is received by each ball that shares a sector with the ball whose velocity has changed. These balls determine whether they are to collide with the ball in question. If a ball predicts a collision then it sends a Collision message to the ball whose velocity has changed and one to itself.

Sector entry and departure. Goldberg identifies the perimeter of a sector by a list of its corners (this representation permits myriad polygonal sector forms). The edges of a sector connect adjacent corners in the list, e.g. a rectangular sector requires a list of five corner points, since the first corner repeats at the end of the list. The sector departure time of a ball from a sector is the instant a ball leaving the sector crosses its perimeter. Thus, the departure time is the maximum of the times at which the ball crosses the sector's edges and corners. The sector entry time is the time an entering ball first crosses the perimeter.

Instantaneous messages. The problem of instantaneous messages, and the resolution of allowing a small delta to separate velocity changes in serial collisions, further complicates Goldberg's sectored model by allowing balls to pass through each other. For example, suppose Ball-1 is stationary against the edge of a sector and Ball-2 collides with Ball-1 as it enters the sector. Because of a the delay in the NewVelocity message (from Ball-2 to the sector to Ball-1 with artificial delay) Ball-1 will not recognize Ball-2 until they overlap. Goldberg addresses this problem by having Ball-1 schedule an immediate collision with Ball-2. This works in most cases, with some loss of accuracy in the solution. However, this

[17]Each of these messages is sent by the object scheduling the interaction to both itself and the other involved object.

solution still allows one ball to pass through another, e.g. if the time it takes for Ball-2 to pass through Ball-1 is less than the delay.

6.4.2.2 The JPL model

The implementation of Goldberg's simulation, as a colliding rigid disks model, for the Time Warp Operating System (TWOS) is described in [29, 103]. According to [29], the pucks model embodies several "fundamental" problems of PDES. The authors describe these as:

1. *Modularization Strategy.* Dividing the work of building software in an organized and rational way.
2. *Object-Oriented Design.* Object-oriented design of sequential simulations often stops with the identification of the software objects corresponding to physical objects in the simulated world or well-defined abstract objects. In distributed simulation, "the designer must also respond to performance concerns [29, p. 27]." Objects (realized as processes) must have an appropriate granularity and bottlenecks should be avoided.
3. *Synchronization of Message Communication.* The number of messages should not grow too rapidly with the number of objects.
4. *Dynamic Recomposition of Objects and Processes.* A desirable quality is the ability of objects to decompose and aggregate for performance enhancement.
5. *Dynamic Load Management.* Process/processor mappings must be amenable to dynamic reconfiguration to admit maximal performance.

A pucks model is implemented using two mini-languages, *Circles* – for the kinematics and dynamics of the system, and *Twang* – containing the object interaction protocols.

The sectored implementation uses a simpler message protocol than that of Goldberg. Each sector examines the trajectories of all pucks within its boundaries and schedules only the earliest predicted collision. The sector *reawakens* at the time of the collision, and then causes the involved pucks to change velocity. This cycle is repeated until the condition for termination is met.

This protocol has the advantage that no mechanism is needed to plan/cancel collisions and therefore the expected number of messages is lower than Goldberg's protocol. It has the disadvantage that the sector must predict collisions for all pucks within its boundaries to find the earliest one. These prediction computations are distributed among the pucks themselves in Goldberg's solution. A risk of excessive synchronization with this protocol is

also present since no interactions later than the earliest certain interaction are scheduled. Speedups of up to 11.5 on a 32 node Hypercube are reported in [103].[18]

6.4.2.3 Lubachevsky's model

Lubachevsky [138] proposes an optimistic implementation of pucks based on the idea that parallelizability arises from the *distance* between events: essentially, if two disks are separated by a large distance, the probability that a causal dependence between their motions will be created in the near future is small. The bounded lag approach is shown to produce superior execution speeds to that of Time Warp when the number of processors falls within a prescribed limit.

Lubachevsky's simulation proceeds optimistically (albeit with some set of safeguards programmed to reduce specific types of rollbacks) until event propagations cause an error in the form of an out-of-order event processing. When this occurs, the system rolls back using a checkpointing algorithm: the entire system is returned to the most recent successfully passed checkpoint and then the "dangerous speed surge" is recomputed (with additional serialization of computations as required for causality) to avoid the error [138, p. 194]. Lubachevsky notes that this checkpointing scheme is asymptotically nonscalable, and thus only a finite number of processors can be effectively employed in the problem.[19]

In this variation of pucks the disks expand at a fixed common rate until the system "jams up." Since the program spends most of its computation in a dense, almost jammed configuration where disk mobility is reduced to oscillations about a stationary position and where boundary crossings (in the sectorized version) are rare, several simplifying assumptions and sundry tricks can be applied to glean execution speed which are not applicable to the general form of pucks. However, to his credit, Lubachevsky does indicate a modeling objective for this version of pucks, noting that it may be utilized to study the short-range order in amorphous solids. Still, no discussion of model validation relative to a specific modeling objective is given.

[18] Here speedup may be exaggerated, since it is calculated by comparing the TWOS execution time of a simulation on multiple processors to the execution time of the identical simulation running on a single processor under the Time Warp sequential simulator.

[19] Lubachevsky sets this number, however, at several thousand.

6.4.2.4 Cleary's model

Cleary [52] presents a solution to pucks in temporal logic using the logic programming language Starlog. The primary difference of this approach (and the contribution of the use of temporal logic) is the provision for collision detection rather than collision prediction. Similar to Linda [4], the fundamental data object in Starlog is the tuple. Each puck is modeled by two classes of tuples. The tuple `collide(T,N,P,V)` indicates that at time `T` a puck `N` collided and started on a new trajectory. `P` gives the position (vector) of the center of the puck at the start of the trajectory. The tuple `trajectory(T,N,V,X)` indicates that at time `T` the puck `N` will be at vector position `X` as a result of the initial velocity at the beginning of trajectory `V`. `N` is the integer id of the puck (this solution assumes all pucks have the same radius and mass). Thus the trajectory of a puck is defined as the sequence of positions of the center of the puck until the next collision involving the puck occurs. This obviates the need for a list of collisions to be explicitly maintained. In the sectorized version of this model, additional information regarding the owning sector is incorporated to reduce the computation required within the `trajectory` calculations.

6.4.3 Pucks model definition

Arguably, the most "natural" way to describe the pucks system is to define the model in terms of a table object and puck objects. This is illustrated in Table 6.14. The attributes *numCollisions* and *maxCollisions* are defined for the top-level object to facilitate termination. Alternatively, the system could be simulated for a specified length of time.

6.4.4 Pucks model specification

A high level description of the model behavior may likely adopt the point of view of the active objects: the pucks. The lifetime of a puck may be described as: (1) travel until a collision occurs, (2) update velocity and (3) repeat cycle. Here, the observation is made that, at the CS level, some notion of how time passes must be described.[20] The modeler must indicate in the above description, *how long* the puck will travel before a collision

[20]The time flow mechanism itself has long been considered an implementation detail, such that model behavior should be expressible independent of time flow. This example indicates that model specification at the CS level may not in fact be time-flow-mechanism independent in all cases.

Table 6.14: CM Object Definition for Pucks I.

Object	*Attribute*	*Type*	*Range*
`CP`	*N*	permanent indicative	nonneg int
	numCollisions	status transitional indicative	nonneg int
	maxCollisions	permanent indicative	nonneg int
`table`	*width*	permanent indicative	nonneg int
	height	permanent indicative	nonneg int
`puck`	*position*	status transitional indicative	(0..table.width, 0..table.height)
	velocity	status transitional indicative	(real, real)
	radius	permanent indicative	nonneg real

occurs. This would seem, at least for this model, to force the modeler into reconciling an implementation detail very early in development. Specifically, the modeler knows the position and velocity of the pucks on the table (as well as the dimensions of the table itself). From this, the modeler must describe what happens next. This could take two forms, each reflecting the adoption of a time-flow mechanism (TFM). Assume that a given puck is at location (x, y) and the time is given by t. The modeler may describe what happens next by:

1. Determining the time until the next collision using the kinematic equations. Allow time to progress that far. Update the positions of all the pucks and resolve the collisions. This reflects a time-of-next-imminent-event TFM.

2. Allow time to pass, update the position of all the pucks, and determine if a collision occurred. If so, resolve any collisions. This reflects the adoption of a fixed-time TFM.

Clearly, an implementation must reflect a choice of time flow (as evidenced by Goldberg's work), and for this model, a CS description also depends on a vision for time flow. Must a high-level representation also be time flow mechanism dependent? Nance [152] illustrates a dependency between model performance and the time flow mechanism. His results demonstrate that for a particular model, *choice* of time flow is important, and the appropriate selection may be counter-intuitive. These observations imply that model representations facilitating the incorporation of a suitable time flow mechanism are desirable. This subject is addressed in greater detail in Chapter 8.

With the above issue in mind, the system may be described using the algorithm in Figure 6.29. This algorithm indicates the adoption of the time-of-next-imminent-event view. To facilitate this view in the CS, the object definitions must be modified to provide

```
Repeat Forever
        For i := 1 to Number of Pucks
                For j := i + 1 to Number of Pucks
                        t1[i, j] ← collision_time(puck i,puck j)
        For i := 1 to Number of Pucks
                For j := 1 to Number of Boundaries
                        t2[i, j] ← collision_time(puck i,boundary j)
        Clock = MIN(∀i, j :: t1[i, j], t2[i, j])
        Update all puck positions to the current value of clock
        Resolve all collisions for the current value of clock
End.
```

Figure 6.29: Algorithm for Pucks Simulation.

sequencing attributes, as illustrated in Table 6.15. The transition specification reflecting this is given in Appendix F. Some questions involving this example are discussed below.

6.4.4.1 Functions revisited

During the development of previous models, the assertion is made that, since functions in the CS have not been defined so as to admit model diagnosis, their use should perhaps be limited to non-model-specific activity. However, in the development of the pucks solution, this recommendation seems overly restrictive. To provide a transition specification for this model composed totally of action clusters, one must in effect choose an *implementation* of the kinematic equations that govern the system. For example, determining the time at which two pucks collide involves solving a quadratic equation. To describe this using action clusters, one could make explicit whether the two roots are to be solved together (in the same AC) or independently, and possibly in parallel (in different ACs). Making these types of decisions during the early specification process is counter to the philosophy espoused in this research. Consider also that when resolving a collision between two pucks, the normal and tangential vectors must be established. To accomplish this entirely in action clusters forces the definition of many "artificial" attributes, such as those required to maintain intermediate values. At the highest level, the description of model behavior should be unencumbered by these details. At the lowest level, these details, obviously, must

Table 6.15: CM Object Definition for Pucks II.

Object	*Attribute*	*Type*	*Range*
`CP`	*N*	permanent indicative	nonneg int
	numCollisions	status transitional indicative	nonneg int
	maxCollisions	permanent indicative	nonneg int
	puckColl	temp. transitional indicative	nonneg real
	bdryColl	temp. transitional indicative	nonneg real
`table`	*width*	permanent indicative	nonneg int
	height	permanent indicative	nonneg int
`puck`	*position*	status transitional indicative	(0..table.width, 0..table.height)
	velocity	status transitional indicative	(real, real)
	radius	permanent indicative	nonneg real

be resolved. At the middle levels, descriptiveness should be controllable. The CS provides this facility through the use of functions: the level of detail may be high, with much of the model behavior encapsulated in functions; or the level of detail may be low, by appealing exclusively to action clusters.

6.4.4.2 Looping constructs

Some mechanism must be provided by a mid-level specification language to permit block instantiation of objects, where the number of instances is given by model input – as in the case of the puck objects. For the CS, a FOR-loop notation may be adopted which provides looping within the context of a single action cluster.[21] The loop control variable is local to the AC and binding in its function. Loop control is more general than that permitted by many programming languages; for example, the statement

FOR i := (1 TO N) AND (i <> j) DO

is permitted. Note also from Appendix F that pucks are referenced using an array subscripting notation, e.g. `puck[i]`. Even though the object definition does not stipulate this, we assume this method of uniquely identifying multiply-instantiated objects through these implicit identifiers. In the absence of the highest-level specifications, the need for such a scheme is somewhat difficult to establish.

[21] An alternative is to implement for-loops within a group of action clusters using the extant CS syntax.

6.4.4.3 Multiple simultaneous updates

In this model, when updating the velocities of two pucks that have collided with each other, both updates must be done in the context of the same "function." That is, suppose two pucks, p_1 and p_2 collide. The new velocities are determined *jointly* based on their previous velocities. In the CS, functions assign a value to a *single* attribute. Thus, the CS solution must somehow utilize a function to change the velocity of p_1, based on the current positions and velocities of the two pucks, then, using a separate function call, update the velocity of p_2 using the original velocity value for p_1. The following solution is offered in Appendix F. The velocity update equations are encapsulated in a function that accepts parameter values for the two involved pucks and returns the new velocity for the puck identified by the first parameter. Thus, the solution requires a "temporary" puck object which maintains the original position and velocity of the first puck updated, for use during the update for the second puck. This solution seems less than ideal. Alternatives may be to: (1) extend the semantics of functions to permit updates to more than single attributes, or (2) allow procedures in the CS. Each of these approaches has potential benefits and drawbacks. Again, in the absence of the highest-level specifications, these issues cannot be completely resolved.

6.5 Example: Machine Interference Problem

The machine interference problem (MIP) is treated in numerous sources within the discrete event simulation community (see [152, 155, 163, 179, 180, 182]). The origins of this example date to Palm [186], and Cox and Smith [62]. Several versions of the problem are defined, each of which describes a class of queueing systems.

6.5.1 Problem definition

A group of N semiautomatic machines ($1 < N < \infty$) fail intermittently and must be repaired by an operator. Both failure and repair rates are distributed as Poisson random variables with parameters λ and μ respectively. The parameters λ and μ are assumed the same for each machine in the assignment. The model may be viewed as illustrated in Figure 6.30 which shows a system with $N = 12$.

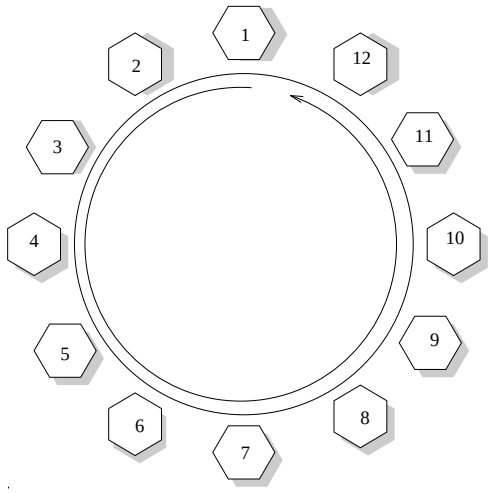


Figure 6.30: A Configuration for the Machine Interference Problem where $N = 12$.

Variations of the problem may be defined based on the method of failure detection.

First-failed. The operator begins at an idle location (usually central to the group of machines). When a failure occurs, the operator travels to the machine and repairs it. Upon completion of a repair, if no machines are failed, the operator returns to the idle location. Otherwise, if one or more machines are failed, the operator travels to each machine (in first-failed-first-served order) and repairs it. If the travel time of the operator is zero, this problem defines the $M/M/1$ class of queueing systems.

Closest-failed. To detect failures, the operator patrols the interior perimeter of the assigned group of machines in a unidirectional path. The distance between machines is assumed equal for each adjacent pair, and the rate at which the operator travels is assumed constant. This problem defines the $M/G/1$ class of queueing systems.

If multiple operators are defined (each following either the first-failed or closest-failed discipline), then the problem defines the $M/G/s$ class of queueing systems.

6.5.2 Single operator/first-failed

The object definitions for the single operator/first-failed (SOFF) model of the machine interference problem are given in Table 6.16. The model contains three object "classes:" (1) the top-level object, which is given attributes describing the number of machines, maximum number of repairs to simulate, and mean values for the operating and repair times, (2) the

Table 6.16: CM Object Definition for Single Operator/First-Failed MIP.

Object	*Attribute*	*Type*	*Range*
`SOFF`	*N*	permanent indicative	nonneg int
	maxRepairs	permanent indicative	nonneg int
	repairMean	permanent indicative	nonneg real
	workingMean	permanent indicative	nonneg real
`machines[1..N]`	*status*	status transitional indicative	(operating,failed, inRepair
	failure	temporal transitional indicative	nonneg real
	arrival	temporal transitional indicative	nonneg real
	endRepair	temporal transitional indicative	nonneg real
`repairman`	*status*	status transitional indicative	(busy,avail,inTransit)
	location	status transitional indicative	(idle,1..N)
	arriveIdle	temporal transitional indicative	nonneg real
	numRepairs	status transitional indicative	nonneg int

machine class, which stipulates N machine *instantiations,* and defines attributes indicating machine status, and times of the next failure, arrival of the repairman, and end of repair, and (3) the repairman, with attributes indicating status, location, and number of repairs completed, as well as an attribute containing the time at which the repairman will next arrive at the idle location.

The transition specification for the SOFF model is given in appendix G. The specification contains eight action clusters: *initialization, termination, failure, begin repair, end repair, travel to failed machine, travel to idle,* and *arrive idle.*

6.5.3 Multiple operator/closest-failed

The object definitions for the multiple operator/closest-failed (MOCF) model of the machine interference problem are given in Table 6.17. The object definition for the MOCF model is similar to that of the SOFF model, except that M instances of the repairman are defined, the attribute *arriveIdle* is replaced by the attribute, *t,* containing the inter-machine travel time, and the attribute *numRepairs* is attached to the top-level object rather than an individual repairman.

The transition specification for the MOCF model is given in appendix G. The specification contains seven action clusters: *initialization, termination, failure, arrival, begin repair,*

Table 6.17: CM Object Definition for Multiple Operator/Closest-Failed MIP.

Object	*Attribute*	*Type*	*Range*
`MOCF`	*N*	permanent indicative	nonneg int
	maxRepairs	permanent indicative	nonneg int
	repairMean	permanent indicative	nonneg real
	workingMean	permanent indicative	nonneg real
	numRepairs	status transitional indicative	nonneg int
`machine[1..N]`	*status*	status transitional indicative	(operating,failed, inRepair)
	failure	temporal transitional indicative	nonneg real
	arrival	temporal transitional indicative	nonneg real
	endRepair	temporal transitional indicative	nonneg real
`repairman[1..M]`	*status*	status transitional indicative	(busy,idle)
	location	status transitional indicative	(inTransit,1..N)
	t	permanent indicative	nonneg real

end repair, and *travel to next machine.*

6.6 Summary

In this chapter, the representational provisions of the CS are evaluated with respect to the CM through the development of four example models: (1) a multiple virtual storage batch computer system, (2) a traffic intersection, (3) a system of colliding rigid disks, and (4) the machine interference problem. The evaluation outlines needed enhancements to the representational facilities of the CS. The collection of CS primitives is extended to include INSERT, REMOVE, MEMBER, FIND and CLASS such that support is provided for CM set definition. A new form for the report specification is described and the notion of an *augmented* specification is introduced. The need for an experiment specification – to capture information such as the condition for the start of steady state – is also identified.

If the CS is viewed as serving a mid-level role in the hierarchy described in Chapter 3, the results of this chapter establish a basis for high-level support within the context of either a wide-spectrum or narrow-spectrum approach.

Chapter 7

MODEL GENERATION

He differentiated between existence and Existence, and knew one was preferable, but could not remember which.

Woody Allen, *Side Effects*

At the outset of this research, the Condition Specification is assessed as most suited to provide model representation at the middle level of the hierarchy described in Chapter 3. The role ascribed to the CS is that of a platform for model analysis. The Conical Methodology is proposed to be part of a next-generation modeling framework in Chapter 5, and toward this end, the development given in Chapter 6 examines methods by which the representational capabilities of the CS may be refined and extended to fully support the provisions and tenets of the CM. The results of Chapter 6 are independent of the adoption of a a narrow-spectrum approach – the existence of a high-level specification language separate from the CS – or a wide-spectrum approach – utilizing the CS as a high-level representation. Model generation is not a primary consideration in this effort, since issues in model generation have dominated SMDE research for many years. For completeness of presentation, this chapter primarily serves as a review and evaluation of the relevant model generation approaches produced by SMDE investigation. Based on the development of Chapter 6, some observations relating to new directions are also offered.

7.1 Prototypes

Model generator investigation within the SMDE may be divided into two categories: (1) dialogue-based approaches that support the Conical Methodology, and (2) graphical-based

approaches that support the definition of a new conceptual framework.

7.1.1 Dialogue-based approaches

The earliest model generator efforts within the SMDE date to the early 1980s. At the time, a primary challenge for the model generator designer was identifying mechanisms through which a model description could be effectively coerced from a modeler given the limitations of the standard character-based terminals. One mechanism that has been investigated is to engage the modeler in a menu-driven "dialogue."

Three dialogue-based model generator prototypes have been developed for the SMDE. Each supports the Conical Methodology, and is briefly described below.

7.1.1.1 Box-Hansen

Hansen [96] describes the first prototype model generator for the SMDE. Developed with assistance from C.W. Box, the Box-Hansen prototype supports model definition under the Conical Methodology. The generator provides an interactive dialogue through which a modeler may define the objects that comprise a model, and *attach* (and type) attributes to those objects. The Box-Hansen prototype also allows the definition of sets within a model. However, the prototype offers little assistance to the model specification phase of the CM, admitting only unstructured natural language descriptions of model behavior. No provisions are given for analysis of this specification nor is the model specification evaluated with respect to the model definition.

