Modeling and Analysis Applications in Manufacturing System Design and Development

by

Pierre E. Brunet

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Signature of Author . . . .

Certified by . . . .

Kevin N. Otto, Assistant Professor of Mechanical Engineering
Thesis Advisor

Accepted by . . . .

Richard de Neufville
Chairman, Technology and Policy Program

Accepted by . . . .

Joseph M. Sussman
Chairman, Departmental Committee on Graduate Studies

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Abstract

This thesis demonstrates how modeling and analysis tools, particularly simulation tools, can be used to facilitate the design of a manufacturing system.

The study is based on visits performed at eight large US manufacturers during the summer 1994. It reflects on the practices encountered at these companies for the design of plants, on the tools identified and examined which help this design process, and on methodologies and policies that contribute to an efficient use of modeling tools.

The main types of modeling tools identified are described in a high level way. Their benefits are stressed in light of the fundamental objectives of the development process as observed at the participating companies: risk control, time and cost reduction, quality and flexibility achievment. A particular emphasis is given to dynamic tools, or simulation. It is shown that two types of simulation can be performed and lead to different benefits: simulation for predictions or simulation for insight into a system.

A model development process methodology is presented, along with recommendations on how to involve all key players in the model building phase: system people, model builders and decision makers. It is argued that this practice greatly improves the usefulness of the model, its acceptance and the learning associated with it. Characteristics of a useful model, and selection criteria for commercial tools are then examined. The fundamental conclusion drawn from the practices of the companies visited is that leverage can be achieved through more communication between model builders, and more interactions between models. It is recommended that harmonization of tools across divisions be aimed at, and that corporate standards be set for modeling tools. Integration of tools used for complementary analyses is also encouraged, and a method to facilitate it is presented. Communication through users' groups or online is suggested as a way to promote the use of modeling.

Thesis Supervisor: Professor Kevin Otto
Title: Assistant Professor of Mechanical Engineering

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Chapter I
INTRODUCTION

I.1. Background

A particular emphasis has been put in industry during the last twenty years on how to improve the operation of plants or engineering design. Less effort has been devoted to the activities occurring "between" product development and the operation of factories: to the design and development of manufacturing systems. Although designs of entirely new plants have occurred less frequently in some industries in the past years, modifications of existing ones are more than common. Because of the size of such projects and the cost associated with them, an efficient development process is critical. Successfully developing a new plant is a required step in the fast and low cost delivery of products that meet customers needs.

Problem solving in manufacturing is becoming increasingly complex. Designers of new factories require more and more guidance from analytical techniques. The use of computer, associated with managerial expertise, has thus become an important part of the decision making process.

US. manufacturing companies all have their own processes for designing and developing the manufacturing systems that will build their products. During these processes, most employ elements from a suite of software packages, including both commercially available ones and internally developed programs. Within each company, there is little guidance for best use of these sets at each stage in the development process and for each function. There is an opportunity for companies to partner and to learn from each other through sharing of development approaches and the application of modeling and analysis tools.

Definitions:

A manufacturing system is the combination of people, processes, organizational structures, information flows, control systems, maintenance, and a set of machines, transportation elements, computers, buffers and other items that are interrelated and used together for the transformation of materials into something useful and portable. It is understood as big-m Manufacturing.

The development of a manufacturing system is the set of activities that need to be undertaken from analysis to concept development, design, implementation build and modification. It does not include product development, nor the operation of a manufacturing system.

Tools are mainly (but not exclusively) PC-based or workstation-based execution platform. We focus on simple ones, for which training and execution do not exceed several days or weeks, not months. An example is the software Witness, a discrete event modeling tool used for throughput analysis.

Methods are even less complex analysis elements, formulas, checklists or organizational ideas which can be followed to complete an activity. An example is a cost/benefit analysis using a spreadsheet.

I.2. Purpose of the Project

This paper is the result of a project undertaken during the year. The purpose of the project is the following: to identify and evaluate robust simple modeling and analysis tools and methods used by the Leaders For Manufacturing (LFM) companies - thirteen major US manufacturing firms - in the development of a manufacturing system, particularly in the design phases. The project relies on the following assumption: although each company has a specific process, similarities exist in the problems that development projects encounter in all industrial settings. Tools and methods that can equally successfully be used in different companies with minor adaptations therefore exist. This project aims at identifying them, when they are used and how they are used. It is a mean to share these tools among the participating companies, and provides a way for them to communicate about their practices. The goal is to have each company learn about the efficient simple tools and methods that others use, and possibly discover tools and methods that it did not know about or did not think of using this way.

