1. INTRODUCTION TO MANUFACTURING SIMULATION

The importance of numerical simulation can be described by the viewpoint that there are three pillars in scientific and technology research; analytic methods, experimental methods and numerical simulation.

For completeness of this report from the view of simulation an introduction of the basic of this field must be included. The word simulation is now being used in a much wider context than only a few years back. Throughout the next few pages I will clarify what area of the world of simulation my work belongs to. I will also link it to production engineering and production management, and state where in these complicated and multi-skilled fields simulation is applicable.

As the potential role of simulation in manufacturing has been dramatically changed, and will probably continue to change, an overview like this is necessary. This must though not be seen as a complete state of the art report. An important purpose of this section is to establish a common framework of terms.

1.1 Simulation

The role of simulation in manufacturing has been changing continually since it was applied in military operations for the first time some decades ago. To be able to narrow the scope of the work a number of definitions needs to be made. The term simulation is throughout this work limited to numerical computer simulation. For obvious reasons this Section 1.1 will not give a thorough description of computer simulation. A number of textbooks, articles and papers can be found on this topic. My background is based on among others the works of Kreutzer [1], Law [2], Birtwistle [3], and Mitrani [4].

There are numerous definitions of numerical computer simulation, and I will here quote two of them.

Definition from Birtwistle [3];

Simulation is a technique for representing a dynamic system by a model in order to gain information about the underlying system.

Definition from Naylor [5] is somewhat more detailed;

Simulation is a numerical technique for conducting experiments on a digital computer, which involves certain types of mathematical and logical relationships necessary to describe the behaviour and structure of a complex real world system over extended periods of time.

From these and any other definitions we can see that any simulation experiment is based on models, and therefore Kreutzer's classification of models is mentioned in Section 1.1.1.

At this point it should also be stated that many simulation experts talk about simulation as being both Science and Art. I will not do any arguing on this, but I will explain why the statement may be true. There are now many excellent tools for building simulation models. But no matter how good they are, there will never be tools where it is possible to model all real-life phenomena in a straight forward manner. It will always be required from a good modeler that he can do more with the tool than it originally was constructed for. And it may well be true that a certain artistic talent is needed to be able to master the model building skill.

1.1.1 Models

In Kreutzer [1], there is a distinction of models which may be visualised by Figure 1.1.

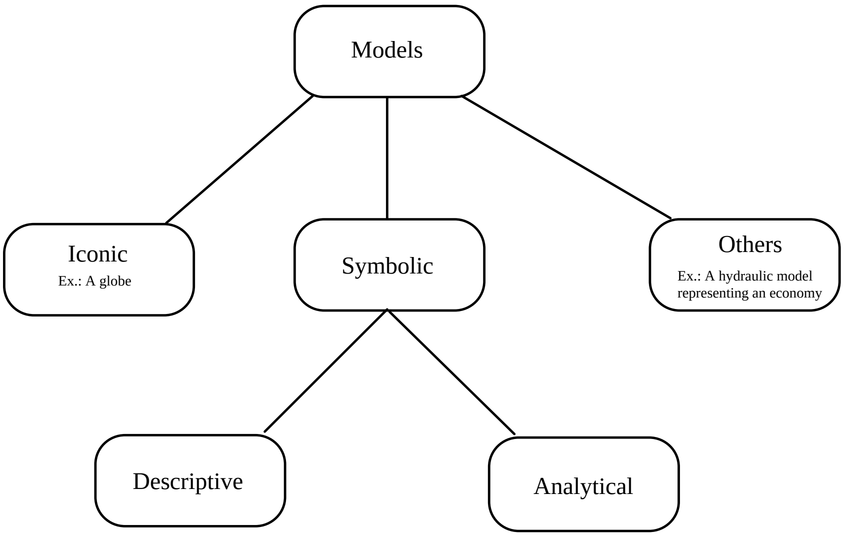

Figure 1.1 Types of models

Working with these *descriptive, symbolic* models on a computer is said to be computer simulation. Please note that Kreutzer talks about *descriptive models,* while Naylor defines simulation as a *numerical technique.*

1.1.2 The simulation process

Although creativeness compared to the level of an artist is sometimes required, performing a simulation experiment is mainly hard work. This work may be described in a ten-point sequence, from Law [2], and slightly changed by Aaram [6], and also generalised by the author to apply both when using a programming language and a simulator.