7.1.1.2 Barger

Barger [25] describes a follow-on effort to the Box-Hansen prototype. Using the existing model generator to capture a CM model definition, the Barger prototype provides a leveled dialogue approach to derive the specification of indicative attributes using the CS as the target form. Barger's prototype also includes provisions for acquiring study documentation. Barger suggests that the specification of status transitional indicative attributes may provide the key to the derivation of a *complete* specification since a modeler is able to provide a "foundation" by describing the value changes of these attributes. Although designed to use the Box-Hansen model generator as a front-end, the two prototypes remain unconnected.

7.1.1.3 Page

The most recent effort in dialogue-based model generators is described by Page [182]. The Page prototype represents the conceptual integration and extension of the Box-Hansen and Barger prototype efforts. Implemented in a window-based environment, the Page prototype fully supports model development under the Conical Methodology utilizing the Condition Specification as the target form for representing model behavior. To enable the specification of sets, four set operations are defined for the CS (similar to those listed in Chapter 6). The Page model generator provides some limited analytic functions such as attribute initialization, utilization and consistency (see Chapter 5), and the CM restriction that model definition precede model specification for any object is also enforced. Page echos Barger's conclusion that status transitional indicative attributes serve a primary role in the derivation of a complete model specification [182, p. 42].

7.1.2 Graphical-Based Approaches

In 1987 a divergence in the SMDE research in model generation occurred. Prior efforts had served strictly to support the Conical Methodology using dialogue-based model generators. The popularization of window-based software, and the potential benefits of animating simulation models, spurred a new investigation to support the definition of a conceptual framework suitable for "visual" simulation model development.

To date, two prototypes have been completed in this graphical-based effort. These are described briefly below. A production system based on these two prototype efforts known as the Visual Simulation Environment (VSE) is scheduled for completion by the fall of 1994.

7.1.2.1 Bishop

Bishop [32] describes the General Purpose Visual Simulation System (GPVSS). GPVSS represents an SMDE prototype for visual simulation; it provides model definition, model specification and model translation into executable code, as well as animation of the simulation. Although congruous with many precepts of the CM, GPVSS does not directly support the methodology. GPVSS is based on a graphical, object-oriented, activity-based approach to model development. GPVSS identifies a model as being composed of submodels which contain static objects through which dynamic objects travel during a simulation. Submod-

els and objects are defined graphically using a graphical editor. The paths that dynamic objects take through the simulation are also graphically defined. Within the GPVSS, specification of model behavior is very low level: the modeler must utilize C-based macros, and in many cases provide C code.

7.1.2.2 Derrick

Derrick [66] describes the Visual Simulation Support Environment (VSSE). The VSSE is a prototype implemented to test the functionality of the *multifaceted conceptual framework for visual simulation modeling (DOMINO),* and represents a major extension of the GPVSS effort. The DOMINO, and its associated *visual simulation model specification language (VSMSL),* represent the core of the production VSE.

The DOMINO. According to [66, p. 38], an important, if not pervasive, influence during the development of the DOMINO was:

> ...the desire for an approach which allows the modeler to represent a model and its components exactly as they are conceptually or naturally perceived. Like [what-you-see-is-what-you-get] WYSIWYG, this could be described as WYSIWYR (What You See Is What You Represent) capability. The modeler needn't have to contort his own view of the model in order to fit the requirements of the conceptual framework under which he is guided.

At the most basic level, a DOMINO *model* of a system is comprised of model components and the interactions among these components. Derrick classifies model components using four categories [66, p. 40]:

- *Real* components have a direct correspondence to a component in the system being modeled. Real components are "visualized."
- *Virtual* components do not have a direct correspondence in the system and are not visualized. Virtual components are typically linked to model features not having a "real" representation such as components for statistics collection, random variate generation, model startup and so on.
- *Dynamic* components are movable. Movement may be in three forms:
  - *Spatial* movement is reflected as physical movement of real dynamic components between model components during animation.
  - *Temporal* movement reflects the passage of time relative to a real or virtual dynamic component.

  - *Logical* movements are changes in the logic decision path of a real or virtual dynamic component.

  Derrick [66, p. 50] points out that dynamic components move throughout the static and dynamic structures (see below) of the model. Movement up and down in the model static hierarchy is via decomposed submodels (see below). Within a submodel, a dynamic component can utilize the resource of a static component. Dynamic components can also move into decomposed dynamic components and among its member subdynamic components and base dynamic components (see below).

- *Static* components are physically at rest (if real) and immovable (whether real or virtual). Furthermore, these components are permanently within the model, staying within the model boundaries for the duration of model execution.

These model components form model structures. Two types of model structures are identified: (1) a *model static structure,* and (2) *model dynamic structures.* Only one model static structure exists for any model – this structure has the model itself as its root – although it may be comprised of a hierarchy of *simple static structures.* A model may have multiple dynamic structures. Based on these structures, five additional classifications for model components are defined [66, p. 41]:

- A *submodel* is the root of a simple static structure with children of zero or more submodels and zero or more static objects.
- A *static object* is the most basic model component of interest in a simple static structure and, as such, cannot be decomposed.
- A *dynamic object* is the dynamic model component which is the basis (root) for model dynamic structures and is decomposable.
- A *subdynamic object* is the root of a simple dynamic structure and can be decomposed into zero or more subdynamic objects and zero or more base dynamic objects.
- A *base dynamic object* is the most basic model component of interest in a simple dynamic structure and cannot be decomposed.

According to Derrick [66, p. 41], the choice to represent a system component which is static as a submodel or static object is based primarily on the expected need for a decomposition point in the model hierarchy.[1]

[1]Derrick [66, p. 42] observes that the greatest flexibility in development is retained by modeling system components as submodels. However, he notes, "other considerations related to visualization/animation requirements could dictate otherwise."

Model definition. Under the DOMINO, modelers identify class information such as attributes, and inheritance hierarchies. Model decomposition points are identified and a background image is associated with each. These background images, called *layouts,* provide the visual landscape over which the dynamic objects travel. A set of images is defined for each class. Each component within the layout image is identified by graphically binding the image portion corresponding to the component.

Dynamic object movement between or among model components is specified for each layout by the creation of roadways or *paths.* These paths connect the model components that exist within each layout. *Connectors* are also created within the layouts to facilitate the movement of dynamic objects, both into (*entry* connectors) and out of (*exit* connectors) the layout, relative to higher levels. Top-level layouts (for the model and decomposed dynamic objects), therefore, do not have connectors.[2]

Interaction points, or *interactors,* are created which permit dynamic object interaction with static and base dynamic objects. During animation, dynamic objects are said to move *into* decomposable components and *to* non-decomposable components.

The spatial description of a layout's image which includes designating model components, connectors, interactors and paths is called a layout *definition.* Each layout image must have a layout definition. Besides layout definitions, a modeler must also state the explicit rules governing component behavior. The mechanism for this is described below.

Model specification. The behavior of model components is described using an English-like specification language called the *visual simulation model specification language (VSMSL).* According to Derrick [66, p. 144] the VSMSL, "enables modelers to specify model dynamics, [and] the rules for component interaction, at a high level." The VSMSL is utilized in three types of "logic specifications" under DOMINO [66, p. 70]:

- *Supervisory* logic. Models built with supervisory logic are *machine-oriented.* The supervisors (machines) are the principle influencers for model execution. The dynamic objects (material, transactions) are manipulated and moved from component to component.
- *Self* logic. Self logic is attached to a dynamic object which executes and determines its own destiny. Models built entirely around self logic are called *material-oriented.*

[2]Movement downward from a level must be directed toward the entry connector at the lower level.

- *Method* logic. Logic attached to a component class and activated by sending a message to an owning component in the class.

The VSMSL contains twenty-five statement types supporting a wide variety of behavior ranging from attribute assignment, to component movement, to display manipulation. In VSMSL, each reference to a model component includes a reference to its type (e.g. submodel, static object, dynamic object, subdynamic object, base dynamic object). The language provides abbreviations, *sm, so, do, sdo* and *bdo* for these types. Figure 7.1 contains a VSMSL description (in supervisory logic) of a queue for a block within a traffic intersection example similar to the one given in Chapter 6. The figure is taken from [66], and is given here simply to provide an indication of the nature of the VSMSL. For a complete description of the VSMSL and the DOMINO, refer to [66].

7.1.2.3 Evaluation

A discussion of the VSSE (as supported by DOMINO and the VSMSL) and the philosophy of this research effort is warranted. Firstly, does the VSSE fit within the structure of a next-generation framework as presented in Chapter 3? The answer is: not directly. The philosophy adopted here is that *visualization* of a simulation model is merely one of a wide variety of implementation options. Iconic forms may indeed be useful for model development (see the discussion in Chapter 3), but they need not *necessarily* correspond to a given set of animation requirements or forms. When animation of the model is not a project objective (and admittedly, this may be a rare occurrence), no animation-related information should be *required* during model development. The DOMINO and the VSMSL tightly couple model development to a particular implementation detail: animation.[3] As such, they are incongruous with the philosophy espoused in this effort. Two additional observations may be made regarding the DOMINO and VSMSL:

- The VSMSL, while English-like in nature and expressive enough to represent a wide variety of behaviors, is in some respects at a lower level than many SPLs. Consider the VSMSL excerpt given in Figure 7.1. The code:

[3]This coupling is largely a function of the philosophy of graphical model development underlying the DOMINO.

```
– BLOCKQUEUE SUBMODEL CLASS SUPERVISORY LOGIC
_ ***********************************************
– * If there are others waiting or the blockspace is busy, join the queue and
– * wait until first in line and blockspace is idle.
_ ***********************************************
if attr numberWaiting of this sm is > 0 or
      attr status of so blockSpace is BUSY@ then
      begin
            add 1 to attr numberWaiting of this sm;
            put attr numberWaiting of this sm into holdingVar;
            put sys attr ident of this do into
                  attr vehicleList[holdingVar] of this sm;

            engageIn waiting until attr vehicleList[1] of this sm is
                  sys attr ident of this do and attr status of so blockspace is IDLE@;

            – Reset every vehicle's position in the queue
            put attr numberWaiting of this sm into holdingVar;
            subtract 1 from holdingVar;
            repeat with i = 1 to holdingVar
            begin
                  put i+1 into dynObjId;
                  put attr vehicleList[dynObjId] of this sm into
                        attr vehicleList[i] of this sm
            end;
            subtract 1 from attr numberWaiting of this sm
      end
_ ***********************************************
– * Otherwise, proceed immediately through queue.
_ ***********************************************
```

Figure 7.1: Supervisory Logic for a BlockQueue in VSMSL.

```
add 1 to attr numberWaiting of this sm;
put attr numberWaiting of this sm into holdingVar;
put sys attr ident of this do into
    attr vehicleList[holdingVar] of this sm;
```

merely implements an enqueue operation. Dequeueing is specified using:

```
put attr numberWaiting of this sm into holdingVar;
subtract 1 from holdingVar;
repeat with i = 1 to holdingVar
begin
      put i+1 into dynObjId;
      put attr vehicleList[dynObjId] of this sm into
            attr vehicleList[i] of this sm
end;
subtract 1 from attr numberWaiting of this sm
```

Some higher-level constructs should be provided to support these common mechanisms.

- The requirement that the possible paths of dynamic objects must be *a priori* determinable limits the classes of systems that can be animated. The static path paradigm is suitable for manufacturing systems, and networks, but less suitable for systems such as a colliding pucks (see Chapter 6) or a typical military simulation – through which targets may travel and are intercepted at any point in a three-dimensional space. To animate systems such as these, a preferred approach is to describe the movement of model objects in terms of a model coordinate system. Movements in the model may then be translated into a display coordinate system for animation.

Despite the obvious differences in the philosophy of this approach and that of the VSSE effort, the VSSE investigation has contributed significantly to the theory of visual simulation, and simulation modeling methodology as well. Conceivably, minor changes in the DOMINO and VSMSL could produce an approach suitable for incorporating visual implementations within the general framework described in Chapter 3. Certainly, the lessons learned from the VSSE effort must be recognized in any framework that supports model animation as a project objective.

7.2 New Directions

Despite the existence of the fully functional Page prototype, the development given in Chapter 6 is accomplished without automated assistance. The two primary reasons for this are:

1. The platform hardware for the prototype is tenuous, and has been unsupported by the manufacturer for several years. Porting the prototype to a new platform would require considerable effort, and has been deemed a low priority for this research effort in light of the second motivation.

2. The desire to permit the development of this research to be unbiased relative to prior efforts and conclusions.

Thus, the following discussion adopts the perspective of a modeler who has worked directly in the Condition Specification, without automated assistance. Based on these experiences, some thoughts are given regarding new ways of coercing a CS from a modeler. First, a discussion of the attribute-oriented approach to model specification provided by the Barger and Page prototypes.

7.2.1 Attribute-oriented development

Both the Barger and Page model generators encourage model specification by starting at the leaves of the model development tree – the attributes. An attribute is selected, a value change is described, and a condition is associated with that value change. The motivation for, and observation resulting from, these two efforts is that by causing a modeler to describe model behavior in this fashion, the specification is quickly "fleshed out," i.e. the value changes of a single attribute are typically described in a consecutive manner. This results in the identification of several model conditions. For typical models, the entire "condition structure" can be generated from the value changes of just a few (typically, status transitional) indicative attributes.

However, the question must be asked: does this conform to a "natural" view of model behavior? That is, when one envisions an object-based model, does the *first* thought regarding model behavior center around an attribute value change? For some modelers, perhaps, but certainly not for all. The models in Chapter 6 are specified in the CS using an action cluster-oriented perspective. Modelers may also prefer other, more traditional, conceptual frameworks. Some alternative approaches for model generation under the CM/CS based on the experience gained from Chapter 6 are described below.

7.2.2 Action cluster-oriented development

When a modeler envisions model behavior, the picture may take the form, "when this occurs, that also occurs." When the CS is the language of discourse – and the modeler is working at the CS level – this phenomenon produces an action cluster-oriented depiction of model behavior. In traditional CFs, and languages supporting these CFs, this phenomenon might describe an event or activity.[4] Interestingly, even when the CS is the target language, a modeler familiar with traditional CFs will likely identify those conditions which represent the "root" condition of an event or activity. Consider the situation depicted in Figures 6.7 and 6.8. These figures represent an end-of-service event at the JESS for the MVS model and the corresponding action clusters. A modeler working in the CS may think of the WHEN ALARM condition first, and mentally lump all the actions from the event into the action cluster for that condition. Only upon recognizing that a "sub-condition" is present will the decomposition given in Figure 6.8 be accomplished. This observation illustrates that the CS, while independent of traditional CFs, does not directly provide a CF facilitating model development at the highest levels. Still, an action cluster-oriented development could be helpful. Two different approaches are evident.

7.2.2.1 Action cluster-oriented dialogue.

A dialogue-based model generator for the CS, such as those of Barger and Page, could readily permit the model to be constructed in an action cluster-oriented fashion. The dialogue would merely involve the primary identification of conditions with a secondary association of actions. A more interesting possibility is the use of the action cluster incidence graph (ACIG) as a basis for graphical development.

7.2.2.2 A graphical approach.

Historically, the ACIG has been constructed from the textual CS representation, and has functioned solely as a platform for model analysis. However, this incidence graph could be utilized to foster model development in an action-cluster oriented approach.

[4] If the modeler naturally views the system using a process view then these events relate to a particular model object.

A model generator could provide an iconic interface through which an ACIG might be constructed. For example, a modeler could create a set of nodes, each identified by a name or perhaps number. Exploiting iterative refinement, a modeler could "click on" a node and be given the opportunity to describe the condition and associated actions. When "sub-conditions" become apparent, the node is decomposed. A modeler might be permitted to connect any two nodes, irrespective of establishing the criteria for connection, using solid or dashed arcs. The system could easily identify all unsubstantiated connections, as well as automatically generating connections between nodes based on the rules for ACIG construction. The ACIG simplification routines identified by Puthoff [194] could also be incorporated.

7.2.3 Traditional world view-oriented development

As observed above, even when the CS is the target language, model development is often facilitated by adopting a traditional world view. Overstreet illustrates how a CS may be transformed into a specification adopting either the event scheduling, activity scan, or process interaction world views. Overstreet also postulates that an equivalent CS can be constructed for any model specification in any programming language [178, p. 247]. While the veracity of this statement is difficult to assess, certainly *any* model specification that conforms to the Conical Methodology can be transformed into an equivalent CS, regardless of its CF.

Similar to the incidence graph-based approach described above, a model generator could be constructed which provides CM-oriented variants of event graphs, process graphs, or activity diagrams which could be used to generate a CS.

Chapter 8

MODEL ANALYSIS AND EXECUTION

For one thing, they used computers constantly, a practice traditional mathematicians frowned on. For another . . . they appeared to care that their mathematics described something that actually existed in the real world.

Michael Crichton, *Jurassic Park*

A set of requirements for a next-generation modeling framework is proposed in Chapter 3. An abstraction that implies model development through transformation is also presented. The basic tenets of modeling methodology stipulate that the overriding objective of simulation is producing a correct decision. Thus the hierarchy of representations suggested by the abstraction must support this objective. As recounted in Chapter 3, history indicates a strong correlation between the correctness of the decision and the correctness of the model upon which the decision is based.

For this research effort, the Conical Methodology has been suggested and evaluated as a suitable methodology to support a next-generation modeling framework. The objective of correctness is facilitated (in part) through the provision of high-level implementation-independent descriptions of the model. These descriptions evolve through a series of refinements until an executable model suitable for a given set of implementation requirements is produced. The nature of the model evolution, and the level of automatability is, however, largely a function of the representational forms, the target implementation, and its concomitant level of maturity as a technology.

The focus of this research in terms of model representation has been at the middle level of the framework. The Condition Specification is proposed as an intermediate represen-

tational form for model diagnosis. The implications of this language choice for envisaged higher-level representations are evaluated in Chapters 6 and 7. In this chapter, the relationship between the CS and lower-level forms is investigated. Generating an executable model from a CS representation may be affected in two ways: (1) translating the CS representation into an (several) appropriate implementation language(s), or (2) directly implementing the CS representation. Addressing the first approach requires the identification of a specific set of implementation requirements. As suggested by Figure 3.4, the number of possible combinations of implementation requirements is considerable. The objectives of this research effort favor broadness of concept and generality of solution. Therefore, the development of this chapter focuses on the area where support is potentially most general: directly implementing a CS representation. Note that translating the CS into a variety of implementation languages fulfills the transformational hierarchy using a narrow-spectrum approach (see Chapter 3). Defining methods for directly implementing the CS effectively widens the spectrum of the language. Both approaches merit investigation, even beyond that possible in the limited scope of this effort. The groundwork is laid here with a precise characterization of the semantics of a CS transition specification.

8.1 A Semantics for the Condition Specification

Overstreet's characterization of a model implementation is reviewed in Chapter 5. If $A(M,t)$ is a model attribute set for a model specification M at time t. A model specification is a model implementation if,

1. For any value of system time t, $A(M,t)$ contains a set of state variables.
2. The transition function describes all value changes of those attributes.

Thus, if "system variables" have been added to the object specification set so that $A(M,t)$ always contains a state set, then the transition description must contain a complete description of how these additional attributes change value. The model implementation serves as the basis for model execution. The nature of the implementation of a simulation model varies according to the representational mechanism, and its associated semantics. In this section, the existing CS semantics are evaluated and, where necessary, re-stated to facilitate the more definitive mid-level role (in either a narrow-spectrum or wide-spectrum context) intended for the language within this research effort.

8.1.1 Interpretation of a condition-action pair

The basic element of a CS is the condition-action pair (CAP). According to Overstreet [178, p. 89]:

> The semantics of a CAP are straightforward: whenever the condition is met in the model, the specified action takes place.

For reasons explicated in the subsequent development of concepts, the semantics of a CAP adopted here are stated as follows:

> *The action of a CAP may occur only if the corresponding condition is true.*

8.1.2 Interpretation of an action cluster

As outlined in Chapter 5, CAPs with identical conditions form action clusters (ACs). Overstreet [178, p. 70] asserts:[1]

> In interpreting a [model specification] MS, each CAP is to be treated as a "while" structure rather than an "if" structure. The difference is this: as an "if" the actions of the CAP would occur exactly once when the condition is met; as a "while" the actions repeat until the condition is no longer met.

The motivation for choosing a while-semantics is to accommodate an envisaged clock update policy: the clock is only updated when all model conditions are false. Thus, when a condition becomes true, it remains true until a specific action causes the condition to become false. For determined action clusters (DACs), the while-semantics is accommodated by implication, i.e. the alarms are assumed to "go off" only once. Overstreet [178, p. 280] states that for each contingent action cluster (CAC):

> at least one output attribute should also be a control attribute for the CAC. ... Recall that the interpretation of a CAC is a "while" construct rather than an "if." If the CAC cannot potentially alter the condition, an infinite loop results. To eliminate the infinite loop, it is not sufficient that some other AC can occur in the same instant as the CAC which can alter the value of the CAC's condition. For if this were true, the CS would contain unresolved order dependencies.

The diagnostic technique of action cluster completeness (or determinancy, see Chapter 5) is defined to detect the presence or absence of these infinite loops under this semantics.