I.3. Problem Definition

The issue dealt with in this paper is that of the use of modeling and analysis tools in manufacturing system development. The focus is particularly on simulation tools. The goal of this paper is to show how modeling tools in general, and dynamic models in particular, can successfully be implemented and used to support the manufacturing system development process and to help meet the most important objectives in this development process.

I.4. Scope of the Study:

The companies participating in this project include Boeing, Chrysler, General Motors (GM), Digital Equipment Corp. (DEC), Intel, Motorola, Hewlett-Packard (HP), Kodak and Square D.

This paper does not present the results of an extensive study of all the tools and methods used at the participating companies. Because it uses information gathered during limited visits at these companies, it does not aim to have an accurate representation of all the practices and of the entire range of tools used at each firm. Therefore, it does not attempt to rate the different participants. Rather, it is intended to disseminate some of the practices encountered at different sites for the development of a manufacturing system, to share some simple tools that are used to facilitate this development process, and to show how they can be used efficiently.

I.5. Approach

The project was divided into three main phases:

<u>Understand the main constraints and objectives of the manufacturing system development process</u>

The first phase of the project and a portion of the company visits focused on the development process itself. The first phase consisted in the elaboration of a high level description of the manufacturing system development process that includes the major activities that need to be undertaken from concept to operation. It served as a common ground for companies operating in different industry segments, and as a framework for the second phase of the project, the identification and description of the tools and methods that can be used for the execution of a the activities identified. During the site visits, some time was spent to understand the practices, goals and constraints of the manufacturing system development process. The analysis of the development process is used to provide some soft benchmarking to the participating companies, and to put the different tools and methods into perspective.

Identify tools used and see how they help to meet these constraints and objectives

The second phase of the project focused on the tools and methods used at the participating companies. A questionnaire was sent to these companies in order to first identify the modeling and analysis tools and methods used in the manufacturing system development process, and to then describe these tools and methods. Each tool was to be described in one page determining the required data, the characteristics of the tool, its use, and providing an evaluation of its performance. Yet, because of the great variety of tools used and the number of people involved, responses to the questionnaire were low. Visits to the companies thus became necessary, and it was decided that one week would be spent at each of them to identify and analyze some of their tools and methods. Being on site permitted to have a more precise appreciation, a deeper understanding of the tools used, by discussions and time spent with people using them.

Examine practices that contribute to an efficient use of modeling

Beyond the identification and description of the different tools used, the visits offered an opportunity to examine how the different tools are selected or developed, how analyses or simulations are performed, and how their results are accepted. It lead to some observations on the use of those tools and on the users approaches.

I.6. Presentation of the Results

This paper focuses on the practices encountered at the participating companies for the development of a manufacturing system. It analyzes the main objectives and strategies in the development process. It also describes in a general way tools that can be used to help meet these objectives. It finally examines how the use of these tools can be made efficient. A more detailed analysis of all the tools identified has been undertaken and is presented separately in a software based on Mosaic: the LFM Electronic Manufacturing Resource (LFM EMR). It was distributed on diskettes to the participating companies.

Mosaic is a tool designed to enable simple and rapid discovery and retrieval of information. It presents information in a hypertext structure with links between different documents on selected words. It is well suited for the presentation of information with a tree structure, which is the case for the results of our study. Indeed, the tools are mapped to the development process along three dimensions:

- phases in the development process: from analysis and concept development to implementation
- functions: Project Management, Interaction with Product, Management of Materials, Production, Equipment, Human Resources, Information and Control Systems
- level in the manufacturing system: from the factory level to the cell level.

Fig. 1 presents the structure of the LFM EMR.

See also Appendix1 which presents the home page of the LFM EMR.

I.7. Thesis Outline

Chapter two analyzes some of the goals of the manufacturing system development process, as encountered at the participating companies. The most important common objectives are underlined. The global strategies of each firm are presented, and some of their practices are examined.

Chapter three describes the main families of tools used for the development of a manufacturing system, as identified during visits to the participating companies. Each family is described in a general way, including what the tools in it are used for, and their main advantages.