1	Problem Formulation
2	Model Design (logical)
3	Data Collection and Parameter Estimation
4	Model Building on Computer
5	Model Verification
6	Model Validation
7	Planning Experiments
8	Model Experimentation, i.e., Run Models
9	Analysis of Results
10	Documentation and Implementation

Table 1.1 The simulation process

For further elaboration on these tasks to general purposes see Kreutzer [1] and Law [2]. The distinctions and overlapping between, and certainly the content of steps 2, 4 and 5 have changed as the available computer tools have been improved. I will deal with several of these tasks in later sections when the scope is narrowed to manufacturing simulation.

There has to be done modifications in this list when discrete event simulation is used as an operational tool in a systems integrated environment. Some tasks are completely automated, others are performed in a different sequence, etc. Others are performed once and for all for a number of experiments. A slightly revised list will be discussed in Section 7.

For many purposes it is convenient to distinguish only three major tasks in a simulation experiment.

Task	Performing steps	Related steps
Feeding information into a system	1,2,3,4 and 7	5 and 6
Running the model	8	5 and 6
Extracting information from the system	9 and 10	5 and 6

Table 1.2 The aggregated simulation process

Again it is necessary to mention the overlapping/cyclic behaviour of feeding (changing) information, running, and extracting information the system. In Section 4, model verification (5) and validation (6) are explained as tasks that go on in parallel with all other activities, and hence should be ever present in a simulation study.

1.1.3 Paradigms of system simulation

Again Kreutzer has drawn some distinctions on this topic which I find clarifying. His figure to visualise how the paradigms fit together is shown below as Figure 1.2 [1, Figure 4.2].

In *Monte-Carlo simulation* the utilities of generating random distributions and the data collection devices are included. This is of course the heart of any dynamic modelling technique.

Continuous system simulation is based on modelling a system’s interacting processes describing the state fluctuations. Systems’ dynamics and differential equations are the most important paradigms within this area. Time measurement is done through slicing time into intervals, the size of which again gives the accuracy of the measurements.

Discrete event models permit modelling of large (limited only by computer power or limitations in chosen simulator) system’s dynamic behaviour based on sub-paradigms like inventory models and queuing networks. A system is modelled by a set of entities competing for access to one or many of a set of resources. The model is driven by events which when performed triggers other events and changes the state of the entities and resources.

If these paradigms are integrated, a *combined simulation* may be performed.

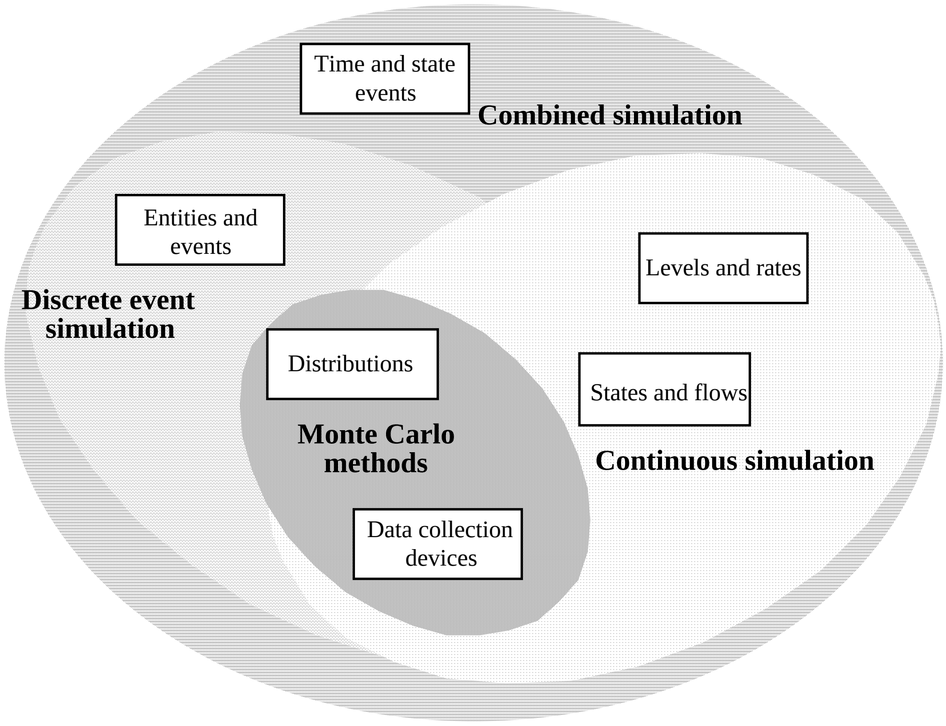

Figure 1.2 Paradigms of system simulation , Kreutzer [1, Figure 4.2]

Examples of continuous system simulation are the study of population dynamics (biology) and economics. In manufacturing the study of transformation of metal in a melting process, or in control systems are well known examples.