[1] In this passage Overstreet refers to a CAP, but actually intends AC.

```
Whenever thisEvent happens
    if x = 10 then
        y := y + 1
        if z then
            p := 2
        if q then
            r := 3
```

```
WHEN ALARM(thisEvent):
    B$1 := true

B$1 AND x = 10:
    y := y + 1
    B$2 := true
    B$3 := true
    B$1 := false

B$2 AND z:
    p := 2
    B$2 := false

B$3 AND q:
    r := 3
    B$3 := false
```

Figure 8.1: An Event Description with Nested Logic and the Corresponding Action Clusters.

A strict while-semantics, and the associated requirement that the intersection of the output attribute and control attribute sets for any CAC be nonempty, is problematic because these requirements presuppose that every AC is always a *candidate* for execution.[2] This fact is readily seen when considering the problem of generating a CS from higher-level forms. Consider the situation illustrated in Figure 8.1. Here a simple event description consisting of some nested logic is presented. Also given are the action clusters that might be generated from this event description using a procedure similar to that described in Chapter 6. Note the "overhead" in terms of assignments to Boolean variables necessary to satisfy the criterion for action cluster completeness. Clearly this technique could easily become "messy" for large models and complex condition structures. While the manipulation of additional Boolean variables may not inhibit automated translation, a significant encumbrance may be introduced *viz.* the human understanding of the CS. Figure 8.1 demonstrates that an event description (at some arbitrarily high level of representation) may contain many conditions, each of which determines one or more actions. However, these actions need not necessarily affect the value of their "owning" condition. Some conditions (e.g. x = 10) may remain true

[2]Here execution refers to the evaluation of the condition on the AC, followed, if the condition is true, by the performance of the actions given by the AC.

after the body of the event routine is exited. An important recognition is that in the case of Figure 8.1, the three CACs *must always be coincident* with the determined AC. If the determined AC is not a *candidate* for execution at some point in a model implementation, then the truth values of the conditions on the coincident CACs are irrelevant.

Based on the above observation (and in order to support the model of computation defined subsequently) the semantics of an AC are revised within the context of this research effort:

> *Whenever the condition is tested, if the condition is true the associated actions occur.*

The ordering of actions in an AC is not stipulated. Overstreet proves that determining an (inter-AC or intra-AC) ordering dependence among arbitrary model actions is undecidable (see Chapter 5). For general purposes, the actions of an AC may be regarded as sequential, given some modeler-specified ordering. However, for certain implementations, e.g. those requiring the exploitation of parallelism, other interpretations may be useful.

8.1.3 Interpretation of action cluster sequences

The execution of a CS on a hypothetical machine may be described in terms of a sequence of action clusters. The first action cluster in the sequence is the initialization AC, and the last, termination. Linking initialization and termination is a collection of time-based, state-based and mixed action clusters. Since any CS containing mixed action clusters may be transformed into an equivalent CS containing only time-based and state-based action clusters ([178, p. 215]), the action cluster sequence may be viewed as containing only DACs and CACs. Overstreet [178, p. 193] observes that this sequence forms a chronology of model actions as depicted in Figure 8.2. The figure illustrates an action sequence graph (ASG). An ASG provides similar information to an ACIG except that an ASG connotes the *actual causal relationships* resulting from some execution of the CS (on a hypothetical machine). A formal relationship between the two graphs is established below.

The ASG in Figure 8.2 depicts a trajectory of model execution at some point in simulation time subsequent to model initialization. State changes occur as the result of a time-ordered execution of determined action clusters.[3] Coincident in (simulation) time

[3]Here time refers to simulation time.

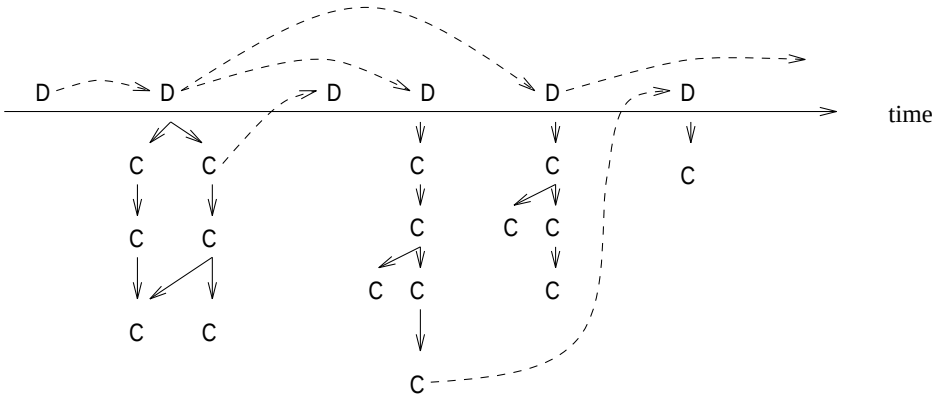


Figure 8.2: Action Sequence Graph. Each determined action cluster (D) must be scheduled prior to its occurrence. After model initialization, some dashed arc must lead into each D. Each contingent action cluster (C) may be caused by either a D or a C, but must occur in the same *instant* as some D. Thus each instance of a D can cause (directly or indirectly) a "cascade" of Cs in the same instant in the following manner: the D may change the condition of one or more Cs to true and their actions may change the conditions of other Cs to true, and so on.

with a determined action cluster are zero or more contingent action clusters. Although not implied by Figure 8.2, determined action clusters may also be coincident in time. This can occur in two ways: (1) two (or more) alarms are set for the same future value of simulation time, or (2) an alarm is set to go off "now." Strict event scheduling paradigms preclude the latter situation (in terms of events), but the former is always a possibility in any discrete event simulation model.

Overstreet's treatment of a semantics for coincident action clusters is incomplete for our purposes. He states [178, p. 89]:

> Note that it is possible for several conditions to be true simultaneously. In this case, the actions are considered to occur simultaneously.

Unclear from this statement is whether this rule applies only to a model specification – in which all the actions may appear to occur, in some sense, simultaneously (at least during the same *instant*), or also to model implementation – for which the validity of such a rule would be difficult to formulate. For this effort, the following semantics for coincident action clusters is proposed.

8.1.3.1 Precedence among contingent action clusters

As indicated by the ASG in Figure 8.2, a "cascade" of CACs may follow the execution of any DAC. This cascade is formed by precedence relationships among CACs for any given instant of model execution. If a directed path exists in the ASG between AC_i and AC_j then AC_i precedes AC_j for a particular instant since the execution of AC_i causes (directly or indirectly) the execution of AC_j. If no directed path between two ACs exists in the ASG, then an ordering on their execution cannot be established. In this case, if the two ACs possess read-write or write-write conflicts (see Chapter 9) then the model implementation may be ambiguous.

8.1.3.2 Precedence among determined action clusters

As previously stated, two or more DACs may be coincident in (simulation) time during a given model execution. These DACs *may* appear as "sources" for a cascade of CACs in the ASG. A sequenced order of execution for the ACs may follow two general patterns: (1) execute all DACs, followed by all CACs subject to the precedence relationships among the CACs, or (2) consecutively execute each DAC and its associated CACs. Based on the translation scheme between the CS and higher-level event-based forms outlined in Chapter 6, only the latter approach is correct when "mutually interfering" events occur during the same instant. This distinction is elaborated below.

For purposes of the following discussion, let E_1 and E_2 be event descriptions in some high-level model representation adopting an event scheduling world view. We say that E_1 and E_2 are *mutually interfering,* denoted $E_1 \bowtie E_2$, if: (1) the actions of E_1 are conditional on the occurrence of E_2 and similarly the actions of E_2 are conditional on the occurrence of E_1, and (2) E_1 and E_2 occur during the same instant.[4] The following are mutually interfering events.

[4]Note that this definition may be extended to more than two events. In fact, it may be readily demonstrated that mutual interference ($\bowtie$) forms an equivalence relation.

```
{ Event  E1 }                    { Event  E2 }
Whenever A happens               Whenever B happens
   if event B has not occurred      if event A has not occurred
   during this instant              during this instant
      do w                             do y
   else                             else
      do x                             do z
```

If these two events occur simultaneously, then a serial execution produces either the state resulting from w and z (E_1 followed by E_2) or the state resulting from y and x (E_2 followed by E_1). If a serial ordering of execution is not provided, the results are indeterminate.[5]

Using the event-AC correspondence illustrated in Chapter 6 the following ACs may be produced from the event routines E_1 and E_2.

```
{ AC1 }                          { AC4 }
WHEN ALARM(A):                   WHEN ALARM(B):
     B$1 := true                      B$2 := true
     A := true                        B := true

{ AC2 }                          { AC5 }
B$1 AND B:                       B$2 AND A:
     x                                z
     B$1 := false                     B$2 := false

{ AC3 }                          { AC6 }
B$1 AND NOT B:                   B$2 AND NOT A:
     w                                y
     B$1 := false                     B$2 := false
```

If the execution of action clusters is such that both DACs are executed prior to the CACs, then the following sequence is possible: AC_1, AC_4, AC_2, AC_5. This sequence produces a state resulting from x and z. Thus, separation of the DACs from their associated CACs during execution may result in an "interleaving" of events. If these coincident events are mutually interfering, such an execution sequence is incorrect.

8.2 Direct Execution of Action Clusters Simulation

Based on the semantics given above, algorithms for the direct execution of action clusters simulations may be defined. Note however, that several properties of interest, such as

[5]For an historical perspective on the problem of handling simultaneous events refer to [187]. Some issues involving simultaneous events and parallel simulation are presented in [60].

the precedence relationship among CACs during any instant, have been defined in terms of the ASG. Since the ASG depicts an *actual* execution sequence and is neither *a priori* determinable nor a general description of *any* implementation of a given model specification, its usefulness for algorithm construction is limited. However, the information available in an ASG, i.e. the causal relationships among ACs during an execution of the CS, is also provided in the ACIG. Specifically, the ASG depicts a time series of instances of subgraphs of the ACIG.

8.2.1 Utilizing the ACIG as a model of computation

We begin with a formal proof that each DAC and associated cascade of CACs in the ASG has a corresponding subgraph in the ACIG. For purposes of the theorem, we say that an ASG is *vertex-contracted* if, for every cascade of CACs, all vertices representing different occurrences of the same AC are contracted into a single vertex.

Theorem 8.1 *For any model specification M in the CS and any implementation M', if N' is a subgraph of a vertex-contracted $ASG(M')$ induced by a single DAC and all CACs reachable from it without passing through another DAC, then N' is a subgraph of $ACIG(M)$.*

Proof: Let M be a model specification in the CS and M' be the implementation of M on a hypothetical machine. Let G' be the action sequence graph of M' and G be the action cluster incidence graph of M. For some DAC, $n \in G'$, let N' be the subgraph of G' induced by n and all CACs reachable from it without passing through another DAC.

Suppose N' is not a subgraph of G.

Case I: $V(N') \not\subseteq V(G)$. Then an AC is executed which does not appear in G. By definition the ACIG contains all model ACs. Therefore $V(N') \subseteq V(G)$.

Case II: $A(N') \not\subseteq A(G)$. Then $\exists\ i, j \in M' \ni AC_i$ causes AC_j but an arc between AC_i and AC_j does not exist in G. However, for AC_i to cause AC_j an output attribute of AC_i must be a control attribute of AC_j. By definition the ACIG contains an arc from AC_i to AC_j. Therefore $A(N') \subseteq A(G)$.

Case III: The restriction of ψ_G to $A(N')$ does not yield $\psi_{N'}$. This is false trivially.

The evaluation of all cases leads to a contradiction. Therefore the supposition must be false and N' is a subgraph of G. □

The proof that a dashed arc in the ASG has a correspondence in the ACIG is trivial. Thus, Theorem 8.1 establishes that the ACIG for a CS contains the requisite information

to provide action cluster precedence consistent with the semantics defined in the previous section. In other words,

the ACIG provides a context for control flow in an implementation of the CS.

Whenever an AC is executed, the only ACs potentially enabled as a result, and therefore the only model conditions which must be subsequently tested, are given by the arcs in the ACIG. Algorithms suitable to exploit the information provided by the ACIG are presented below.

8.2.2 Minimal-condition algorithms

Figures 8.3 and 8.4 present algorithms for direct execution of action clusters (DEAC) simulations that are described as "minimal-condition." Minimal-condition implies that given a completely simplified ACIG as a basis, and using the semantics for a CS defined above, the number of state-based conditions evaluated upon the execution of any given AC is minimal. Note that the optimality of these algorithms depends, to a large extent, on their implementation (as briefly discussed below). Two algorithms are defined. For both algorithms a list, $\mathcal{A}$, of scheduled alarms is maintained as well as a list of state-based action clusters, $\mathcal{C}$, whose conditions should be tested within the current context of model execution. The simplified ACIG provides a list of state-based successors for each AC which is used to maintain $\mathcal{C}$.

Figure 8.3 presents a minimal-condition algorithm for a CS containing mixed ACs. Efficiently handling mixed action clusters requires a somewhat sophisticated approach. If σ_j is a mixed AC and a solid arc exists in the ACIG from AC σ_i to σ_j, then let $\sigma_j \in \sigma_{i_S}$ (the set of state-based successors of AC σ_i). When a mixed AC is a state-based successor of an executing AC, only place the mixed AC in $\mathcal{C}$ (the list of potentially enabled ACs) if the AC is in $\mathcal{M}$ (i.e. its alarm part has already gone off). When the mixed AC executes, that AC is removed from both $\mathcal{M}$ and $\mathcal{C}$.

Figure 8.4 depicts a minimal-condition algorithm for a CS without mixed ACs. Note that in both algorithms, executing the termination AC (as either a determined, contingent or mixed AC) causes an exit from the simulation proper. Note also that an AC may appear in multiple successor sets. Therefore, an efficient implementation of both algorithms might, among other things, check for duplicates when inserting into the list $\mathcal{C}$.

Let $\mathcal{A}$ be the ordered set of scheduled alarms.
Let $\mathcal{C}$ be the set of state-based and mixed action clusters whose conditions should be tested immediately.
Let $\mathcal{M}$ be the set of mixed action clusters whose alarms have "gone off" but whose Boolean condition has not been met.
Let σ_{i_S} be the set of state-based successors for action cluster σ_i (where $1 \leq i \leq |$ ACs $|$).

Initially

$\forall\, \sigma_i$, set σ_{i_S} (from simplified ACIG)
$\mathcal{A} = \mathcal{C} = \mathcal{M} = \emptyset$
Perform actions given by the initialization AC and state-based successors

Simulate

```
while (true) do

    clock ← time given by FIRST(A)
    while (clock = time given by FIRST(A)) do
        let σ_a be the AC corresponding to FIRST(A); remove FIRST(A)
        if (condition on σ_a is WHEN ALARM) or (condition on σ_a is AFTER ALARM and Boolean part is true)
            perform actions of σ_a
            add σ_{a_S} to C

            while (C ≠ ∅)
                remove σ_c ← FIRST(C)
                if condition on σ_c is true
                    perform actions of σ_c
                    if σ_c ∈ M, remove σ_c from M
                    for each σ_i ∈ σ_{c_S} do
                        if condition on σ_i is not mixed then add σ_i to C
                        if condition on σ_i is mixed and σ_i ∈ M then add σ_i to C
                    endfor
                endif
            endwhile
        else
            add σ_a to M
        endif
    endwhile

endwhile
```

Figure 8.3: The Minimal-Condition DEAC Algorithm for a CS with Mixed ACs.

Let $\mathcal{A}$ be the ordered set of scheduled alarms.
Let $\mathcal{C}$ be the set of state-based clusters whose conditions should be tested immediately.
Let σ_{i_S} be the set of state-based successors for action cluster σ_i (where $1 \leq i \leq |$ ACs $|$).

Initially

$\forall\, \sigma_i$, set σ_{i_S} (from simplified ACIG)
$\mathcal{A} = \mathcal{C} = \emptyset$
Perform actions given by the initialization AC and state-based successors

Simulate

```
while (true) do

    clock ← time given by FIRST(A)
    while (clock = time given by FIRST(A)) do
        let σ_a be the AC corresponding to FIRST(A); remove FIRST(A)
        perform actions of σ_a
        add σ_{a_S} to C

        while (C ≠ ∅)
            remove σ_c ← FIRST(C)
            if condition on σ_c is true
                perform actions of σ_c
                add σ_{c_S} to C
            endif
        endwhile
    endwhile

endwhile
```

Figure 8.4: The Minimal-Condition DEAC Algorithm for a CS without Mixed ACs.

Another factor relating to the execution efficiency of these algorithms is the potential loss of structure information within an ACIG. For example, if a high-level representation provides a case, or switch, selector, then the ACIG produced from this description contains an AC, say AC_i with multiple, say n, state-based successors. The semantics provided by the higher-level representation, permit determination that a singular successor AC exists whose actions are enabled by the exeution of AC_i. However, the ACIG does not reveal this information. Thus, during execution each condition is tested. If these conditions are suitably complex, the efficiency of this approach may be substantially inferior to a target language where an optimizing compiler may provide such mechanisms as lazy evaluation and short circuiting (see [5]). Conceivably, the ACIG could be annotated to indicate these, and similar, types of situations. Such details, however, are beyond the scope of this research effort.

8.3 Provisions for Model Analysis and Diagnosis

Clearly, a major strength of the CS is its facilitation of model analysis and diagnosis, a capability that distinguishes it from extant simulation languages – both specification and implementation. *Model analysis* is considered to include all operations on a model representation made with the intent to extract information regarding properties or characteristics of the model representation. *Model diagnosis* is model analysis with the objective of establishing the truth of some assertion(s) regarding the model representation or assisting the modeler in resolving potential questions regarding the representation. Section 8.3.1 examines the impact of the proposed CS semantics on the extant provisions for model diagnosis. The remaining sections describe some issues in model analysis raised by this research effort.

8.3.1 Impact of proposed semantics on extant diagnostic techniques

The diagnostic techniques given in Table 5.4 are re-stated here and assessed in terms of the proposed CS semantics. The techniques are divided into three categories: (1) analytical techniques, (2) comparative techniques, and (3) informative techniques. The definitions below are adapted from [163, 164, 194].

Analytical techniques. Analytical techniques indicate the presence or absence of specific properties in a model specification. Eight analytical techniques are defined in [163].

- *Attribute utilization.* An attribute is utilized if the attribute affects the value of another attribute. Utilization cannot be guaranteed, only estimated. If an attribute appears in as a control attribute or input attribute in some action cluster, the attribute is considered utilized (even though the action cluster itself may never be utilized). This technique is unaffected by the proposed semantics.
- *Attribute initialization.* All model attributes should be given an initial value before they are used. If an attribute is an output attribute of the initialization AC then attribute initialization is guaranteed.[6] Otherwise attribute initialization may only be estimated. However, if the attribute has a zero in-degree in the ACAG, the attribute is guaranteed to be uninitialized. This technique is unaffected by the proposed semantics.
- *Action cluster completeness.* Referred to as action cluster *determinacy* in [194], this technique determines if the intersection of the output attribute and control attribute sets for any action cluster is nonempty. The proposed action cluster semantics and resultant DEAC algorithms obviate this technique.
- *Attribute consistency.* The usage of an attribute should be consistent with its type. This technique is unaffected by the proposed semantics.
- *Connectedness.* When the initialization AC and its arcs are removed from the ACIG, if the remaining graph has multiple components this typically (although not necessarily) indicates an incomplete model specification. This technique is unaffected by the proposed semantics.
- *Accessibility.* An action cluster, AC_j, is accessible if there exists a directed path in the ACIG from the initialization AC to AC_j. This technique is unaffected by the proposed semantics.
- *Out-complete.* A model specification is out-complete if the only AC in the simplified ACIG with an out-degree of zero is the termination AC. This technique is unaffected by the proposed semantics.
- *Revision consistency.* This technique establishes the degree of consistency in the ACIG between model revisions. This technique is unaffected by the proposed semantics.

Comparative techniques. Comparative techniques provide relative measures of a model representation characteristic, i.e. these measurements may only be assigned meaning in the comparison of model specifications. Three comparative techniques have been proposed.

[6] If the attribute is also an input attribute of the initialization AC, statement ordering must also be considered.

- *Attribute cohesion.* The degree to which attribute values are mutually influenced. Powers of the AIM (see Chapter 5) indicate attribute cohesion. This technique is unaffected by the proposed semantics.
- *Action cluster cohesion.* The degree to which action clusters are mutually influenced. Powers of the ACIM (see Chapter 5) indicate action cluster cohesion. This technique is unaffected by the proposed semantics.
- *Complexity.* The complexity of a model specification may be assessed in terms of its elegance as a communicative model (psychological complexity) or perhaps in terms of its transformational relationship to a programmed model (computational complexity). The effect of the proposed semantics on a complexity measure depends upon the measure. Wallace's control and transformation metric [238], for example, relates only to the structure of the ACIG and to the classification of attributes, and is unaffected by the proposed semantics.

Informative techniques. Informative techniques provide measurements of quantifiable model specification properties. However, these measurements typically demand interpretation and inference on the part of a modeler or analyst to be effective. Three informative techniques have been identified.

- *Attribute classification.* Attributes may be classified as: (1) input, (2) output, or (3) control. This technique is unaffected by the proposed semantics.
- *Precedence structure.* An indication of a mandated ordering on the execution of action clusters for any given instant. The proposed semantics provide explicit rules for generating precedence structures.
- *Decomposition.* Typically applied to the ACIG, a model specification may be alternatively composed (see Chapter 5). This technique is unaffected by the proposed semantics.

8.3.2 On multi-valued alarms

Overstreet permits an alarm to be set for multiple values. Ostensibly, multi-valued alarms provide a substantial amount of flexibility in model description. However, if the condition on an alarm is an AFTER ALARM, the possibility of multiple values may potentially lead to an ambiguity in the model implementation. Consider the ACIG fragment illustrated in Figure 8.5. If x becomes 5 between time 10 and 20, then two "instances" of the AFTER ALARM AC occur. If x doesn't become 5 until time 30, then only one occurrence of the AFTER ALARM AC is produced.

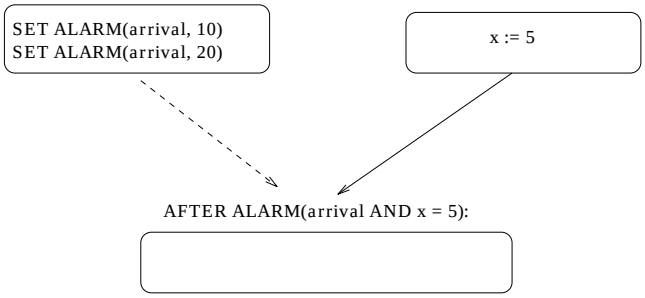


Figure 8.5: An Improper Usage of Multi-Valued Alarms.

By simple extension of Overstreet's arguments involving the inherent limitations of static analysis on a CS, no technique can be defined to automatically detect this type of misuse of multi-valued alarms. However, a modeler should be wary of this possibility when utilizing the AFTER ALARM construct.

8.3.3 On time flow mechanism independence

In his 1971 paper, Nance [152] illustrates that, counter to a widely held belief, next-event time flow is not always computationally superior to fixed-time. He further observes [152, p. 72]:

> The concept of a continuum of time flow algorithms seems warranted ... At separate ends of the continuum are the fixed time and next-event methods, which are simply algorithms themselves. For any specific simulation application, the most efficient algorithm may be anywhere along the continuum with its location reflecting the degree to which it reflects the characteristics of either pole.

When this position is logically resolved with Nance's subsequent writings on modeling methodology, the role of the time flow mechanism becomes that of an implementation detail – which should be separable from model representation at high levels of description. In defining the CS, Overstreet enunciates a congruous philosophy [178, p. 79]:

> Since *system time* is a model input attribute, the model contains no description of how it changes value (except for its initialization). Thus a choice of time advance mechanism can be based on analysis of the model specification. Either a fixed or varying time increment could be used, (for that matter the model could be run in "real time"); the model specification does not dictate the choice.

Because of the results reported by Nance, the concept of a time flow mechanism-independent representation is appealing. However, as indicated in the development below, the CS, while supporting both the next-event and fixed-time mechanisms, does not provide an independence from their selection.

Consider a very simple version of the Pucks model described in Chapter 6 in which a single puck is placed on a frictionless table. Assume that an initial position and velocity are specified and the system is to be simulated for a specific number of collisions after which the final position of the puck is reported. As illustrated in the development of the Pucks model in Chapter 6, the description of model behavior is *dependent upon a particular view of time flow.* In other words, model behavior may be described along two basic lines (the poles of Nance's continuum): (1) schedule the next collision, collide, schedule the next collision, collide, etc. or (2) travel for a certain period of time, see if a collision occurred, travel some more, see if a collision occurred, and so on. Figure 8.6 contains two CS specifications for this model and their respective action cluster incidence graphs. The specification for each reflects a different view of time flow, one next-event, and the other fixed-time.

Thus, the evidence suggests that the CS does support a variety of time flow mechanisms. However, the CS is *not independent* of the underlying time flow mechanism; the manipulation of alarms in the CS directly reflects a perception of time flow. The assertion is made here, but not proven, that *any* operational representation (see [8]) is inextricably bound to a perception, if not a precise description, of the underlying time flow mechanism. Conceivably, a definitional representation defining a model more in terms of a set of objectives and rules, may provide the true independence from time flow for which Nance clearly demonstrates the need.

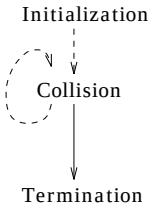
8.4 Summary

In this chapter, issues in model analysis and execution within the CM/CS approach are investigated. The semantics of the CS are refined to provide support for model execution. Based on a model of computation provided by the ACIG, an implementation structure referred to as a direct execution of action clusters (DEAC) simulation is defined, and two DEAC algorithms are presented. The extant provisions for model analysis and diagnosis in the CS are evaluated with respect to the refined semantics (and the syntax extensions from

```
{Initialization}
initialization:
    INPUT(maxCollisions, x, y, vx, vy)
    pos := (x, y)
    vel := (vx, vy)
    numCollisions := 0
    SET ALARM(collision, timeToCollision())

{Collision}
WHEN ALARM(collision):
    pos := updatePosition()
    vel := updateVelocity()
    numCollisions := numCollisions + 1
    SET ALARM(collision, timeToCollision())

{Termination}
numCollisions = maxCollisions:
    STOP
    PRINT REPORT
```



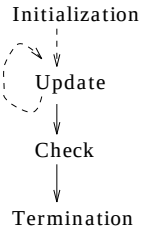
(a) Next-Event Specification

```
{Initialization}
initialization:
    INPUT(maxCollisions, x, y, vx, vy, delta)
    pos := (x, y)
    vel := (vx, vy)
    numCollisions := 0
    SET ALARM(update, delta)

{Update}
WHEN ALARM(update):
    pos := updatePosition()
    SET ALARM(update, delta)

{Check for Collision}
puckPositionVersusBoundaryFnc():
    vel := updateVelocity()
    numCollisions := numCollisions + 1

{Termination}
numCollisions = maxCollisions:
    STOP
    PRINT REPORT
```



(b) Fixed-Time Specification

Figure 8.6: Two Perceptions of Time and State in Specifications for a Simple Pucks Model.

Chapter 6).

The chapter concludes with an evaluation of the CS as a time-flow-mechanism-independent representation. We demonstrate that the use of the alarm construct in the CS *must* reflect some view of the passage of time. We postulate that this problem exists for any operational specification language.

Chapter 9

PARALLELIZING MODEL EXECUTION

For the earliest system of philosophy . . . was like unto one articulating with a stammer, inasmuch as it was new as regards first principles, and a thing the first in its kind.

Aristotle, *The Metaphysics*

One of the underlying themes of this research is that the preeminent role of decision support within the context of simulation persists under *any* particular set of study requirements. By extension, the modeling practices that facilitate the development and assessment of model correctness *must be preserved* within any modeling approach. The observations of Nance and Sargent which provide the foundation for the requirements of a next-generation modeling framework (Chapter 3) adhere to this philosophy. However, the simulation literature is replete with examples of approaches where recognition of the fundamental nature of simulation as a decision support tool is missing, or unstated. As discussed in the development of the colliding pucks model in Chapter 6, parallel discrete event simulation supplies several such examples.

In this chapter, the Conical Methodology/Condition Specification (CM/CS) approach to model development is evaluated in terms of its provisions for incorporating parallelism into model execution. A characterization of the *inherent* parallelism available in a CS model specification is given. This characterization is based on Nance's delineation of the time and state relationships in a simulation model. Algorithms suitable to permit the exploitation of parallelism within the execution of an ACIG-based simulation model are presented. To preface the development of these algorithms, Section 9.1 contrasts the model development approach (typically) adopted within parallel discrete event simulation with the philosophy

that guides this research. For completeness of the presentation, a few basic parallel discrete event simulation concepts are also reviewed.

9.1 Parallel Discrete Event Simulation: A Case Study

Parallel discrete event simulation (PDES) is usually regarded as the method of executing a single simulation program on multiple processors.[1] Typically, PDES refers to simulation on a multiprocessor – either MIMD or SIMD (see [224]). However, several PDES techniques stipulate a strict message passing communication scheme and therefore are applicable to distributed (network-based) approaches. In this chapter, the primary focus is on PDES techniques suitable for MIMD architectures. Distinctions between parallel computation and distributed computation are made where appropriate.

9.1.1 A characterization of sequential simulation

The characterization of discrete event simulation commonly held in PDES is rather narrow – focusing strictly on the implementation requirements. According to Fujimoto [78, p. 31], "sequential simulators" typically utilize three data structures: (1) the *state variables* that describe the state of the system, (2) an *event list* containing all pending events, and (3) a global *clock* that denotes how far the simulation has progressed.[2] Model execution involves the repeated process of removing the event with minimum timestamp, E_{min}, from the event list and modifying state variables, and/or scheduling other events as prescribed by the event routine corresponding to E_{min}. The process continues until the condition for termination is met, or until no unprocessed events remain – in which case the simulation is not well-defined.

Fujimoto notes that in the traditional sequential execution paradigm, selection of the next event (on the event list) to be processed, E_{min}, as the one with the smallest timestamp

[1] Several alternate views of PDES have been proposed, such as the execution of independent replications of a single simulation experiment on multiple processors, or parallelization of simulation support routines such as the event list. However, the problem of applying multiple processors to a single replication of a given program is viewed as the most general (and difficult) problem.

[2] In its purest form, the activity scanning world view does *not* prescribe an event list. The three-phase and process interaction approaches, however, do include abstractions built upon the event list structure (see [19]).

is crucial. Otherwise, if an event, say E_x, is selected such that E_x modifies one or more state variables used by E_{min}, the simulated future may affect the simulated past. Fujimoto refers to errors of this nature as *causality* errors.

> *A defining characteristic of PDES approaches is the need to synchronize processors such that causality in the simulation is preserved.*

Nicol and Fujimoto [171] observe that interest in parallel simulation arose first with the problem of synchronization, and this problem has remained the focus of most research in PDES for the last 15 years.

The simplest method of processor synchronization is for all processors to perform in lock-step fashion. These *synchronous-time* (global clock) approaches, such as the one proposed by Jones [116, 117], are particularly suited for shared-memory multiprocessors and models in which a large proportion of the model objects are involved in any given event.[3] In a typical queueing network simulation, on the other hand, the proportion of model objects involved in a single event is often quite small. Networks of queues are of *fundamental* utility in many areas, such as computer architecture and component design, communications and manufacturing. Resulting from a combination of their relative importance, and their general lack of amenability to synchronous-time parallel implementations, an alternative paradigm has emerged to support the efficient parallel execution of queueing networks. These *asynchronous-time* (local clock) approaches fall broadly into two categories: (1) conservative, and (2) optimistic. These approaches, or protocols, typically center around a set of logical processes, one per physical "real-world" process. All interactions between physical processes are modeled by timestamped event messages sent between the corresponding logical processes [78]. Each logical process contains a local clock which indicates the progression, in simulation time, of the logical process. Using this logical process paradigm, a sufficient condition to guarantee that no causality errors occur in the model is for each logical process to execute events in nondecreasing timestamp order [78, p. 32].

Unquestionably, the conservative and optimistic asynchronous-time methods have received more focus than any other techniques for parallelizing model execution. The consensus among PDES researchers is that if a "general-purpose" parallel discrete event simulation engine is to be defined, it must be based on an asynchronous-time mechanism. A

[3] This point is elaborated in Section 9.2.3.

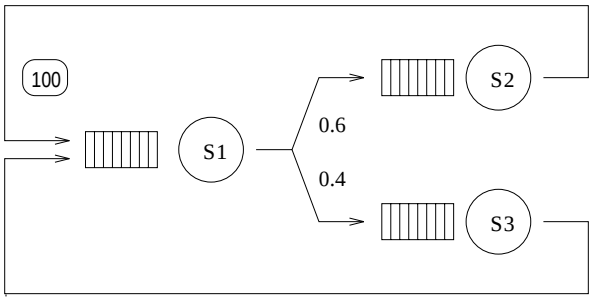


Figure 9.1: A Closed Queueing Network with Three Servers. Server S2 sends a message to server S1 with timestamp 100.

brief description of the conservative view versus the optimistic view follows. For a detailed treatment of the underlying concepts in PDES, refer to Fujimoto [78]. Another valuable source is Nicol and Fujimoto [171]; the authors provide a state-of-the-art survey of research directions in PDES, dividing these directions into 6 categories: (1) protocols, (2) performance analysis, (3) time parallelism, (4) hardware support, (5) load balancing, and (6) dynamic memory management.

9.1.2 Conservative approaches

The first asynchronous-time algorithms for PDES were conservative algorithms [41, 46]. Conservative algorithms are characterized by the fact that no process executes a message (event) until a *guarantee* is given that no message will arrive later in the simulation such that the simulation time (timestamp) of the new message is earlier than the one just executed, i.e. events occur locally in strictly chronological (nondecreasing timestamp) order. Accordingly, processes must *block* until this guarantee can be met.

Figure 9.1 illustrates a closed queueing network with three servers. In the figure, a message from S2 is being sent to S1 with timestamp 100. If the last message from S3 was processed by S1 at time 70, and no other information regarding the time of the next message from S3 is available to S1, under a conservative protocol S1 must block. S1 blocks since the possibility exists that S3 may send a message with timestamp between 70 and 100. This blocking requirement can lead to deadlock in the simulation – for example, if S3 has no messages left to process, and is therefore waiting for a message from S1. Methods for dealing

with deadlock are the focus for much of the research in conservative PDES. Deadlock can be avoided through the use of *null* messages [13, 46] or deadlock can be detected and recovered from [47, 93]. Other efforts aimed at improving the performance of these basic conservative mechanisms include using barrier-type synchronization techniques [172], precomputation within the simulation [168], conservative Time Windows [137], and application-specific optimizations [85, 92, 192].

Fujimoto observes that an obvious drawback of conservative approaches is their inability to fully exploit the parallelism available in a simulation model [78, p. 39]. If event dependencies are unknown, event execution must often be serialized, even though parallel execution of the events would not violate simulation causality.

9.1.3 Optimistic approaches

Optimistic algorithms are characterized by the fact that each process executes events as they arrive and *assumes* that events arrive in nondecreasing timestamp order. When causality is violated, optimistic algorithms *rollback* and execute the events in proper order. Thus, in Figure 9.1, under an optimistic protocol S1 would process the message from S2 immediately upon its receipt. If a message subsequently arrives from S3 with timestamp less than 100, S1 must rollback, undue the effects of any out-of-order events, and re-execute the events in proper order. On the other hand, if the next message from S3 has timestamp larger than 100, no processing time was "wasted" due to unnecessary blocking. Optimistic algorithms are not subject to deadlock, since no process blocks during execution, but must ensure that simulation activity progress forward (in some global sense) so that the simulation eventually terminates. The most widely recognized optimistic protocol is Time Warp [114, 115] based on the concept of *virtual time* [113]. Time Warp has received substantial investigative research, and considerable effort has been expended to understand and improve the performance of the protocol (for examples, see [44, 53, 81, 84, 132]). Recently, other optimistic protocols have been proposed, these include optimistic Time Window approaches [217, 218], and Space-Time [49].

Some experiments using optimistic methods have yielded impressive speedups (see [79]). However, state-saving overheads can significantly degrade the performance of an optimistic method like Time Warp. Hence, both conservative and optimistic protocols have relative

strengths and weaknesses. No single protocol is ideally suited for all imaginable models – particularly those whose dynamic behavior is a function of model input. Fujimoto [78] identifies some criteria for the selection of an implementation algorithm based on system characteristics. However, these heuristics are insufficient to guarantee algorithm selection yielding optimal performance, and in some instances utilize properties which are difficult to quantify. Some other attempts to analyze and quantify the performance bounds of PDES protocols may be found in [127, 131, 133, 173].

9.1.4 A modeling methodological perspective

In a series of articles published in the Summer 1993 volume of the *ORSA Journal on Computing,* several of the leading researchers in parallel discrete event simulation assess the state of the field. In the lead article, Fujimoto observes that despite many reported successes in terms of improved performance, PDES has failed to "make a significant impact in the general simulation community" during the last 15 years of its development [79, p. 228]. Several factors are identified as contributing to this lack of impact, and various approaches are proposed to make parallel simulation "more accessible to the simulation community." Each companion article, [1, 10, 129, 200, 235], acknowledges the *acceptance* problem. Fujimoto's proposals to increase accessibility are critiqued, and several alternatives are presented.

Abrams [1] suggests that the precipitate cause of *the problem* is a dichotomy in the perspectives and priorities of modeling methodologists – the primary purveyors of discrete event simulation, and parallel programmers – the leaders in parallel discrete event simulation, noting that until these two camps come to terms it is unlikely that PDES will thrive. Fujimoto [80, p. 247] acknowledges the correctness of this assertion and labels the potential collaborative attack as a "worthy goal." Page and Nance [185] elaborate on Abrams' assertion, and present a view of the parallel discrete event simulation problem from a modeling methodological perspective. The major themes of that source are summarized briefly here.

9.1.4.1 Observations

If PDES research is contrasted with the modeling methodological perspective outlined in Chapter 3, differences become evident in two areas: (1) the enunciation of the relationship

between simulation and decision support, and the guidance provided by the life cycle in this context, and (2) the focus of the development effort.

Life cycle and decision support. Using [12] as a framework for the discussion, Page [183] characterizes the directions of PDES research as displaying an incognizance of the fundamental nature of simulation as a decision support tool, and the importance of the life cycle as supportive of simulation in *all* contexts. The opening lines of the response from Chandy et al. [50] are illuminating:

> Discrete event simulation is a vibrant field. It has many subfields. The software engineering of simulation is such a subfield, and the "simulation life cycle" is an example in this subfield. Our paper is focused on a different subfield: parallel simulation.

These comments present a stark contrast between the philosophies of modeling methodology that have developed over the past four decades, and a prevalent viewpoint in PDES research. To suggest that parallel simulation may somehow be divorced from the simulation life cycle indicates a potentially significant misperception regarding the fundamental nature of simulation. As Page responds [183, p. 286]:

> The simulation model life cycle is most certainly *not* a topic in any subfield of discrete event simulation. The simulation model life cycle is the foundation upon which all of discrete event simulation is placed. Everything that is DES flows from the life cycle – be it modeling, requirements analysis, executable representations, verification and validation, or presentation of results to decision makers – it *all* emanates from the life cycle.

The primacy of decision support seems to be often overlooked – or at least regarded as inconsequential, or as a detail that can be "filled in later" – in PDES research. Perhaps this perception explains why the big payoff of PDES, the heralds of improved performance, fall largely on deaf ears in the general discrete event simulation community. To evaluate the benefits of applying parallelism to simulation solely on the basis of typical evaluative measures for parallel programs, such as *speedup* in runtime, is specious – at best. Such a view casts simulation as merely a piece of code which is run to produce *the* answer. This view is overly simplistic. To gain "general" acceptance, PDES research must examine the methods used to attain execution speed *explicitly* in terms of their relationship to the central objective of any simulation: arriving at a correct decision.

```
Whenever Arrival:
    if machine status is failed
        set repairman status to busy
        schedule end repair
    else
        schedule arrival at next machine

Whenever End Repair:
    set machine status to operational
    set repairman status to idle
    schedule next failure for this machine
    schedule arrival at next machine

Whenever Failure:
    set machine status to failed
```

Figure 9.2: A Partial Event Description for the Patrolling Repairman Model.

Moving toward the machine. The majority of PDES research has been conducted with little regard for the role of the conceptual framework within the model development process. The following quote (from [225, p. 612]) represents a typical (asynchronous-time) PDES problem description:

> We assume the system being modeled consists of some number of physical processes which interact in some manner. The simulation program consists of a collection of logical processes each modeling a single physical process.

Little distinction between *model* and *program* is made, and the paradigms prescribe a singular perspective: a contrived form of process interaction. This "logical process" view is characterized as contrived because its definition is motivated more by execution concerns than by an accurate representation of the physical counterpart. Fujimoto [78, p. 33] notes that this (logical process) view enables application programmers to partition the simulation state variables into a set of disjoint states, to ensure that no "simulator event" accesses more than one state. Such a partitioning permits "minimal" processor synchronization. Figures 9.2, 9.3 and 9.4 contrast three views of a partial specification (initialization and termination are omitted) of the patrolling version of the machine interference problem (see Chapter 6). Figure 9.2 illustrates an event scheduling representation. Figure 9.3 depicts a process interaction description using the SIMULA concepts *activate* and *passivate,* and Figure 9.4 illustrates a logical process representation of the model. Note the somewhat convoluted communication structure in Figure 9.4, resulting primarily from the inability of the repairman to directly examine attributes of a machine (e.g. machine status).

REPAIRMAN:

```
while true
    wait travel time
    if status of current machine is failed
        set my status to busy
        wait repair time
        set status of current machine to operational
        activate current machine
        set my status to idle
    end if
    update current machine
end while
```

MACHINE:

```
while true
    wait until failure
    set my status to failed
    passivate
end while
```

Figure 9.3: A Partial Process Description for the Patrolling Repairman Model.

REPAIRMAN:

```
case message_type of:
    End Repair::
        set my status to idle
        send travel msg to self (now)
    Begin Repair::
        set my status to busy
    Travel::
        send arrival msg to next machine
end case
```

MACHINE:

```
case message_type of:
    Arrival::
        if my status is failed
            send begin repair msg to repairman (now)
            send end repair msg to self, repairman
        else
            send travel msg to repairman
    End Repair::
        set my status to operational
        send failure msg to self
    Failure::
        set my status to failed
end case
```

Figure 9.4: A Partial Logical Process Description for the Patrolling Repairman Model.