In the discrete event paradigm examples like service contentions in shops are obvious. In discrete parts manufacturing discrete event simulation of work shops analysing capacities, utilisation rates, etc. has been performed with success for decades.

Discrete event simulation (DES) is by many experts classified as belonging to operations research. DES as a method was established to be able to model the stochastic behaviour of systems, a behaviour that was not covered by mathematical formulations.

1.1.4 World views of discrete event simulation

The definition of different world views of discrete event simulation is important. Although this exercise may seem confusing, the distinction between the world views or orientation must be made;

An *event* defines the simultaneous state changes in the model. The event is connected to an entity, and nothing happens between the events. In a model of a post office the opening of the office, the arrival of a customer and the ordering of a stamp are all events.

A *process* is a sequence (in time) of events all concerning the same entity, often called the life cycle of the entity. In the post office the sequence; customer arrives, orders stamp, pays for stamp, receives stamp and departs from office is a process.

An *activity* is a time consuming action performed by an entity. There is a set of conditions under which it may start. An activity is often limited by two events; start-up and finishing the activity.

In the post office case examples of activities are the actions of buying a stamp and leaving the office.

A figure may explain the difference and connection between the world views.

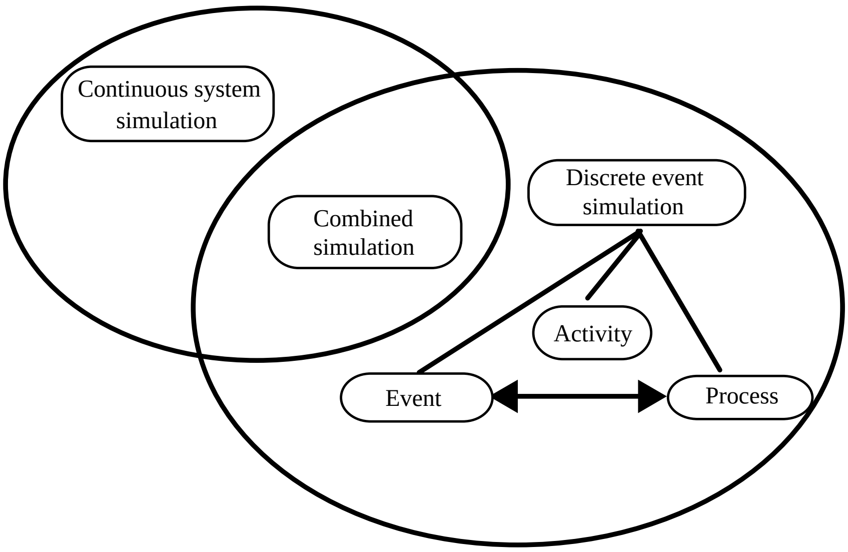

Figure 1.3 World views of simulation

When deciding upon which one of these world views is going to be applied in a certain experiment, one also decides to a large extent which (type of) programming languages/tools to use. This will be dealt with in more detail in the section on the SIMMEK tool.

1.1.5 The connection between queuing theory basis and discrete event simulation

Queuing theory can be seen as a part of the basis for discrete event simulation of manufacturing systems and is in some ways obvious, but still simulation is by many people considered as an alternative solution of a class of problems.

Queuing theory is the study of the randomly fluctuating waiting lines, or queues [7]. It is a description (or model) of the arrival process, the queue discipline (priority rules), and the service process of one or more waiting lines. To represent the arrival and service process, probability distributions are used. Analytical methods are then used to calculate average and expected waiting times, units in system, etc.

Many manufacturing systems may be described with queuing theory. The real challenge appears when the queues are a network of jobs being performed on a set of machines. The arrival processes are the result of “earlier” service processes in the network, and it is impossible to find distributions to model these situations.

Discrete event simulations are also using distributions to model arrival and service processes, as well as modelling queuing disciplines. But instead of an analytical calculation of averages and expected values, the values are drawn from the distributions. In this way one possible outcome for a period of time is experienced. By running through a number of this outcome, and averaging over them, reliable results can be obtained.

So instead of using A. K. Erlang’s formulas for waiting times, queues, etc., the results are obtained by simulation. But the basis of a queuing model and a simulation model, the distributions describing the processes are the same.