The evidence is incontrovertible: in typical PDES approaches, the requirements of a "logical-process-oriented" implementation are allowed to dictate the conceptualization of the model itself. Clearly, any such requisite perspective is counter to Derrick's precepts of conceptual framework selection, and further, this movement "toward the machine" reverses that which has taken place in both simulation and software engineering over the several decades. The conceptual restrictions prevalent within PDES, as well as a penchant for working from a program view, result in model representations (the programs) that are often contrived and unnatural descriptions of the system being modeled. Execution requirements force model perturbations unrelated to the (often unstated) study objectives and the natural system description that exists in the mind of the modeler. Further, the problems of model verification and validation as well as those of life-cycle support become greatly exacerbated. Without a clear picture of the objectives and priorities of the general DES community, however, these problems remain largely unrecognized. For PDES to realize the desired level of acceptance in the DES community, performance gains must be achievable without sacrificing software quality objectives. Existing techniques may well provide this capability; that remains to be demonstrated. Perhaps this demonstration has been delayed by a lack of agreement as to its need.

9.1.4.2 Recommendations

Chapter 3 presents a philosophy that prescribes the fundamental *nature* of simulation, i.e. what simulation *is*. Also provided by the philosophy are theories of how simulation should be *applied*. The philosophy describes a "modeling methodological" view of simulation: simulation is a model-centered, problem-solving technique that serves first and foremost as a basis for decision support. This view is by no means exclusive. The prevalent treatment of DES by the parallel discrete event simulation community would seem to offer an example of one alternative.

The argument is made here that the view of discrete event simulation presented in Chapter 3 largely reflects that of the "mainstream" of DES – for better, or for worse. Therefore, if PDES seeks to make a broader impact within the general DES community, then the methods of PDES *must* be resolved, at least to some degree, with the modeling methodological view. This resolution might be accomplished in myriad ways; no single

"silver bullet" is evident. Nonetheless, the following list appears to be a logical starting point:

1. *Focus on the model.* The move from a program-centered view to a model-centered view has been documented. Many methodologies and environments for DES provide programming-language-independent forms for model description. Even those approaches that advocate a "program-as-model" description provide architectural independence: the same program is executable on machines with disparate architectures, as long as each machine has the requisite compiler. Without question, *any approach to discrete event simulation that ties the modeling task directly to the implementing architecture is destined to meet with failure.*

2. *Consider the simulation study objectives.* Many published efforts in PDES demonstrate speedup by *changing the model.* The tradeoff of speed for accuracy is a legitimate modeling issue. However, the degree to which model changes are acceptable is a direct function of the objectives of the study. Rarely are these objectives stipulated, however, and the reader is often left with questions concerning the validity of the resulting program, and by implication, the viability of the approach. With very few exceptions, every paper in which a simulation is involved should include a set of study objectives. Changes to the model made in an effort to exact speedup must then be addressed in terms of their effect on model validity. Some popular PDES benchmarks such as colliding pucks (see Chapter 6) and sharks world (see [11, 169, 193]) are unsatisfactory in this regard.

3. *Examine the methods in terms of a given simulation approach.* As outlined in Chapter 1, discrete event simulation is utilized in a wide variety of contexts. The context of the model's usage may influence the suitability of a given approach to obtaining speedup in execution. For example, if the simulation is used in an evolutionary form to design or optimize a system, then *a posteriori* analysis and subsequent modification of code to obtain speedup is likely to be less feasible than in a situation where a model, once constructed, is run many times with few changes.

4. *Examine the relationship of speedup to software quality.* How does the method used to exact speedup affect the model in terms of its: maintainability, correctness, reusability, testability, reliability, portability, adaptability? To what extent are these objectives enhanced or sacrificed to increase execution speed?

In summary, PDES can – and should – play a significant role in the future of discrete event simulation. The need for computational efficiency is a persistent characteristic of simulation software. However, recognition of the larger map formed by the DES research community is required. Working within recognition of the mainstream of DES research places PDES in a contributive posture. Continuing the preoccupation with execution efficiency, *to the exclusion of constraining and overriding model quality issues,* could potentially relegate PDES findings to the domain of irrelevant results – a loss for all.

Having examined PDES from a modeling methodological perspective, and having made recommendations for the mechanisms by which extant PDES research and techniques may achieve a broader, "mainstream," acceptance, the remainder of this chapter addresses the problem of parallelizing the execution of discrete event simulation models from a different direction: evaluating the capacity of the CM/CS approach in this regard.

9.2 Defining Parallelism

Not all models are created equal. Even if two models are "equivalent" (see Chapter 5), such that they may be used interchangeably to investigate a given system, the models may differ in many respects: (1) they may reflect different perspectives, (2) one may be more maintainable than another in a given setting, (3) one may facilitate analysis in a superior fashion, or (4) one may be more suitable for parallel execution than another. We refer to the fourth quality as the *inherent parallelism* of the model. According to the philosophy described below, inherent parallelism should be regarded as a function of the model representation, not the physical system. This important distinction is clarified in the subsequent discussion.

9.2.1 Informal definitions

PDES protocols, in their usage and evaluation, describe a notion of inherent parallelism. However, the concept is typically implicit, and vague in its characterization. Explicit formulations of inherent parallelism have appeared in [30, 128, 135] as a basis for *critical path* analysis. These efforts are discussed in detail below. A characterization of inherent parallelism, based on the time and state relationships described by Nance [156], is offered here. Recall from Chapter 2, that an event is a change in an object state that occurs at an instant. The change in state is comprised of value changes for one or more attributes. Since the model itself may be viewed as an object, the behavior of the model may be described in terms of a time-series of "model-level" events.

Definition 9.1 *For any model M, the available parallelism may be defined as a function of the independence of attribute value changes of M at each instant during the execution of an implementation of M.*

This definition, which is formalized below, states essentially that the parallelism available in the model is related to the level of *independence* within a state change (event) during a given instant in an execution of the model implementation.[4] We refer to the parallelism characterized by Definition 9.1 as the *inherent event parallelism.* The following characterization is adopted, or implied, by most PDES approaches.

Definition 9.2 *For any model, M, and set of model objects, O, the available parallelism may be defined as a function of the independence of attribute value changes over all $o \in O$ and all instants, during the execution of an implementation of M.*

Definition 9.2 is *strictly weaker* than Definition 9.1, since the parallelism defined by Definition 9.2 includes the parallelism defined by Definition 9.1.[5] Recall from Chapter 2, that an activity is the state of an object between two successive instants. Definition 9.2 states that if an event – that either initiates or terminates an activity – for one object is independent of an event – again, that either initiates or terminates an activity – for the same or another object, these events may be processed in parallel. We refer to such parallelism as the *inherent activity parallelism.*

9.2.2 Formal definitions

Inherent event parallelism and inherent activity parallelism are formalized as follows. Let,

M = a model specification
M' = an implementation of M
n = the number of instants produced by some execution of M'
σ_i = the set of attribute value changes occurring at instant i
ρ_i = the proportion of value changes from σ_i that are independent

Then the inherent event parallelism may be estimated by:

$$\Pi_E = \frac{1}{n} \sum_{\forall i} \rho_i \tag{9.1}$$

Π_E is the mean level of state change independence in M'. The inherent activity parallelism is simply given by the estimator, ρ^*, which is defined as the proportion of independent value

[4]The criteria for independence is generally relative to a given model representation and implementation environment. This notion is further detailed in Section 9.3.

[5]The term "strictly weaker" is used here in the sense of a weakest precondition, as in [67].

changes over all objects and instants in M'. Note that ρ_i and ρ^* may be impractical or impossible to measure directly, and further that the definition of "independence" is relative to characteristics of both the model representation and the underlying implementation algorithm (see Section 9.3). Note also that these estimators are based on implementations of a model, since the number of instants is dictated by a terminating parameter value (in simulated time or events).

9.2.3 Observations and summary

Three observations regarding Definitions 9.1 and 9.2 are warranted. First, in conceptualizing a model, a modeler with no experience in parallel simulation may have some intuition regarding inherent parallelism. Parallelism is most naturally perceived as it relates to "things happening at the same time" in the model, and the degree to which these "things" are independent of each other. This intuition is partially captured by Definition 9.1, since only state changes that occur during the same instant contribute to the level of parallelism. However, a modeler might not always perceive simultaneous behavior strictly in terms of events, but might also perceive such behavior over spans of simulated time. The parallelism provided by Definition 9.2 captures this behavior. But Definition 9.2 also describes parallelism in terms of simultaneous execution of independent state changes that occur at *different* instants. Intuition for this type of parallelism might be attainable only after extensive and sustained exposure to protocols designed to exploit it.

Second, if the level of parallelism given by Definition 9.1 is high, speedup may be achieved through fairly simple synchronous-time algorithms where the overhead of implementing a global clock and shared state can be amortized.

Third, we offer the conjecture that, in actual practice, the class of problems for which the parallelism provided by Definition 9.2 is *very* high, is small. The reasoning behind this conjecture is that discrete event simulation is utilized, by definition, when "intermediate states" are important. Otherwise, continuous or Monte Carlo techniques are suitable. The importance of the intermediate states is often due to their impact on future model behavior. Thus, in a discrete event simulation, the model affects itself over time, i.e. events are seldom temporally independent. When the model is decomposed into objects, these object-level events may be independent over time. However, looking at this another way, under such

a partitioning if a large degree of parallelism is available, then the behavior of one or more model objects rarely, or never, affects the behavior of other objects in the model during any instant in model execution. In this case, the presence of such objects may be suspect. Relative to the study objectives, the model might contain superfluous, or perhaps incomplete, information. In which case the model should be reformulated.

Of course, the demonstrated successes of asynchronous-time PDES techniques for various queueing network configurations (see [79]) illustrate examples of systems where the inherent activity parallelism is high and the inherent event parallelism is low. However, as has been stipulated, exploiting the available parallelism in these cases can require sophisticated formulations of both the protocol and the model. One possible alternative in this situation is to reformulate the model such that the event parallelism is high, i.e. formulate the model with a fixed-time increment time flow algorithm. The benefits of this type of reformulation may be in the provision of a simple and suitably efficient implementation algorithm. The cost of this reformulation comes in terms of losses in model fidelity and must, in all cases, be assessed in terms of the model objectives.

Also worthy of note is that, for queueing networks, the inherent event parallelism is low because the model-level events usually include only one or two model objects, and in general, simultaneous events are not common. For models that contain highly synchronous objects, i.e. each model-level event includes state changes for a large proportion of the model objects, extant PDES protocols may "perform" poorly compared to simpler algorithms.[6] For example, consider a military simulation in which one process causes a large explosion at time t. If a majority of model objects are within the kill-range of this explosion at t, then model execution must essentially *synchronize* at t. Copious amount of parallelism may be available, since each object may be responsible for determining its own damage-level as well as its own future actions. However, in optimistic PDES protocols, many of these objects may have to be rolled back – perhaps a considerable distance if the object triggering the explosion is a "stealth threat" having had few prior interactions with other model objects. The overhead here, especially in terms of storage, is potentially large. A conservative algorithm would not incur costs for rollback, all objects would be blocked until t. But these approaches would also block at every *potential* time the stealth object could cause such

[6] Where performance is defined in terms broader than speed of model execution.

an explosion. If these times cannot be adequately predicted (i.e. if no lookahead exists), a conservative approach may perform poorly. On the other hand, a simple synchronous-time algorithm may provide near optimal performance for this type of model.

This example is something of a strawman, however. Parallelized warfare simulations have demonstrated success in terms of speedup, e.g. [85, 86]. The point made here is that queueing network simulations generally follow a pattern of behavior in which only a few objects are involved in a given event, and each event schedules only one or two subsequent events. As a result, a rather complex decomposition into logical processes is required to parallelize the execution of these models. We might reasonably expect that, for other classes of systems, parallelism may be achievable without the imposition of such a restrictive conceptual framework.

9.3 Estimating Parallelism

The definitions for inherent event parallelism and inherent activity parallelism given above provide little more than intuitive guidance since they are predicated on the unquantified concept of *independence*. This concept can be more rigorously defined. To do so, however, requires a specific characterization of several parameters in a parallel model implementation.

In this section, the extant techniques for quantifying simulation model parallelism are reviewed.

9.3.1 Protocol analysis

Several efforts have sought to define model-independent characterizations of the relative and expected performance of parallel simulation under a variety of protocols. Felderman and Kleinrock [69] show that the average performance difference between a synchronous parallel simulation protocol and an asynchronous optimistic protocol (e.g. Time Warp) is no more than a factor of $O(\log P)$ on P processors. This result assumes that the "task" times for each process are exponentially distributed. The improvement when using a distribution with finite support, e.g. uniform, is reduced to a constant independent of P.

Lin and Lazowska [130] demonstrate the "optimality" of Time Warp under certain assumptions, showing that Time Warp outperforms conservative protocols for every feedfor-

ward network simulation, and for most feedback networks with poor lookahead. The authors indicate that the optimality of Time Warp is related to whether or not correct computations are ever rolled back. In a related effort, Lipton and Mizell [134] provide a model that identifies conditions under which an optimistic protocol may arbitrarily outperform a conservative protocol. The authors also use this model to demonstrate that no example to the contrary exists.

Other efforts examine self-initiating parallel simulations [70, 170] and analysis based on Markov chains [71]. Each of the above techniques attempt, in some sense, to quantify the expected performance of a particular protocol irrespective of the characteristics of the model being executed.

9.3.2 Critical path analysis

According to Lin [128, p. 241], parallel simulation has as its basis the following observation:

if two events are independent of each other, they may be executed in parallel.

If the model is partitioned into logical processes such that no two logical processes share any state variables, then two events e and e', realized in the execution of the two logical processes, are *independent* if the resulting model state is identical given either serial event execution ordering, e, e' or e', e.[7]

Once the simulation is partitioned, execution of the logical processes produces events subject to two sequential constraints: (1) if two events are scheduled for the same process, the event with the smaller timestamp must be executed first, and (2) if an event executed at a process results in the scheduling (or cancellation) of another event at a different process, then the former must be executed before the latter.

Lin notes that if a model partitioning contains too many processes, the communication overhead due to the second constraint may be prohibitive. On the other hand, if too few processes are defined, independent events may be executed sequentially due to the first constraint.

Based on the twin constraints, Lin defines an *event precedence graph* for a parallel simulation. Each vertex represents an event and each edge represents a communication. An

[7]Such a model partitioning eliminates the possibility of race conditions.

event execution time is associated with each vertex. A *communication delay* is associated with each edge. Since the event precedence graph is acyclic, a maximal weighted path can be found. This path is called the *critical path,* and its cost is the minimal time required to finish the execution of the parallel simulation.

The cost of the graph may be derived as follows.[8] Let g_e be an event such that event e is scheduled due to the execution of event g_e. If g_e is not defined for an event e, then e is *prescheduled.* Let p_e be an event such that both events e and p_e are scheduled for the same process, and the execution of p_e is followed by the execution of e. Let $\tau(e)$ be the earliest time when execution of e starts. Let $\eta(e)$ be the execution time of e. Let $\overline{\tau}(e)$ be the earliest time when execution of e completes. If every process is executed by a dedicated processor, then,

$$\overline{\tau}(e) = \tau(e) + \eta(e) \tag{9.2}$$

Let $\delta(e)$ be the time to schedule event e. If g_e and e are scheduled at different processes, then $\delta(e)$ represents the message-sending delay. Otherwise, Lin assumes $\delta(e)$ is zero. This gives,

$$\tau(e) = \begin{cases} 0 & \text{if neither } g_e \text{ nor } p_e \text{ exist,} \\ \overline{\tau}(p_e) & \text{if } g_e \text{ does not exist,} \\ \overline{\tau}(g_e) + \delta(e) & \text{if } p_e \text{ does not exist,} \\ \max[\overline{\tau}(p_e), \overline{\tau}(g_e) + \delta(e)] & \text{otherwise.} \end{cases} \tag{9.3}$$

Finally, the cost for the critical path, T_p, and the sequential execution time, T_s are given by,

$$T_p = \max_{\forall e} \overline{\tau}(e), \text{ and } T_s = \sum_{\forall e} \eta(e) \tag{9.4}$$

The *optimal* parallel simulation time is computed based on Equation (9.3). However, the equation is only adequate for the case where every process is executed on a dedicated processor. If the number of processors, P, is less than the number of processes, N, then T_p is also affected by process assignment and process scheduling. Lin [128] considers only static process assignment, but investigates three process scheduling policies: (1) all events at a processor are executed in nondecreasing timestamp order, (2) among the events (of different processes) available for execution at a processor, the event with the earliest arrival

[8] Note that in this development, *time* refers to wall clock (or real) time, as opposed to simulation time.

time is selected, and (3) among the events available for execution at a processor, the event with the smallest timestamp is selected.

Several approaches to critical path analysis have been proposed. Lin couples the critical path analyzer to a generic sequential simulator. Berry and Jefferson [30] instrument a sequential simulation and take a trace of the events executed. The trace is then transformed into an event precedence graph. Finally, the cost of the critical path is computed from the graph. Livny [135] integrates a critical path analyzer with the DISS simulation. No event trace is required, and graph construction is implicit. Both Berry and Jefferson and Livny limit the case to $P = N$. Som et al. [220] describe a method based on analyzing events in a constrained execution graph. This method does not require a logical process decomposition of the model, although a corresponding model execution environment is not described.

Finally, some observations due to Lin [128]: (1) A large number of events must be processed in critical path analysis before a reliable speedup prediction can be obtained. Transient events should not be considered part of the total if the simulation is intended to produce steady state results. (2) The number of processors for parallel simulation must be selected to balance the effects of the twin constraints in order to yield maximal speedup, and (3) When communication cost is much higher than event execution cost (e.g. $20:1$), the amount of speedup may be very low. In this case, adding processors has no benefit.

9.4 Parallel Direct Execution of Action Clusters

Overstreet [178] demonstrates that a CS can be converted into an equivalent specification reflecting a process view. Conceivably this specification could be adapted to reflect a logical process view and thereby utilize the extant PDES techniques and protocols. Such integration with existing approaches requires: (1) selecting an implementation environment, and (2) describing a suitable translation scheme. Defining a general translation scheme appears to be difficult and deserving of investigation. Another, perhaps more interesting, question is that given the ACIG-based model of computation described in Chapter 8, what parallelism can be identified and can it be effectively exploited? This question is investigated here. The focus of this development is contrasted with traditional PDES in the following manner. Within PDES the focus is singular: speed; that is, given a discrete event simulation model (program) and a particular parallel machine, make the program run as fast as possible.

Thus, the techniques of PDES center on perturbations of the model (program) such that processor utilization is maximized. The approach taken in this effort adopts a somewhat different focus: specifically, can the parallelism available in a given model representation (the ACIG) be exploited without additional burden being placed on a modeler?

In a DEAC simulation, action clusters define the "level of granularity." A logical starting point in a search for parallelism within a DEAC simulation is therefore at the level of action clusters. The action cluster incidence graph does not naturally partition the state space of the model; therefore expectations regarding asynchronous algorithms – to exploit inherent activity parallelism – should perhaps be limited. This issue is addressed in greater detail subsequently. If the exploitation of inherent event parallelism is considered, intuition provides that such parallelism exists in the cascade of CACs that accompanies each DAC. In order to focus the development of concepts, for the remainder of this chapter we assume that the transition specification is comprised entirely of ACs, i.e. the use of functions is not considered.

9.4.1 ACIG expansion

Since action clusters provide the level of granularity, and the basis for parallelism, the requirements of an implementation favor as many ACs as possible. More ACs means more potential parallelism. The opposite is often true, however, at the specification level. For a model specification in the CS, fewer ACs generally equates to a more understandable communicative model.

For example, consider the MVS model in Chapter 6. If a large number of CPUs are defined, a modeler is likely to describe the model (under the CM/CS approach) using indexed objects. As a result, a single action cluster for begin-service might be defined as follows:

FOR ALL $i : 1 \leq i \leq N$ :: Cpu[i].status = idle AND NOT EMPTY(CpuQ[i]):
    Cpu[i].status := busy
    SET ALARM(Cpu[i].end_service, exp(Cpu[i].service_mean))

If a begin-service may occur during the same instant for multiple CPUs, clearly these actions are independent and may be processed in parallel. Thus, whenever a model specification includes quantified ACs such as the one given above, during the creation of the model

implementation, a translator (perhaps with assistance required from the modeler) may *expand* the specification thereby affording an the capability to execute these ACs in parallel on separate processors. The ACIG corresponding to this specification is referred to as the *expanded* ACIG.[9] Although the two forms are closely related, an important distinction must be made: the ACIG is part of a model specification, the *expanded* ACIG provides a basis for a model implementation.

9.4.2 A synchronous model for parallel execution

In this section, a pedagogical model for a synchronous parallel execution of an ACIG on a hypothetical machine is described. The goal of this development is to enhance the reader's insight into the nature of the inherent event parallelism within an ACIG.

Let M be a model specification in the CS and let G be a simplified, expanded ACIG for M. In a manner similar to Petri nets (see Chapter 4) we define a *marking* on the ACIG as the distribution of *tokens* within the graph. Assume the existence of a hypothetical machine capable of executing an ACIG. Graph execution is governed by the following rules:

- Whenever a token is passed to an AC, the condition is tested. If the condition evaluates to false, the token is consumed. Otherwise, the actions are executed, a token is created and passed to each of the state-based successors of the AC, and the token originally passed to the AC is consumed.
- Whenever the situation develops that no tokens exist in the graph, the earliest scheduled alarm (and all those with identical alarm times) is (are) removed from a list of scheduled alarms, and a token is passed to each of the corresponding AC(s).

Execution begins by passing a token to the initialization AC and ends when the actions of the termination AC are executed.

If an omniscience is permitted such that the ACIG and its markings are visible during execution, what we observe is a static graph within which tokens flow sporadically: a token appears in the initialization AC, is consumed, and tokens flow to its state-based successors. Tokens continue to flow through the graph and are consumed and others created to take their place until the last token reaches a "dead end" on its path from the initialization AC. This occurs when the condition on the AC failed or no state-based path out of the AC

[9]The concept of ACIG expansion appears closely related to the common multiprocessor technique of "loop unrolling" (see [224, Chap. 7]).

exists. Then a brief pause – discernible only to the truly omniscient – and a token appears at a DAC somewhere in the graph. Then, another cascade of tokens flowing, and so on. From this vantage, the parallelism is visible. Namely,

> *the available parallelism at any point in (real) time is defined by the number of tokens in existence in the graph at that time.*

Of course, this model describes an ideal situation that cannot exist in actual practice. In the following sections, some limitations on this ideal are quantified.

9.4.3 Specification ambiguity

In Chapter 5, Overstreet's characterization of specification ambiguity is given. Overstreet defines two types of ambiguity: state ambiguity and time ambiguity. State ambiguity relates to a dependency among simultaneously enabled contingent action clusters, and time ambiguity relates to a dependency among simultaneously enabled determined action clusters. He further shows that detecting either state ambiguity or time ambiguity cannot be accomplished automatically for an arbitrary model specification.

To provide consistency with the DEAC model of computation defined in Chapter 8, and to establish a basis for denoting that the parallel execution of two action clusters is well-defined, Overstreet's definitions for ambiguity are modified slightly here. First, a characterization of dependency among two model actions (in a CS) must be given.

Definition 9.3 *Two model actions a and b are said to be write/write conflicting if the intersection of their output attribute sets is non-empty.*

Definition 9.4 *Two model actions a and b are said to be read/write conflicting if the intersection of the input and control attribute sets of one and the output attribute set of the other is non-empty.*

Definition 9.5 *Two model actions a and b are said to be dependent if they are write/write or read/write conflicting. Otherwise a and b are independent.*

The characterization of dependency given by Definition 9.5 is stronger than the definition typically used in PDES.[10] The PDES requirement of a totally partitioned state space makes

[10] As presented in Section 9.3.2, two events are independent if any serial ordering of their execution yields the same state.

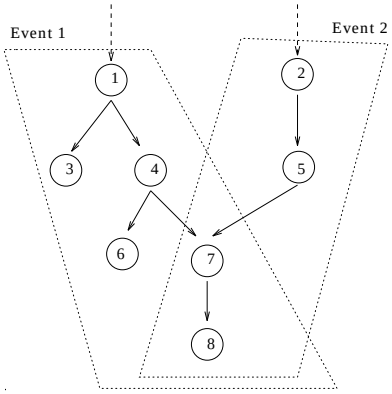


Figure 9.5: A Partial ACIG Showing Two Events with Common Actions.

considerations for processor contention unnecessary. However, in a parallel execution based on an ACIG, the possibility exists for contention on model attributes.

For the following definitions, the relationship between action clusters in an ACIG and action clusters corresponding to an event must be provided. At first glance it may appear that to delineate the events in an ACIG, merely removing the dashed arcs is sufficient. The remaining connected components should contain the events. This approach is almost correct, but must be adapted slightly. Consider the ACIG fragment given in Figure 9.5. The figure illustrates two events which *share* CACs. This type of specification often results whenever a series of common actions occurs over several model events. For example, a group of actions representing *get-proper-signatures* may occur both for the event that an order is placed for spare parts, and the the event that a seaman is transferred.

To identify events in an (simplified) ACIG, a collection of graphs is constructed each of which consists of a single DAC and all CACs reachable from it without passing through another DAC. Algorithms for this are straightforward and may be found in [178, 194].

Definition 9.6 *Let M be a model specification in the CS and let $G = ACIG(M)$. Let E be the graph induced from G by a single DAC and all CACs reachable from it without passing through another DAC. We call E an event-cluster.*

Using these event-clusters as a basis, the ambiguity problem reduces to an examination of conflicts within an event-cluster and among pairs of event-clusters.

Definition 9.7 *Let M be a model specification in the CS, and let a and b be dependent model actions. If a and b are in distinct CACs of the same event-cluster, E, and if no ordering information is available relative to a and b, then M is said to be state ambiguous.*

Definition 9.8 *Let M be a model specification in the CS, and let a and b be dependent model actions. If a and b are in ACs of distinct event-clusters, E_1 and E_2, and if no ordering information is available relative to a and b, then M is said to be time ambiguous.*

Essentially, ambiguity can arise from two sources. First, ambiguity may be the result of a poorly defined event. That is, within the cascade of CACs that accompanies a DAC some dependency exists on attributes of two ACs whose respective order of execution is not prescribed. This is *state ambiguity* as given by Definition 9.7. *Time ambiguity,* as given by Definition 9.8, arises as the result of simultaneous (interfering) events.

The fundamental limitation confronting the automated detection of ambiguity is an inability to statically determine read/write and write/write conflicts. Still, an ACIG may posses certain properties which tend to indicate the presence of, or at least the possibility for, ambiguity. We now describe a necessary condition for state ambiguity in a CS. The Theorem clarifies the nature of the "ordering information" referred to in Definition 9.7. Let,

M	=	a CS model specification comprised of action clusters $(AC_1, \ldots, AC_n)$
$O(AC_j)$	=	the set of output attributes for AC_j
$I(AC_j)$	=	the set of input and control attributes for AC_j
WW	$\equiv$	$\exists\, i, j \ni O(AC_i) \cap O(AC_j) \neq \emptyset$
RW	$\equiv$	$\exists\, i, j \ni (O(AC_i) \cap I(AC_j) \neq \emptyset) \vee (I(AC_i) \cap O(AC_j) \neq \emptyset)$
G	=	simplified, expanded ACIG
E	=	the set of event-clusters in G

Theorem 9.1 *Let M be a model specification in the CS. If M is state ambiguous then $\exists\, e \in E \ni$ for the DAC $d \in e$, and two CACs $i, j \in e$, RW or WW holds for i, j and either no directed path between i and j exists or multiple paths from d to either i or j exist.*

Proof: Let M be a model specification in the CS such that M is state ambiguous. Then by definition, there exists $e \in E$ and CACs $i, j \in e \ni RW$ or WW holds.

Let $d \in e$ be the DAC. By the construction of $e, \forall\, x \in e\ \exists$ a directed path from d to x. Let P_i denote the path from d to i. Let p_j denote the path from d to j.

Suppose p_i is the *unique* path in e from d to i, and p_j is the *unique* path in e from d to j. Further, suppose that a directed path, p_*, between i and j exists. Without loss of generality, suppose p_* is a path from i to j.

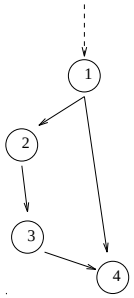


Figure 9.6: A Partial ACIG Showing Multiple Paths Between a DAC and CAC.

> Let M' be an implementation of M under the DEAC algorithm. Let t be any instant of M' during which i and j occur. Then i and j must be coincident in time with d. Further, d must precede both i and j. Therefore, during instant t execution begins at d and follows the path p_i to i and p_j to j. Since p_j is the unique path from d to j, p_* must lie on p_j. Otherwise, the concatenation of paths p_i and p_* form a directed path from d to j distinct from p_j. Therefore, execution must begin with d, follow p_i to i and then follow p_* to j.
>
> This contradicts the fact that M is state ambiguous since an explicit ordering between i and j exists. Therefore the supposition must be false and either multiple paths exist in e from d to one of i or j, or no directed path exits in e between i and j. □

The proof of Theorem 9.1 is complicated by the fact that the members of E are not required to be rooted trees, i.e. cycles in the underlying graph are possible. For example, an event-cluster of the form illustrated in Figure 9.6 is permitted. This figure illustrates a significant ambiguity problem with the ACIG itself. Specifically, when an AC has multiple incoming arcs, e.g. AC_4, the graph itself does not contain sufficient information to indicate the conditions under which that AC may *actually* be enabled during an execution of the CS. Is the information passed along one arc sufficient to enable the execution of the AC or must information arrive at the AC from all incoming arcs? In the case of Figure 9.6, if either of AC_1 or AC_3 can enable the execution of AC_4, then the specification is potentially ambiguous – if AC_2 or AC_3 conflicts with AC_4. Otherwise, if both AC_1 *and* AC_3 must execute prior to the execution of AC_4 for any given instant, the specification is not ambiguous.

A necessary condition for time ambiguity is trivial, and little can be gleaned from the

graph structure. Essentially, if a CS is time ambiguous, some pair of event-clusters contains conflicting actions. To resolve time ambiguity, a model analyzer must scan pairs of event-clusters for conflicts – not guaranteed *a priori* determinable – and rely on the modeler's understanding to determine if the two events can occur during the same instant.

9.4.4 Critical path analysis for PDEAC simulation

Characterizations of inherent parallelism are formulated in Section 9.2. The position is advanced that inherent parallelism should be regarded as a function of the model representation and not the underlying system. This point is worthy of elaboration. To be precise, the available parallelism in a model is relative to the degree of dependence among model components – for some given definition of dependence and some level of component, e.g. event, activity, action. The dependence *might* reflect a dependence in the system, or it *can* be an artifact of the model itself. Since the number of possible models for any given system and set of objectives is likely to be very large, demonstrating that some dependency in the system must be reflected in *any* model of that system is typically impractical. Hence, the adoption of the position that inherent parallelism should be considered a property of the model representation.

In Section 9.4.2 a model of the synchronous parallel execution of an ACIG is described. In this section, a technique to establish the optimal parallel simulation time based on the synchronous model of execution is defined. Such an assessment is desirable in order to evaluate "how well" an actual PDEAC algorithm is performing, not relative to an artificial constraint such as the maximum utilization of available processors, but relative to the natural limitation of the available parallelism in a given model representation.

Lin [128] shows that a critical path analyzer can be incorporated into a sequential simulator. While this approach is less than ideal in many PDES settings – it requires the development of both a sequential and a parallel model (program) – such an approach is perfectly suited for the CM/CS development described by this research since the same model specification may be used as the basis for both the sequential and the parallel implementation.

9.4.4.1 The synchronous critical path

Using the synchronous model for execution described in Section 9.4.2, the critical path in a direct execution of action clusters simulation may be defined as follows.[11] Based on Lin's development, let,

a	=	an action cluster
p_a	=	the action cluster that precedes a (from ACIG) if a is a CAC
α_a	=	the set of ACs executed during the instant immediately preceding the instant during which a executes
$\tau(a)$	=	the earliest time when execution of a may begin
$\zeta(a)$	=	the time required to test the condition of a
$\eta(a)$	=	the time required to perform the actions of a
$\overline{\tau}(a)$	=	the earliest time when execution of a may complete

If every AC is executed by a dedicated processor, then,

$$\overline{\tau}(a) = \tau(a) + \theta(a) \tag{9.5}$$

Where $\theta(a) = \zeta(a) + \eta(a)$ if the condition on a is true, and $\theta(a) = \zeta(a)$ otherwise. The earliest time when the execution of a may begin is given by,

$$\tau(a) = \begin{cases} 0 & \text{if } a \text{ is the initialization AC,} \\ \overline{\tau}(p_a) & \text{if } p_a \text{ exists,} \\ \max_{\forall x \in \alpha_a} \overline{\tau}(x) & \text{otherwise.} \end{cases} \tag{9.6}$$

Finally, the cost for the critical path, T_p, and the sequential execution time, T_s are,

$$T_p = \overline{\tau}(t), \text{ and } T_s = \sum_{\forall a} \eta(a) \tag{9.7}$$

where t denotes the termination AC. The *optimal* parallel simulation time of any synchronous PDEAC algorithm for a given model is T_p, with a best possible speedup of $\frac{T_s}{T_p}$.

9.4.4.2 The critical path algorithm

An algorithm to compute the (synchronous) critical path of a DEAC simulation is given in Figure 9.7. The algorithm is simply an augmentation of the standard DEAC algorithm (Figure 8.4). Initially, $\overline{\tau}(p_a)$ is set to zero for all CACs, a, in the CS. Whenever an AC is

[11] Recall from Chapter 8 that *execution* of an AC is defined as the evaluation of the condition on the AC, followed by *activation* of the AC – performing the specified actions – if the condition evaluates to true.

Let $\mathcal{A}$ be the ordered set of scheduled alarms.
Let $\mathcal{C}$ be the set of state-based clusters whose conditions should be tested immediately.
Let $\sigma_{i_\mathcal{S}}$ be the set of state-based successors for action cluster σ_i (where $1 \leq i \leq \mid \text{ACs} \mid$).

Initially

1 $\forall\, \sigma_i$, set $\sigma_{i_\mathcal{S}}$ (from simplified ACIG); $\mathcal{A} = \mathcal{C} = \emptyset$; $\forall$ CACs $j, \overline{\tau}(p_j) \leftarrow 0$
2 perform actions of initialization AC, σ_I
3 $\overline{\tau}(\sigma_I) \leftarrow \eta(\sigma_I)$; max $\leftarrow \overline{\tau}(\sigma_I); \forall\, j \in \sigma_{I_\mathcal{S}}, \overline{\tau}(p_j) \leftarrow \overline{\tau}(\sigma_I)$
4 add $\sigma_{I_\mathcal{S}}$ to $\mathcal{C}$

5 while ($\mathcal{C} \neq \emptyset$)
6 remove $\sigma_a \leftarrow$ FIRST($\mathcal{C}$)
7 $\overline{\tau}(\sigma_a) \leftarrow \overline{\tau}(p_{\sigma_a}) + \zeta(\sigma_a)$
8 if condition on σ_a is true
9 perform actions of σ_a
10 $\overline{\tau}(\sigma_a) \leftarrow \overline{\tau}(\sigma_a) + \eta(\sigma_a); \forall\, j \in \sigma_{a_\mathcal{S}}, \overline{\tau}(p_j) \leftarrow \overline{\tau}(\sigma_a)$
11 add $\sigma_{a_\mathcal{S}}$ to $\mathcal{C}$
12 endif
13 if $\overline{\tau}(\sigma_a) >$ max, max $\leftarrow \overline{\tau}(\sigma_a)$
14 endwhile

Simulate

15 while (true) do
16 clock $\leftarrow$ time given by FIRST($\mathcal{A}$)
17 $\alpha \leftarrow$ max
18 while (clock = time given by FIRST($\mathcal{A}$)) do
19 remove FIRST($\mathcal{A}$); let σ_a be the AC corresponding to FIRST($\mathcal{A}$)
20 perform actions of σ_a
21 $\overline{\tau}(\sigma_a) \leftarrow \alpha + \eta(\sigma_a)$; emax $\leftarrow \overline{\tau}(\sigma_a); \forall\, j \in \sigma_{a_\mathcal{S}}, \overline{\tau}(p_j) \leftarrow \overline{\tau}(\sigma_a)$; add $\sigma_{a_\mathcal{S}}$ to $\mathcal{C}$
22 while ($\mathcal{C} \neq \emptyset$)
23 remove $\sigma_a \leftarrow$ FIRST($\mathcal{C}$)
24 $\overline{\tau}(\sigma_a) \leftarrow \overline{\tau}(p_{\sigma_a}) + \zeta(\sigma_a)$
25 if condition on σ_a is true
26 perform actions of σ_a
27 $\overline{\tau}(\sigma_a) \leftarrow \overline{\tau}(\sigma_a) + \eta(\sigma_a); \forall\, j \in \sigma_{a_\mathcal{S}}, \overline{\tau}(p_j) \leftarrow \overline{\tau}(\sigma_a)$
28 add $\sigma_{a_\mathcal{S}}$ to $\mathcal{C}$
29 endif
30 if $\overline{\tau}(\sigma_a) >$ emax, emax $\leftarrow \overline{\tau}(\sigma_a)$
31 endwhile
32 if emax > max, max $\leftarrow$ emax
33 endwhile
34 endwhile

Figure 9.7: The Critical Path Algorithm for a DEAC Simulation.

invoked: (1) its completion time is recorded as the completion time of its predecessor plus the execution time of the AC itself,[12] and (2) if the actions given by a are taken, for all ACs i in the successor set of a, the completion time of a is recorded as the completion time of the predecessor of i. In the simulation proper (lines 15 - 34), three variables are utilized to track the critical path: *max* contains the largest value of $\overline{\tau}$ for each instant, *emax* contains the largest value of $\overline{\tau}$ for each event-cluster, and α contains the largest value of $\overline{\tau}$ for the previous instant. We now formally establish the correctness of the critical path algorithm.

Lemma 9.1 *In the critical path algorithm, whenever the clock is updated (line 16), max contains the maximum value of $\overline{\tau}(a)$ for all ACs a executed during the previous instant.*

Proof: Execution of a model under the DEAC algorithm may be viewed as a sequence of instants, I_1, I_2, $\ldots I_m$. We proceed by induction on $j : 1 \leq j \leq m$.

Basis. $j = 1$. Under the CM, initialization is not considered an instant. Model execution begins with the first update to the system clock (line 16). Therefore, in the critical path algorithm, the beginning of the jth instant is defined by the jth execution of line 16.

Consider $j = 1$. The body of the simulation proper (the while loop of line 15) has not executed. Therefore the value of *max* is determined in the initially section of the algorithm (lines 1 - 14). We see that *max* is first assigned to the earliest possible completion time of the initialization AC at line 3. If initialization has no state-based successors, the assignment to *max* is correct and the hypothesis holds. If initialization has state-based successors, the loop of line 5 is executed. In all cases (i.e. whether or not the condition on the AC evaluates to true) *max* is updated correctly (line 13). Therefore the hypothesis holds for $j = 1$.

Inductive step. Assume that the hypothesis holds for $j \leq n$ for some $n \geq 1$. We show that it also holds for $j = n + 1$.

The jth instant begins with the jth execution of line 16. Consider the $j - 1$st execution of line 16. By the inductive hypothesis, *max* contains the maximum value of $\overline{\tau}(a)$ for all ACs a executed during the preceding ($j-2$nd) instant (or initialization, if the $j-2$nd instant does not exist). This value is placed in α by the $j - 1$st execution of line 17.

The completion time of the DAC defining the $j - 1$st instant is calculated at line 21 as $\overline{\tau}(\sigma_a) \leftarrow \alpha + \eta(\sigma_a)$ and this value is stored in the variable *emax.*

[12] The completion time of the predecessor of AC i is given by $\overline{\tau}(p_i)$ if i is a CAC, or by α if i is a DAC.

If the DAC has no state-based successors, the while loop given by line 22 is not iterated. Otherwise *emax* is updated for each CAC, if necessary, such that *emax* contains the largest value of $\overline{\tau}$ for that event-cluster (line 30).

In either case, *max* is assigned the final value of *emax* at line 32.

If no other DAC occurs during instant $j-1$, then the while loop given by line 18 terminates and the hypothesis holds.

If another DAC occurs during instant $j-1$, then the earliest completion time of that DAC is calculated correctly using α (line 21) and this value is assigned to *emax*. As before, the while loop given by line 22 is iterated for any CACs as necessary and *emax* is correctly updated at line 30.

After all ACs defining the event-cluster have executed, *max* is updated, if necessary, at line 32. If another DAC occurs during instant $j-1$, this process repeats. Otherwise the while loop terminates and the hypothesis holds. □

Lemma 9.2 *In the critical path algorithm, following the execution of an AC, $a, \overline{\tau}(a)$ contains the earliest possible finishing time of a.*

Proof: Execution of a model under the DEAC algorithm may be viewed as a sequence of ACs, AC_1, AC_2, $\ldots \mathrm{AC}_m$. We proceed by induction on $j : 1 \leq j \leq m$.

Basis. $j = 1$. The first AC executed in the critical path algorithm is the initialization AC, i. Immediately following the execution of $i, \overline{\tau}(i)$ is computed as $\overline{\tau}(i) \leftarrow \eta(i)$ (line 3). If execution begins at time 0, then i may complete no earlier than $\eta(i)$. Therefore the hypothesis holds for $j = 1$.

Inductive step. Assume that the hypothesis holds for $j \leq n$ for some $n \geq 1$. We show that it also holds for $j = n + 1$.

Case I. j is a DAC. Immediately following the execution of $j, \overline{\tau}(j)$ is computed as $\overline{\tau}(j) \leftarrow \alpha + \eta(j)$ (line 21). By Lemma 9.1, α contains the maximum value of $\overline{\tau}(a)$ for any AC a executed during the preceding instant. Therefore $\overline{\tau}(j)$ is assigned the correct value and the hypothesis holds.

Case II. j is a CAC. Immediately prior to the evaluation of the condition on j, $\overline{\tau}(j)$ is assigned the value of $\overline{\tau}(p_j) + \zeta(j)$ (lines 7, 24). Let l be the index of p_j. $l \leq n$. Therefore, by the inductive hypothesis, $\overline{\tau}(p_j)$ is the earliest possible finishing time for p_j. So $\overline{\tau}(j)$ contains the earliest possible completion time for the evaluation of the condition on j and if the condition evaluates to false, the hypothesis holds.