1.2 The purpose of simulation

If this section was to be worked out completely at this general level, it would be a textbook on its own. At this level I will only state that simulation in principle can serve two different purposes;

* As a decision support tool
* For understanding and learning about complex systems

In the traditional approach of using simulation in decision making it is used for comparisons, tuning and prediction of system performance.

In our work with simulation we also use a further distinction between two of these different application areas of simulation in decision support. Those two uses are;

* Simulation for comparisons
* Simulation for predictions

The distinction between these two areas is certainly not a clear one. In most experiments there are elements of both. I have a favour towards the first type; simulation for comparisons. The reason for this favour is the following;

* Results based on comparisons are more reliable
* Comparisons are more appropriate in the production management field

The reason why the results are more reliable is deducted from the fact that any model is based on simplifications of the real system. These simplifications influence the result so that they are never exactly the same as the results from the real system. Using simulation as a prediction tool, trying to predict the performance of a planned system, will because of this be connected with much uncertainty and possibly misleading conclusions.

If simulation is used for comparisons, for instance an existing system versus a planned one, the simplifications are also there. But now these simplifications are in both (all) models, and it is not unlikely that they will affect all models to mainly the same extent, and therefore not be too influencing on the results.

Concerning the last of the factors, simulation for factory planning is simulation using predictions, while simulation for production management (tactical and operational simulation) is more simulation using comparison. See Section 1.5.2, which deals with this in more detail.

The role of computer simulation in training, education and as a demonstration tool has exploded the last half decade. This has of course to do with the development of computers concerning computing power, speed and costs as well as new generations of software. But this is only half the truth, because as Hamming [8] summarises the essence of this second purpose, he states;

The purpose of modelling is insight not numbers.

To this I must also remark that studying the numbers gives insight.

1.3 Success factors in simulation

There is almost an infinite number of factors involved in simulation which we could call critical success factors. These vary to a very large extent both considering the influence they have on the final results, and the type of the factor. I will not elaborate on factors like whether your boss is interested in new computer and management techniques, or whether the company has a budget for exploiting the possibilities in simulation. But this is certainly a problem in very many cases, and should be given some concern. The success factors mentioned are concerned with the technical facilities of the simulation tools and the way they are used.

1	The ability to produce results that are interesting to the user
2	The ability to produce results that cannot be obtained by other methods
3	The resemblance between the modelling facilities and the real world system being modelled
4	The time an inexperienced user has to spend from the time he starts using the tool and till he has a model running
5	The validity and accuracy of results and hence the accuracy of the models

Table 1.3 Success factors in simulation

Again the scope of this work is limited to elaborate these factors within the application area of discrete event simulation in manufacturing. It is evident that the third of these factors influences heavily on the last two. The fourth is the factor that may stop the simulation experiment in the birth.

These factors may be supported by the visualised simulation process in the following figure.

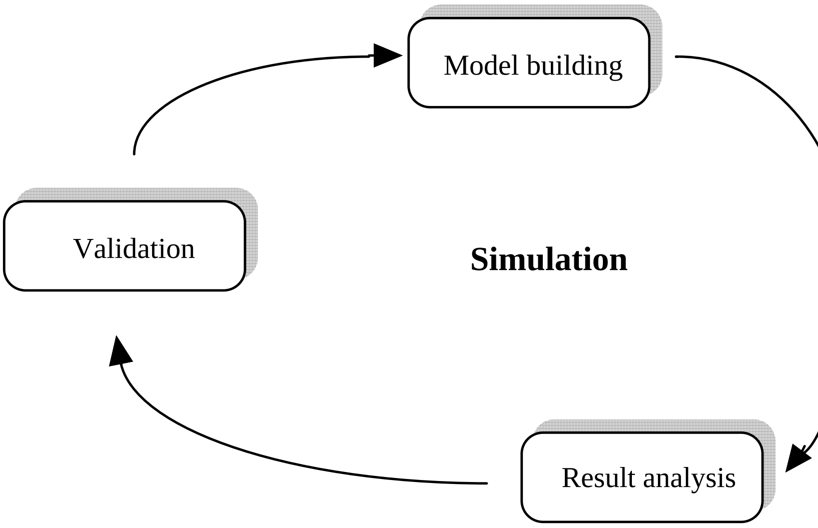

Figure 1.4 "A circle" of simulation processes

1.4 Simulation in manufacturing - Some definitions

For the rest of this work whenever the word simulation occurs, it should be interpreted as discrete event simulation on a computer, unless clearly stated otherwise. This leaves out continuous simulation of systems like melting processes, robot arm movement, tension and forces inside a piece of metal, etc.