If the condition on j evaluates to true, $\overline{\tau}(j)$ is incremented by $\eta(j)$ (lines 10, 27). In this case, $\overline{\tau}(j)$ contains the earliest possible completion time for the evaluation and activation of j, and therefore the hypothesis holds. □

Theorem 9.2 *If the critical path algorithm terminates, $\overline{\tau}$(termination) contains the cost of the critical path.*

Proof: Lemma 9.2 establishes that following the execution of any AC a, $\overline{\tau}(a)$ contains the earliest possible finishing time for AC a.

Therefore if the termination AC, t, appears in the sequence of ACs produced by an execution of the critical path algorithm, $\overline{\tau}(t)$ contains the earliest possible finishing time of the termination AC. This value defines the earliest possible completion time for the model, which is defined to be the cost of the critical path. □

Note that $\overline{\tau}$(termination) may *not* be equal to $\max\overline{\tau}(a)$, for all ACs a in the execution sequence, since some ACs may be coincident with termination such that the execution time of one or more of these ACs is greater than the execution time of the termination AC. However, the semantics of a DEAC simulation are such that termination during an instant supersedes any attribute value changes that occur during that instant. Therefore, in a typical model, if n CACs, one of which is the termination AC, are coincident with a DAC, d, then a directed path from each of the remaining $n-1$ CACs to the termination AC exists in the ACIG. In this case, and in the case where termination is a DAC, $\overline{\tau}$(termination) = $\max\overline{\tau}(a)$ for all ACs a in the execution sequence.

9.4.5 PDEAC algorithm

In this section, an algorithm for a parallel direct execution of action clusters (PDEAC) simulation is described. The algorithm reflects the synchronous model of computation described in Section 9.4.2. Recall that the model of computation maintains the AC as the element of interest. Thus, the algorithm described here equates AC and process. In an ideal situation, each AC would be executed on a dedicated processor. This situation is assumed in the critical path calculations (Section 9.4.4.2). Note that in such a configuration, a maximum utilization of available processors would not be achieved. But such is not the aim of this approach. The goal here is that a model implementation produce an execution time as close as possible to that of the critical path.

For a typical model, the number of ACs is probably much greater than the number of available processors. As a result, processor mapping and load balancing become issues of concern if the critical path time is to be approached. Several methods for dealing with these

```
while true do
    passivate
    if condition on AC is true
        perform actions
        activate state-based successors
end while
```

Figure 9.8: An AC Process in the PDEAC Algorithm.

issues are evident:

- A static assignment of ACs to processors. This approach incurs the least overhead relative to the underlying computation. Static analysis methods such as the principal components and factor analysis techniques suggested by [26, 27, 145] could be adapted to map ACs to processors such that the likelihood that any two ACs on the same processor could be simultaneously eligible for execution is minimized. However, the limitations of such static analysis follow from Overstreet's Turing evaluation of the CS [178, Ch. 8].
- An assignment of ACs to processors with migration under dynamic load balancing. The limitations of static process mapping have been noted within PDES, and dynamic techniques are currently the subject of intensive research effort (see [171]). As these techniques mature, they should be readily adaptable within the CM/CS approach.
- Dynamic process scheduling. A central (or perhaps distributed) process scheduler could be utilized such that during clock update the scheduler assigns ACs to processors. The list of ACs eligible for execution during an instant is derivable from the state of the alarm list and from the event-clusters as given by the ACIG.

In the PDEAC algorithm, the behavior of an AC may be described as given by Figure 9.8. The figure presents logic suitable for both CACs and DACs if the condition on a DAC is defined as a tautology. Upon activation, an AC evaluates its condition. If the condition is true, the actions given by the AC are performed and the state-based successors of the AC are activated. Initialization and time flow within the algorithm are governed by a manager process as depicted in Figure 9.9.

The manager activates the initialization AC and then enters the simulation proper. After all ACs during an instant (or initialization) have finished executing, the manager updates the clock based on the alarm list, and activates the DAC(s) whose alarm time(s) is (are) equal to the current clock value.

```
activate the initialization AC
while true do
    when no ACs can execute
        update clock
        activate DAC(s) with current clock
end while
```

Figure 9.9: The Manager Process in the PDEAC Algorithm.

The primary technical issue to resolve in this algorithm is the detection of when the clock may be safely updated. In the model of computation described in Section 9.4.2, when the last AC for a given instant consumes its token, the DAC(s) defining the next instant are "magically" (via omniscience) passed tokens. Implementing this exchange, however, requires global knowledge in a distributed environment – an historically challenging problem.

A simple solution is for each AC to send the list of ACs it activates to the manager, and for each AC to notify the manager upon its own completion. Such an approach may likely produce a bottleneck within the computation. Alternatives may be to distribute the manager process itself, or exploit the facilities of a given architecture or thread package. We leave these important details for future research.

9.4.6 Unresolved issues

The efforts of this chapter represent the first small steps toward effective mechanisms for the parallel execution of simulation models within a CM/CS development framework. The goal of this chapter is to establish the definitional and methodological basis which must underly any execution environment. The concept of *inherent parallelism* and its relationship to an action-cluster-based simulation is crucial in this regard, and is established here. Further, an algorithm with which to estimate the inherent parallelism in a CS representation is defined and its correctness formally established.

These efforts make a significant contribution to the theoretical basis for exploiting parallelism within the CM/CS framework, but much work remains to be completed in the practical application of the theory. Perhaps the best way to proceed from here is to establish an experimental environment within which the practical ideas and methods from

PDES research may be applied and resolved with the context and theories of the CM/CS approach. To this end, several issues of substance need to be addressed:

- *Contention on the alarm list.* The PDEAC approach does not partition the state space among the available processors. Therefore contention on shared variables must be explicitly handled. However, given a CS model representation that contains no state or time ambiguities, the only contention caused by actions of ACs executing in parallel occurs at the alarm list. To prevent the scheduling of alarms from becoming a bottleneck, mechanisms exploiting the "event horizon" concept may prove useful (see [221, 222]).

- *Action-level parallelism.* The efforts described here have only considered parallelism at the level of the action cluster. Each action cluster is regarded as a small sequential algorithm. The actions within an AC may exhibit a degree of independence and may permit the definition, and exploitation, of "finer grains" of parallelism.

- *Handling functions.* In the development of Chapters 8 and 9, a CS is assumed to be comprised solely of ACs. Allowing functions to be utilized in the specification of model behavior leads to many questions regarding analyzability and also implementability. One possible solution is to define techniques by which functions may be translated into ACs.

- *Asynchronous execution.* The models and algorithms described in this chapter are synchronous in nature – dealing with inherent event parallelism as defined in Section 9.2.1. Adapting extant asynchronous techniques from PDES, e.g. optimism, for use within the CM/CS approach merits investigation. Such efforts, however, require reconciling the ACIG representation with the requirements of a partitioned state space.

Clearly, the CM/CS approach requires much further investigation in this area. Just as clear, hopefully, is that the CM/CS approach has much offer.

9.5 Summary

The execution of discrete event simulation programs using multiple processors is investigated in this chapter. Parallel discrete event simulation is evaluated from the modeling methodological perspective identified in Chapter 3. Differences are noted and recommendations made to reconcile these two disparate views. The capabilities of the CM/CS approach relative to parallel execution are also investigated. The concept of *inherent* parallelism is described. Inherent parallelism is a function of a given model representation and establishes a bound on the expectations for speedup resulting from the application of multiple processors to an implementation of the model.

A synchronous model of execution is defined for the CS, and a parallel direct execution of action clusters (PDEAC) algorithm – based on this model – is given. A critical path algorithm, also based on the synchronous model, is defined as an augmentation of the standard DEAC algorighm (see Chapter 8) such that inherent parallelism is readily quantifiable.

The concepts of state ambiguity and time ambiguity in a CS are refined, and a necessary condition for state ambiguity is identified.

Chapter 10

CONCLUSIONS

"Oh, now, don't underestimate the abacus," said Reg. "In skilled hands it's a very sophisticated calculating device, furthermore it requires no power, can be made with any materials you have to hand, and never goes bing in the middle of an important piece of work."

Douglas Adams, *Dirk Gently's Holistic Detective Agency*

The proposition underlying this research is a basic one: discrete event simulation model development must be guided by recognition of the fundamental role of decision support and its relationship to model correctness. Motivating this effort is an observation that *technology,* and not the principles of decision support, is exerting *major* influences on the course of simulation research in many areas – parallel discrete event simulation and distributed interactive simulation being two examples.

In Chapter 1, a set of objectives for this research is identified. The most basic objective is described as seeking an answer to a central question of discrete event simulation modeling methodology: what is the nature of the *ideal* framework for simulation model development where the models may be used for a wide variety of purposes, and implemented on varying architectures? Such an ambitious objective cannot be realistically achieved within the scope of a Ph.D. dissertation. Still, its formulation is important because the objective represents a target toward which the research described here must move. The map within which the tasks comprising the research effort are charted is provided by a more focused set of objectives:

1. Identify an extensible framework for model development which permits the integration of emerging technologies and approaches, and demonstrate its feasibility using an

existing methodology and representation form(s).

2. Recognize a potential problem with the focus of parallel discrete event simulation research, and demonstrate how the framework described above may be utilized to cost-effectively incorporate parallel execution within the general discrete event simulation paradigm.

An evaluation of this work with respect to the research objectives appears in Section 10.2. Prefacing the evaluation is the summary of results and identification of research contributions presented in Section 10.1. Finally, in Section 10.3, some directions for future research are described.

10.1 Summary

The most tangible contributions of this research result from developments with the Condition Specification. This work represents the most intensive investigation of the language since its development in 1982. Research contributions *are* made in many areas. However, several contributions are solely in terms of the global objective – an objective not attainable within the scope of this effort – and are therefore resistant to conclusive evaluation. In the following sections, the research is summarized, and contributions noted, by chapter.

10.1.1 Discrete event simulation terminology

The terminological basis for this research is outlined in Chapter 2. Discrete event simulation is distinguished from other types of simulation, and noted to be at the focus of this effort. Definitions are provided for the ubiquitous terms *system* and *model,* and Nance's [156] characterization of the time and state relationships in a simulation model is reviewed.

10.1.2 A philosophy of model development

Chapter 3 outlines a philosophy of simulation model development characterized as representative of the "modeling methodological view" of discrete event simulation. The view holds that the *primary* function of discrete event simulation involves decision support. The presentation covers a broad range of topics including: (1) a delineation of the relationship among life cycle, paradigm, methodology, method and task; (2) a review of the life-cycle

model for a simulation study proposed by Balci and Nance; (3) a discussion of some important issues in model representation; and (4) a brief description of the simulation model development environment (SMDE) project. The research contributions from Chapter 3 are the following:

- *Requirements for a next-generation modeling framework.* In a 1977 report, Nance [153] identifies six criteria for a simulation model specification and documentation language. Sargent [205], in a 1992 conference paper, offers fourteen requirements for a modeling paradigm. These two sets of criteria are reconciled to produce a list of ten requirements for a next-generation modeling framework (see Table 3.1):

  1. Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.
  2. Permits model description to range from very high to very low level.
  3. Permits model fidelity to range from very high to very low level.
  4. Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.
  5. Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.
  6. Exhibits broad applicability.
  7. Model representation is independent of implementing language and architecture.
  8. Encourages automation and defines environment support.
  9. Support provided for broad array of model verification and validation techniques.
  10. Facilitates component management and experiment design.

  These requirements serve as the evaluative basis for the survey in Chapter 4.

- *An abstraction based on a hierarchy of representations.* The model development paradigm utilized within the SMDE is abstracted to accommodate multiple implementations as illustrated in Figure 3.4. The abstraction identifies three levels of model representation:

  1. *Modeler-generated specifications.* These representational forms permit a modeler to describe system definitions, assumptions and the set of objectives for a given study, as well as the model behavior in a manner suitable to meet the objectives. While a canonical form is implied by the figure, the nature of this form has not been defined.
  2. *Transformed Specifications.* Adhering to the principle of successive refinement, automated and semi-automated transformations are defined to various forms that enable analysis and translation to implementations meeting a specified criteria.
  3. *Implementations.* The lowest level of the transformed specifications are the implementations. These executable representations satisfy the particular constraints of a given simulation study.

The hierarchy may be envisaged as being composed of a set of cooperative and congruent narrow-spectrum languages, or as a single wide-spectrum language. In either approach, the representation should be the focal point, and the subject of explicit methodological support.

10.1.3 Formal approaches to discrete event simulation

In Chapter 4, a survey of formal approaches to discrete event simulation modeling is presented. The research contributions from Chapter 4 are the following:

- *Survey and evaluation of formalisms.* Eight categories of formal methods are identified and surveyed. Each category is reviewed in terms of its underlying concepts, historical development, and directions of current and future research. The categories surveyed are: (1) Calculus of Change, (2) systems theoretic approaches (DEVS, System Entity Structure), (3) activity cycle diagrams, (4) event-oriented graphical techniques (event graphs, simulation graphs), (5) Petri nets, (6) logic-based approaches, (7) control flow graphs, and (8) generalized semi-Markov processes. The formalisms are evaluated with respect to the requirements for a next-generation modeling framework identified in Chapter 3. The evaluation procedure defines four levels of support for a requirement: (1) not recognized, (2) recognized, but not supported, (3) demonstrated, and (4) conclusively demonstrated. The evaluation summary is given in Table 4.8.

  The survey indicates that no existing approach fully satisfies the requirements for a next-generation modeling framework. Of the approaches considered, the systems theoretic approaches rate highest, and generalized semi-Markov processes rate lowest.[1] The requirement for an "unobtrusive conceptual framework" is viewed as least supported by the surveyed approaches, and is the area where the greatest strides can be made.

10.1.4 Foundations

Nance's Conical Methodology (CM) and Overstreet's Condition Specification (CS), which provide the basis for the majority of tasks comprising the research, are reviewed in Chapter 5.

The Conical Methodology is a model development approach that is intended to provide neither abstract nor concrete definitions of general systems. The CM adopts the view that model development leads potentially to myriad evolutionary representations, but that the *mental perception* is the initial representation for every model, and that assistance in the area of mental perception, or *conceptualization*, is (should be) a critical aspect of any

[1] Note that the CM/CS, as evaluated in Chapter 5, receives the highest overall rating.

modeling methodology. The CM identifies two processes in model development: (1) model *definition,* during which a model is described in terms of objects and the attributes of those objects, and (2) model *specification,* during which the attribute value changes are described.

The Condition Specification is a world-view-independent model representation designed primarily to support analysis. The CS permits model behavior to be described in terms of a set of conditions and a set of actions. An action may be paired with the condition that causes it, forming a condition-action pair (CAP), or groups of actions with the same condition may be formed into an action cluster (AC).

10.1.5 Model representation

The CS is most suited for the middle level of the hierarchy described in Chapter 3. The extensions and modifications described in Chapters 6 through 9 are primarily directed to widen the spectrum of the language, and thus provide support throughout the hierarchy. In Chapter 6, the CS provisions for model development, with respect to the CM, are investigated. The research contributions from Chapter 6 are the following:

- *Complete development of four models.* To evaluate the pertinent model representation concepts, a complete development of four models is accomplished using the CM and CS. These models are: (1) a multiple virtual storage batch computer system, (2) a traffic intersection, (3) a system of colliding rigid disks, and (4) the machine interference problem.

- *New operations for the CS.* The collection of primitives for the CS is extended to support CM facilities for set definition. Operations defined are: INSERT, REMOVE, MEMBER, FIND and CLASS.

- *Redefinition of form for report specification.* Overstreet does not prescribe a specific form for the report specification, but instead indicates how the interface between the report specification and the transition specification might be formed using a program designed to compute statistics. A higher-level form for the report specification is defined (see Figures 6.9 and 6.25).

- *Definition of the concept of "augmented" object and transition specification.* A transition specification need not contain any information regarding the collection of statistics (as long as this information is captured in the report specification), however, if the transition specification is to serve as a basis for a model implementation, then the actions required to facilitate statistics gathering – either "on-the-fly" or via logs – must be incorporated into the transition specification. The concept of an "augmented" specification is outlined whereby the object specification and transition specification may be automatically transformed to include the objects, attributes and actions necessary

to provide statistics gathering. This transformation occurs as part of the movement from specification to implementation.

- *Definition of the concept of experiment specification.* Similar to the need for an "augmented" specification to capture the statistics gathering aspects of model behavior, an experiment specification is proposed to capture details, e.g. the condition for the start of steady state, necessary to produce an experimental model.

- *Evaluation of object-based versus object-oriented.* The object-oriented paradigm has arguable advantages over traditional programming approaches for large systems (from a software engineering perspective). The question is asked: from the point of view of *discrete event simulation* model development, is a strict object-oriented approach superior to the object-based perspective of the CM? The suggestion is that the very constrained notions of method, and communication by message passing, may lead to an unnatural description of systems. Thus, the less constraining object-based perspective of the CM is viewed as superior in terms of discrete event simulation model development.

10.1.6 Model generation

In Chapter 7, the extant methods to provide automated assistance in the generation of a CS are reviewed. The model generation and related issues within the SMDE are surveyed. Based on the model development lessons of Chapter 6, new directions for CM/CS-based model generators are described. These new directions include: (1) AC-oriented development, and (2) graphical front ends.

10.1.7 Model analysis and execution

In Chapter 8, issues in model analysis and execution are investigated. The research contributions from Chapter 8 are the following:

- *A semantics for the CS.* In order to provide support for model implementation, the semantic rules for the CS are reformulated. The reformulation includes interpretations for: (1) CAP, (2) AC, and (3) sequence of ACs.

- *Definition of direct execution of action cluster simulation.* Based on a model of computation provided by the ACIG, an implementation structure referred to as a direct execution of action cluster (DEAC) simulation is defined. A DEAC simulation is simply an execution of an augmented CS transition specification.

- *Definition of minimal-condition DEAC algorithms.* Figures 8.3 and 8.4 present algorithms for DEAC simulations that are described as "minimal-condition." Minimal-condition implies that given a completely simplified ACIG as a basis, and using the semantics for a CS mentioned above, the number of state-based conditions evaluated

upon the execution of any given AC is minimal. Two algorithms are defined. Figure 8.3 illustrates the minimal-condition algorithm for a CS containing mixed ACs. Figure 8.4 illustrates the minimal-condition algorithm for a CS without mixed ACs.

- *Evaluation of new CS syntax and semantics on provisions for model analysis.* Since the primary purpose of the CS has been to facilitate model analysis, the new CS syntax and semantics are evaluated with respect to the extant provisions for model analysis in the CS. The evaluation indicates that only one analysis technique, action cluster completeness, is affected by the expanded spectrum of the CS.

- *Evaluation of multi-valued alarms.* A potential source of ambiguity is identified in the possibility of having a multi-valued alarm with a corresponding AFTER ALARM statement. Static analysis cannot guarantee the correct use of the AFTER ALARM construct, therefore a caveat should be provided to modelers regarding their use.

- *Evaluation of CS as time-flow-mechanism-independent.* One of the original goals for the CS is time-flow-mechanism-independence. The failure of the CS in this regard is demonstrated. The use of the alarm construct in a CS *must* reflect some view of the passage of time (although not necessarily the implementation of time flow). We postulate that this problem exists for any operational specification language.

10.1.8 Parallelizing model execution

In Chapter 9, some issues relating to discrete event simulation and parallel execution are addressed. The research contributions from Chapter 9 are the following:

- *Case study of parallel discrete event simulation.* Parallel discrete event simulation (PDES) research is evaluated from the modeling methodological perspective identified in Chapter 3. Differences are evident in two areas: (1) the enunciation of the relationship between simulation and decision support, and the guidance provided by the life cycle in this context, and (2) the focus of the development effort. Four recommendations are made for PDES research to be reconciled with the "mainstream" of DES: (1) return the focus of the development effort to the model, (2) formulate examples with enunciation of simulation study objectives, (3) examine methods to extract speedup in terms of the particular model development approach and envisaged model purpose, and (4) examine the relationship of speedup to software quality.

- *Definitions for inherent parallelism.* The concept of *inherent parallelism* is implicit in the majority of PDES approaches, but has found explicit formulation within the critical path literature. A new characterization, based on the time and state relationships identified by Nance, is given. Two types of inherent parallelism are described: (1) inherent event parallelism, which relates to the independence of attribute value changes that occur during a given instant, and (2) inherent activity parallelism, which relates to the independence of attribute value changes that occur over all instants of a given model execution.

- *Definition of the concept of ACIG expansion.* Since action clusters provide the basis for parallelism, the requirements of an implementation favor as many ACs as possible.

An increased number of ACs yields more potential parallelism. The opposite is often true, however, at the specification level. For a model specification in the CS, fewer ACs generally equates to a more understandable communicative model. Conditions are described by which ACs with quantified conditions may be *expanded* into a set of ACs, thus producing an *expanded* ACIG, which provides the basis for a parallel implementation.