1.4.1 Definition of types of manufacturing organisations

There is also a need to agree on a definition on which type of manufacturing we are attaching with this type of simulation. Wild [9] identifies two basic categories of industrial plants, namely continuous process industries and discrete parts manufacturing. Examples of continuous process industries are production of fertilisers or sugar.

Discrete parts manufacturing involves the production of individual items, and may be subdivided into mass, batch and jobbing shop production as in Browne et. al [10]. It should come as no surprise that the scope of this work is limited to discrete parts manufacturing.

Along another axis manufacturing may be divided into engineer/make to order or make to stock, and a number of intermediate variants between these two extremes.

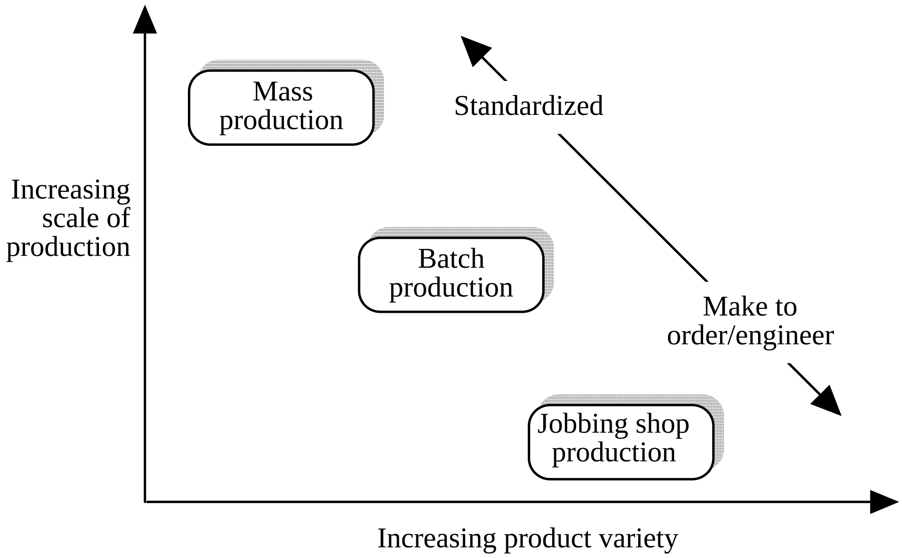

Figure 1.5 Classification of discrete production. From Browne et. al [10]

1.4.2 Definitions of types of simulation experiments in manufacturing

In our work with manufacturing simulation a distinction between the type of experiments has been appropriate. This distinction has mainly to do with the time range or time span of the decision that are to be supported by simulation experiments. The distinction is between *strategic, tactical or operational* use of simulation. This distinction is valid also when we are talking about simulation for learning and training purposes. (See Section 1.5.2 for elaborate definition).

A comment on this is needed. An experiment that would be considered a strategic issue in production management would probably be a tactical issue in the context of business management. At some stages and publications of this work the word semi-operational is used instead of tactical.

1.4.3 Types of manufacturing simulation tools

An agreed definition on categorisation or classification of computer tools for simulation of manufacturing systems does not exist. We frequently use the classification found in Table 1.5. A distinction that is not so disputable is the distinction between;

* Programming tools
* Simulators, where no programming is needed

This work will deal mainly with the second group of tools, under the name of Manufacturing Simulators.

1.5 Simulation in manufacturing - Why, when, with what and how?

1.5.1 Decision support and training - or the answer to why

In Section 1.2, the two main purposes for using simulation were pointed out as being;

* Decision support tool
* For understanding and learning about complex manufacturing systems

Although many authors, specially from the operations research field, characterise simulation as a "method of last resort", like Philips et. al [7], there seems to be a growing interest in the potentials of simulation in manufacturing. And this seems to be true also for surprisingly small companies, even down to companies with 50-200 employees. The major findings from an informal survey performed in some Norwegian companies some years ago concerning the current use of simulation and the potentials of the method that were seen, are found in Section 2.1.

1.5.1.1 Understanding and learning about complex systems

In Section 1.2 the use of simulation in training and teaching was pointed at as one of the two most important areas of application. And this is certainly the most obvious one of the two seen from the modelling viewpoint. Models, either mental, on drawings, in reduced scale, or as analogue models have been used in teaching as far as human history is known. What is more natural than to use the fascinating world of computers to create models, animate them and learn about "the real world"? It must be pointed out that when using simulation as a tool for better understanding, the model building is the crucial part. An informal survey was performed among a group of students attending a course on Computer Based Production Management Systems at NTH. The major finding was that using a simulator where the models were pre built, and the student through an exercise filled some important parameter values, were of little or no use to the majority of students (see also Section 2.1). The students wanted to build the model from scratch, and then play with the parameters.