- *Synchronous model of execution.* In a manner similar to Petri nets, we define a *marking* on the ACIG as the distribution of *tokens* within the graph. Graph execution is governed by the passing of tokens. Whenever a token is passed to an AC, the condition on the AC is tested. If the condition evaluates to false, the token is consumed. Otherwise, the actions of the AC are executed, a token is created and passed to each of the state-based successors of the AC, and the token originally passed to the AC is consumed. Whenever the situation develops that no tokens exist in the graph, the earliest scheduled alarm (and all those with identical alarm times) is (are) removed from the list of scheduled alarms, and a token is passed to the corresponding AC(s).

  Execution begins by passing a token to the initialization AC and ends when the actions of the termination AC are executed. The available parallelism at any point in (real) time is defined by the number of tokens in existence in the graph at that time.

- *Redefinition of time ambiguity and state ambiguity.* Overstreet defines two types of ambiguity: state ambiguity and time ambiguity. State ambiguity relates to a dependency among simultaneously enabled contingent action clusters, and time ambiguity relates to a dependency among simultaneously enabled determined action clusters. New definitions for these terms are developed. The development includes characterizations of two central elements: (1) action dependence, and (2) event-cluster. State ambiguity is defined as the existence of dependent actions (and the absence of execution ordering information) within a single event-cluster, and time ambiguity is defined as the existence of dependent actions among simultaneously enabled event-clusters.

- *Formulation of a necessary condition for state ambiguity.* The fundamental limitation confronting the automated detection of ambiguity is an inability to statically determine action dependencies. Still, an ACIG may posses certain properties which tend to indicate the presence of, or at least the possibility for, ambiguity. A necessary condition for state ambiguity in a CS is formulated. The condition establishes that if a CS is state ambiguous then two ACs exist such that they are in the same event-cluster and either no directed path (in the ACIG) exists between the two ACs, or multiple paths (in the ACIG) exist from the DAC defining the event-cluster to one of the ACs. This condition is proved as Theorem 9.1.

- *Definition of a critical path algorithm for PDEAC simulations.* Based on Lin's development, a critical path algorithm for parallel direct execution of action cluster (PDEAC) simulations is developed. The algorithm is an augmentation of the standard DEAC algorithm (defined in Chapter 8) and computes the synchronous critical path for a given model representation. The algorithm is given in Figure 9.7, and its proof of correctness established in Lemmas 9.1 and 9.2, and Theorem 9.2.

- *Description of synchronous PDEAC algorithm.* Based on the synchronous model of execution, a PDEAC algorithm is described (Figures 9.8 and 9.9). The algorithm is

complete but does not dictate a mechanism for detecting when the clock should be updated. A suggestion is made for such a mechanism, but we note that the efficiency of the mechanism hinges largely on the choice of implementation architecture and language.

10.2 Evaluation

The research is evaluated with respect to the focused objectives identified in Chapter 1.

Objective 1. Identify an extensible framework for model development which permits the integration of emerging technologies and approaches, and demonstrate its feasibility using an existing methodology and representation form(s).

A set of requirements for a next-generation modeling framework, and an abstraction based on a hierarchy of representations is given in Chapter 3. The framework and abstraction are extensible in their provisions for both wide-spectrum and narrow-spectrum approaches. New technologies are accommodated, and their influence encapsulated, at the implementation level of model representation.

The Conical Methodology appears suitable to underly a next-generation modeling framework. Much of the research described in Chapters 6 through 9 widens the spectrum of the CS to support all three levels of representation described by the abstraction. Although many issues remain unresolved, the feasibility of the framework, abstraction, and the CM/CS approach have been demonstrated. The research involving the CM/CS approach is assessed with respect to gains in terms of the requirements for a next-generation modeling framework.

Requirement 1. Encourages and facilitates the production of model and study documentation, particularly with regard to definitions, assumptions and objectives.

A distinctive characteristic of the CM, the research makes no specific contribution in this area.

Requirement 2. Permits model description to range from very high to very low level.

By defining primitives for set manipulation in the CS, higher level descriptions of model behavior than previously possible may now be captured in the CS. For example, descriptions of queueing behavior are simplified with the CS extensions.

Requirement 3. Permits model fidelity to range from very high to very low level.

Characteristic of an object-based model development approach, the research makes no specific contribution in this area.

Requirement 4. Conceptual framework is unobtrusive, and/or support is provided for multiple conceptual frameworks.

Although the CS is conceptual-framework-independent, working directly at the CS level imposes a somewhat restrictive CF. Chapters 6 and 7 describe methods by which models may be developed at high levels under a variety of CFs, and how such a model description may be reflected in the CS.

Requirement 5. Structures model development. Facilitates management of model description and fidelity levels and choice of conceptual framework.

An important attribute of a model generator, the research makes no specific contribution in this area.

Requirement 6. Exhibits broad applicability.

Through the complete development of the four disparate models in Chapter 6 – only one of which, the machine interference problem, having been previously developed – the research adds to the claim of the broad applicability of the CM/CS.

Requirement 7. Model representation is independent of implementing language and architecture.

The CS, designed as a simulation model specification language, has always been implementation-language-independent. The development of Chapter 8 defines a close relationship between the CS specification and an implementation through the DEAC algorithm. Still, the model specification and model implementation *are distinct.* The processes of augmentation (see Chapter 6) and expansion (see Chapter 9) define the translation between the two forms.

In Chapter 9, the architecture-independence of the CS is established. The key here is that a model developed only with concern to a natural description of system behavior – to facilitate the establishment of model correctness – may be executed in a parallel environment.

Requirement 8. Encourages automation and defines environment support.

This research is predicated on the recognition that environment support is integral to the simulation modeling process, and as such is framed within the broader context of the SMDE. Automated production of an implementation, and the automated exploitation of inherent parallelism in a model representation are important contributions in this regard.

Requirement 9. Support provided for broad array of model verification and validation techniques.

A distinctive characteristic of the CS, the research makes only minor contributions in this area, with a refinement of the CS semantics, and a reformulation of the notion of ambiguity.

Requirement 10. Facilitates component management and experiment design.

A distinctive characteristic of the supporting environment, the research makes only minor contributions in this area, with a refinement of the report specification and the definition of the concept of the experiment specification.

Objective 2. Recognize a potential problem with the focus of parallel discrete event simulation research, and demonstrate how the framework described above may be utilized to cost-effectively incorporate parallel execution within the discrete event simulation life cycle.

In Section 9.1.4, PDES is examined from the modeling methodological perspective characterizing this research, and found to be largely incognizant of the fundamental importance and nature of decision support within DES. Recommendations are made such that this problem may be addressed from the "PDES side." The development regarding parallelizing model execution within the CM/CS approach (Chapter 9) shows how the problem may be addressed from the "DES side." For any solution to be cost-effective, however, it must explicitly recognize the role of decision support. The framework and development abstraction described in Chapter 3, and their realization in the CM/CS approach, seem well-suited in this regard.

A final, and best, solution to the parallel simulation problem, no doubt will be achieved by attacking the problem from both sides.

10.3 Future Research

Proper evaluation of the efficacy of the CM/CS approach requires additional work in several areas. The most immediate need is for an environment in which the CM/CS can be applied. While the SMDE initiated with a CM/CS-oriented configuration, this platform has been abandoned in recent years in favor of the visual simulation methodology supporting the DOMINO conceptual framework. The widened spectrum given the CS by this research effort mandates a fresh look at a CM/CS-oriented SMDE. To this end, several model representation issues must be addressed. CM-oriented event, activity and process graphs should be defined such that these graphs may be constructed and transformed into an ACIG. Provisions for looping constructs and multiple updates within a single action, useful in high level specification, must be assessed relative to their expression at the CS level.

Within the realm of model execution, several questions remain unresolved. Three versions of the minimal condition DEAC algorithms have been coded (in Pascal, C and C ++) to validate the algorithms. The MVS model is implemented and the results correspond to the known values. The remaining models must be implemented. To realize the CM/CS en-

vironment, rules for translating a CS into an implementation (compilable) language must be established, i.e. a grammar for the CS must be defined and a CS compiler constructed. The unresolved issues noted in Chapter 9 must also be addressed within the context of a CM/CS environment. Primary among these are: (1) defining methods to resolve contention for the alarm list in a synchronous PDEAC simulation, (2) investigating action-level parallelism, and (3) defining a suitable method for handling CS functions. Models for asynchronous PDEAC should also be investigated.

Most of these issues are simply matters of construction, experimentation and interpretation that are not likely to enable methodological breakthrough. Nonetheless, they are important in the transfer of technology from research speculation to accepted practice. Several "grand challenges" are evident in this line of investigation, however. Perhaps the most interesting open question is that when an upper bound on model execution speed is a defined requirement for a simulation study, and the inherent parallelism of a model representation is insufficient to meet that upper bound, can automated assistance be defined to lead the modeler into a reformulation of the model such that the inherent parallelism is sufficiently increased? Such a capability is clearly needed if an *ideal* framework for discrete event simulation modeling is to be defined.

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Appendix A

LIFE CYCLE COMPONENTS

The definitions presented here are adapted largely from [16, 17, 20].

A.1 Phases

The phases of the life-cycle model in Figure 3.2 generally fall into three groupings: problem definition phases (communicated problem, formulated problem, proposed solution technique, system and objectives definition), model development phases (system and objectives definition, conceptual model, communicative models, programmed models, experimental models, simulation results), and decision support phases (simulation results, integrated decision support). Each phase is briefly described below.

Communicated Problem. The problem that is to be solved in its most elemental sense is the communicated problem.

Formulated Problem. The problem is stated such that a decision can be made regarding the most viable and cost effective method of solution to apply.

Proposed Solution Technique. Here we assume simulation is proposed as the most cost effective method of solution to the formulated problem.

System and Objectives Definition. Once simulation is proposed, the system that is to be modeled is defined and the objectives of the simulation delineated.

Conceptual Model. The conceptual model is the model that exists in the mind(s) of the modeler(s). In all likelihood, it is incomplete and ambiguous, and constantly in flux.

Communicative Model. A communicative model, or model specification, is a model that exists in some form such that it can be presented to persons other than the modeler and subjected to prescribed verification and validation techniques.

Programmed Model. The programmed model is an executable representation equivalent to the communicative model (or models) in some high level general purpose, or simulation language. The language chosen is suitable for the machine(s) on which the program is to be executed.

Experimental Model. The programmed model is instrumented to facilitate a particular purpose of investigation. This instrumented model is the experimental model.

Model Results. Model results are produced by execution of an experimental model on a given machine(s).

Integrated Decision Support. The model results are presented to decision makers who propose action based on these results. (Note that these decisions may have no relation to the validity of the model or its results.)

A.2 Processes

The processes of the life-cycle model indicate how progress from one phase to another should be made.

Problem Formulation. The process by which the initially communicated problem is translated into a formulated problem sufficiently well defined to enable specific research action.

Investigation of Solution Techniques. Determine if a solution can best be derived analytically, by numerical approximation, or simulation. The technique applied should yield a low cost/benefit ratio.

System Investigation. Examine the system for: (1) change, (2) environment, (3) counter-intuitive behavior, (4) drift to low performance, (5) interdependency, and (6) organization.

Model Formulation. The process by which the conceptual model is envisioned to represent the system under study.

Model Representation. Translating the conceptual model into communicative models using established specification techniques and languages.

Programming. Translating the specification into a high level programming language or simulation programming language representation that can be compiled and executed on a computer.

Design of Experiments. The process of formulating a plan to gather the desired information at minimal cost to enable the analyst to draw valid inferences.

Experimentation. The process of experimenting with a model for a specific purpose.

Redefinition. Changing the model to facilitate some new understanding/representation of the system.

Presentation of Model Results. Model results are interpreted and presented to the decision makers for their acceptance and implementation.

A.3 Credibility Assessment Stages

Formulated Problem VV&T. Substantiation that the formulated problem contains the *actual* problem in its entirety and is sufficiently well structured to permit the derivation of a credible solution. (This can be determined via questionnaire.)

Feasibility Assessment of Simulation. Is simulation cost effective? Can the study be accomplished under given time constraints? Are the required resources available/obtainable?

System and Objectives Definition VV&T. Expert knowledge must be applied to assess the accuracy and validity of system definitions and objectives.

Model Qualification. Justify all model assumptions with regard to the study objectives.

Communicative Model VV&T. Confirm the adequacy of the model specification. Use: desk checking/walkthroughs, graph-based analysis, proof of correctness, prototyping, etc.

Programmed Model VV&T. Confirm the adequacy of the simulation program. Use: functional testing, instrumentation-based testing, scree testing, etc.

Experimental Design VV&T. Are the random number generators used good ones? Are they being applied properly (common random numbers, etc.)? Are proper statistical techniques being applied?

Data VV&T. Assess (1) model input data, (2) model parameter data.

Experimental Model VV&T. Substantiate that the experimental model, within its domain of applicability, behaves with satisfactory accuracy consistent with the study objectives. (Compare model behavior to system behavior using event validation, hypothesis testing, turing tests, confidence intervals, etc.)

Credibility of Model Results. Statistically validate the model results (as well as the model itself).

Presentation VV&T. Verify the presentation of model results before presentation for acceptability assessment. Four criteria: (1) interpretation of model results, (2) documentation of the simulation study, (3) communication of model results, and (4) presentation technique.

Acceptability of Model Results. This is an attribute of the decision makers or sponsors. (Hard to verify, but adherence to the life-cycle should produce acceptable results with high probability.)

Appendix B

SMDE TOOLS

B.1 Project Manager

The Project Manager is a software tool that: (1) administers the storage and retrieval of items in the project database; (2) keeps a recorded history of the progress of the simulation modeling project; (3) triggers messages and reminders; and (4) responds to queries (in a predescribed form) concerning project status.

B.2 Premodels Manager

The Premodels Manager administers the reuse of previously developed models (or model components). Two Premodels Manager prototypes have been developed [28, 37].

B.3 Assistance Manager

The Assistance Manager provides: (1) information on how to use any of the SMDE tools; (2) a glossary of technical terms; (3) introductory information about the SMDE; and (4) assistance for tool developers in supplying "help" information. Frankel [75] describes the Assistance Manager prototype.

B.4 Command Language Interpreter

The Command Language Interpreter (CLI) is the language through which a user invokes an SMDE tool. Early prototypes are described by [107, 150]. The graphical user interface provided by the Sun workstation currently serves as the CLI within the SMDE.

B.5 Model Generator

The Model Generator assists the modeler in: (1) creating a model specification in a predetermined analyzable form; (2) creating stratified model documentation; and (3) performing model qualification i.e. are the model assumptions acceptable with regard to the model objectives. The Model Generator has been at the focus of most of the research activity within the SMDE. Five Model Generator prototypes have been developed [25, 32, 66, 96, 182].

B.6 Model Analyzer

The Model Analyzer diagnoses the model specification produced by the Model Generator and effectively assists the modeler in communicative model verification. Four Model Analyzer prototypes have been created [66, 151, 194, 238].

B.7 Model Translator

The Model Translator translates the model specification into an executable representation after the quality of the specification is determined (and assured) by the Model Analyzer. Model Translators have been built to accompany the two Model Generators [32, 66].

B.8 Model Verifier

The Model Verifier performs programmed model verification. It provides assurance that the simulation model is programmed from its specification with "sufficient" accuracy. To date, one Model Verifier prototype has been developed [66].

B.9 Source Code Manager

The Source Code Manager configures the run-time system for execution of the programmed model, providing the requisite input/output devices, files, and utilities.

B.10 Electronic Mail System

The Electronic Mail System facilitates the necessary communication among project personnel by controlling the sending and receiving of mail through computer networks.

B.11 Text Editor

The Text Editor is used for preparing technical reports, user manuals, system documentation, correspondence, and personal documents.

Appendix C

GOLDBERG'S COLLIDING PUCKS ALGORITHMS

```
CushionBehavior(messages,CushionState)
    Eliminate pairs of messages that cancel each other
    for all messages do
        case (message_type)
        NewVelocity:
            identify sender of NewVelocity message as ball X
            cancel any planned collision with ball X
            if (the time of a collision with ball X > the current time) then
                schedule a collision with ball X
                add the collision to the set of planned interactions
            endif
        Collision:
            identify sender of Collision message as ball X
            remove ball X from the set of planned interactions
        endcase
    end
endprogram
```

Figure C.1: Goldberg's Algorithm for Cushion Behavior.

```
BallBehavior(messages,BallState)
    Eliminate pairs of messages that cancel each other
    CollisionHasOccured ⟵ False
    For all messages do
        case(message_type)
        NewVelocity:
            identify sender of NewVelocity message as ball X
            if (this ball is not in a pocket) then
                cancel all planned collisions with ball X
                if (the time of a collision with ball X < the current time) then
                    schedule a collision with ball X
                    add the collision with ball X to the set of planned interactions
                endif
            endif
        Collision:
            identify sender of Collision message as object Z
            CollisionHasOccured ⟵ True
            case(object type of object Z)
                Ball: BallState:velocity ⟵ BallCollision(BallState:trajectory, Ball Z's trajectory)
                Cushion: BallState:velocity ⟵ CushionCollision(BallState:trajectory, cushion Z's position)
                Corner: BallState:velocity ⟵ CornerCollision(BallState:trajectory, corner Z's position)
                Pocket: BallState:pocket ⟵ pocket Z
            endcase
            BallState:trajectory:position ⟵ current position
            BallState:trajectory:fix_time ⟵ current time
            remove the collision from the set of planned interactions
        endcase
    end
    if (CollisionHasOccured) then
        cancel all planned interactions
        empty the set of planned interactions
        for all other balls do
            send a NewVelocity message to the ball
        for all cushions do
            send a NewVelocity message to the cushion
        for all pockets do
            send a NewVelocity message to the pocket
        for all corners do
            send a NewVelocity message to the corner
    endif
endprogram
```

Figure C.2: Goldberg's Algorithm for Pool Ball Behavior.

```
BallBehavior(messages,BallState)
    Eliminate pairs of messages that cancel each other
    Order messages by priority
    /* Even if there are several collisions, only one VelocityChange message needs to be sent */
    CollisionHasOccured ⟵ False
    for all messages do
        case (message_type)
        NewVelocity for ball X:
            cancel all collisions with ball X
            if (the time of a collision with ball X > the current time) then
                schedule a collision with ball X
                add ball X to the set of planned interactions
            endif
        Collision with ball X:
            CollisionHasOccured ⟵ True
            update this ball's trajectory
            remove ball X from the set of planned interactions
        SectorEntry:
            add the sector to the set of occupied sectors
        SectorDeparture:
            remove the sector from the set of occupied sectors
        endcase
    end
    if (CollisionHasOccured) then
        cancel all planned interactions
        empty the set of planned interactions
        for all sectors the ball occupies
            send a VelocityChange message to the sector
        end
    endif
endprogram
```

Figure C.3: Goldberg's Algorithm for Ball Behavior in Sectored Solution.

```
SectorBehavior(messages, SectorState)
    Eliminate pairs of messages that cancel each other
    Order messages by priority
    for all messages do
        case (message_type)
        VelocityChange from ball X:
            for all adjacent sectors
                send the sector a NewVelocity message for ball X
            end
            for all balls in this sector
                if (ball ≠ ball X) then
                    send the ball a NewVelocity message for ball X
                endif
            end
            cancel any planned interaction with ball X
        NewVelocity for ball X:
            if (ball X is not in the sector) then
                cancel any planned interaction with ball X
                if (the ball will enter the sector on its new trajectory) then
                    schedule a SectorEntry
                    add the ball to the set of planned interactions
                endif
            endif
        SectorEntry for ball X:
            for all adjacent sectors
                send the sector a NewVelocity message for ball X
            end
            for all balls in this sector
                send the ball a NewVelocity message for ball X
            end
            add ball X to the set of balls in the sector
            remove the interaction with ball X from the set of planned interactions
        SectorDeparture for ball X:
            remove ball X from the set of balls in the sector
            remove the interaction with ball X from the set of planned interactions
        endcase
        if (message_type = VelocityChange or message_type = SectorEntry) then
            if (the velocity of ball X ≠ 0) then
                schedule a SectorDeparture for ball X
                add ball X to the sector's set of planned interactions
            endif
        endif
    end
endprogram
```

Figure C.4: Goldberg's Algorithm for Sector Behavior.

Appendix D

MVS TRANSITION SPECIFICATION

Appendix E

TI TRANSITION SPECIFICATION

Appendix F

PUCKS TRANSITION SPECIFICATION

Appendix G

MIP TRANSITION SPECIFICATIONS

Vita

Ernest Henry Page, Jr. was born in Alexandria, Virginia on 7 February 1965 – or at least that's what he's been told. The first son of Ernest Henry and Barbara Baker Page, he mostly ate, slept and produced diapers until the family moved to Pound, Virginia in 1967.

After graduating from Pound High School in June of 1983, he entered Virginia Tech where he earned the B.S., M.S. and Ph.D. degrees in Computer Science in 1988, 1990 and 1994 respectively. During this same period, he was engaged and subsequently married to Larenda Salyers on 12 August 1989, and became father to Julia on 18 December 1991, and Ernie III on 16 September 1993.

Dr. Page is a member of the Association for Computing Machinery (ACM), the Special Interest Group on Simulation (ACM SIGSIM), the Society for Computer Simulation (SCS), and the Computer Society of the Institute of Electrical and Electronics Engineers (IEEE CS). He is also a member of Upsilon Pi Epsilon, the national honor society for the computing sciences. Dr. Page has served on the faculty of Radford University and is currently a Research Associate with the Systems Research Center. His research interests are mostly documented in this tome. He is quite fond of playing golf and referring to himself in the third person.