To elaborate a little more on the use of simulation as a tool for better understanding manufacturing systems, the following purposes are considered as important;

* In general education and training of manufacturing theory (at universities, schools, short courses, etc.)
* Training of new employees in a company or organisation
* Training employees in new situations
* System analysis for better understanding on an individual basis

The first of these points refers to using simulation as a tool where it is possible to make examples to visualise theory and system performance. Simply to see how things work and are tied together.

When a new person is employed in a company, or when he is transferred to another department or position, there is obviously a number of things to learn. The quality of this learning may be significantly improved if he is able to "play with" a simulation model of his new environment. Let him make his trials and errors on the computer first, and he will be more able to perform his duties.

Whenever a major change is performed in factory, there is always a period of dissatisfying production rates, not scheduled stops, co-ordination problems, etc. At least some of these may be avoided if these situations were modelled and simulated, and the people working in and controlling the system had the chance to learn something before the actual start-up. If the decision of implementing the change was supported by a simulation study, the ground is really set for using the same model for training purposes.

1.5.1.2 Decision support tool

The traditional use of simulation, seen from the viewpoint of simulation as scientific methodology on its own, is as a supporting tool in decision making. In this the system’s analysis approach is also included, although this approach certainly belongs to the training approach as well.

At this stage I will merely list the most widely accepted arguments used in promoting simulation as a not replaceable support tool in decision making.

* Simulation allows uncertainty in models

* Simulation handles the dynamics and domino effects apparent in any manufacturing systems

* Consequences are evaluated without interrupting the system

* A large number of possible solutions may be investigated

* The model building, the simulation runs and study of results invoke new alternative solutions that were not thought of initially

All these arguments are based on the use of tools that satisfies all the success factors of Section 1.3.

1.5.2 Areas of application in decision support - or the answer to when

A list of all areas of application of simulation as a decision support tool is probably infinite. The table below is used to show the diversity in the problem areas where simulation may be applied. It also serves as a classification of some problems into strategic or operational, or as is often the case somewhere in between (often called tactical). Referring back to Section 1.2, and looking at the examples below, it is very tempting to exchange strategic with tactical. But it will be confusing at this stage.

Strategic		
	Factory planning, including layout, grouping, automation	
	Market strategies and product ranges	
	Use of subcontractors, outsourcing	
Tactical		
	Lot sizes	Job priorities
	Sequencing	Logistics rules and systems
	Market fluctuations (seasons, trends, etc.)	
Operational		
	Rush orders	Scheduling problems
	Use of operators	Handling emergencies

Table 1.4 Strategic, tactical and operational use of simulation in manufacturing

At this point it is necessary to emphasise that only discrete event simulation is concerned when constructing this list.

1.5.3 Simulation tools - or "the answer to with what"

The purpose of this scheme is not to list all the available tools for performing discrete event simulation experiments in manufacturing. It is an attempt to find the different categories of tools, and name some examples within each category.

Type	*Examples*
General programming languages	FORTRAN, Pascal, C
General programming languages well suited for DES	Simula, APL
Programming environments for DES, some are for special purpose in manufacturing, others are not	Siman, GPSS, Slam II, Simscript, II.5, DEMOS
DE-Simulators for data input, special purpose in manufacturing	Pocus, Mast
DE-Simulators using graphics to build models. The actual program is generated for each model. Special purpose in manufacturing	See Why, SIMFactory II.5 Witness, SIMAN/CINEMA SIMMEK

Table 1.5 Computer software systems for manufacturing simulation

Most of the simulators in the last two groups are in addition to being specialised for use in manufacturing, also even more specialised or well suited for specific problems within manufacturing. An example of this is Witness, a brilliant tool for evaluating the consequences of for instance factory automation in manufacturing. A new version of Witness also suitable for use as a support tool in production management was released in January 91.

1.5.4 Performing DES experiments - or "a reference to how"

Keeping the ten steps of the simulation process in mind (Section 1.1.2), there is a number of excellent books on simulation theory and practice. Recommendations are always difficult because of individual preferences, skills, etc., so the list of references is the most specific I will get on this topic. Some of the books focus mainly on the programming/model building side of simulation, while others cover the statistical parts of simulation as well. In any case additional study of statistics and queuing theory is often useful and sometimes required.