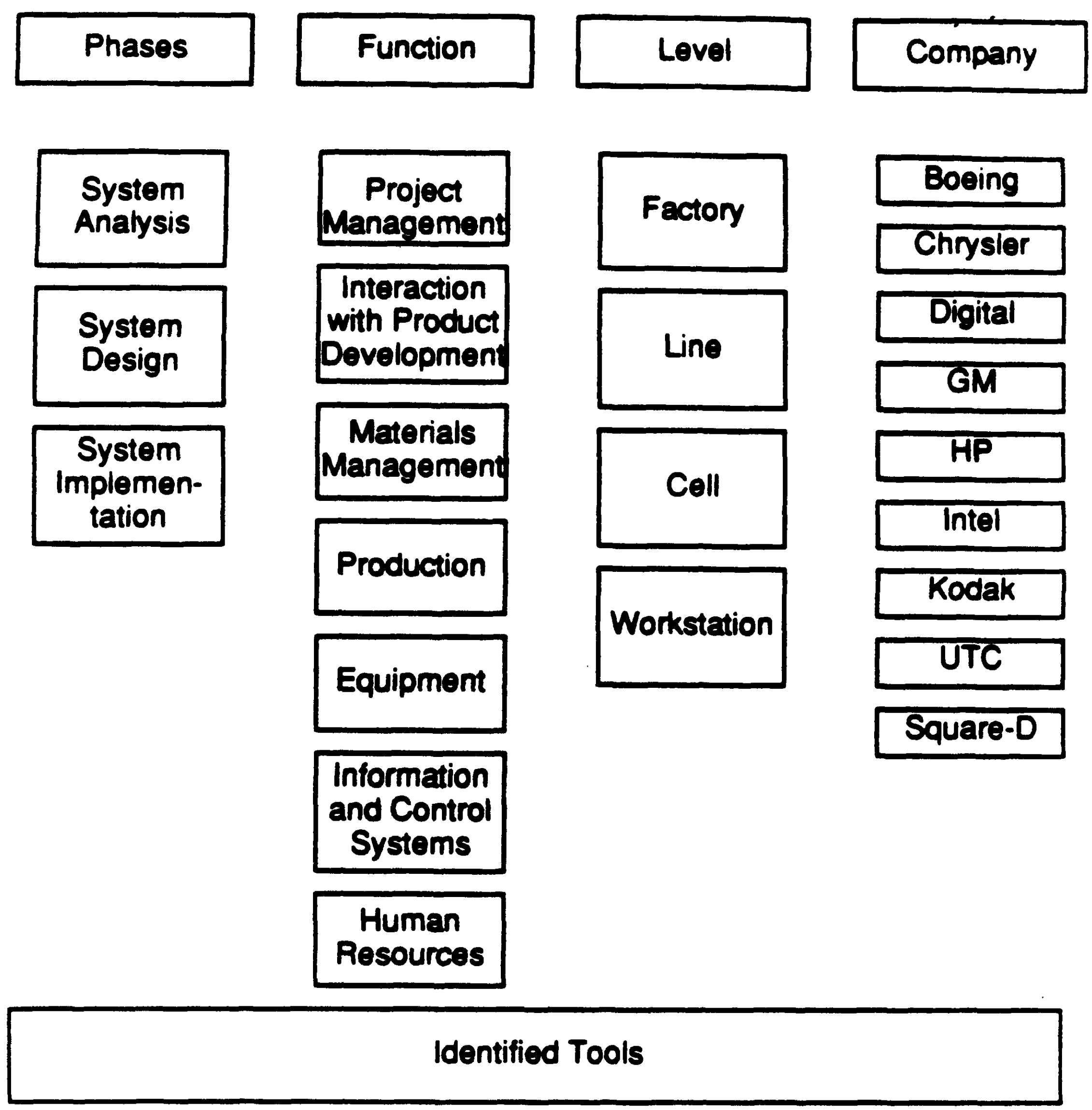
Chapter four focuses on simulation, or dynamic modeling. It examines its main advantages and drawbacks to show how an increased use of it can lead to important benefits. It also suggests a broader perception of simulation that should help promote its development and acceptance.

Chapter five examines how tools are developed or selected, used and implemented at the different companies. It uses these practices to define methods to develop models effectively. It presents a technique used to identify leverage through the integration of different tools.

Chapter six summarizes most of the recommendations of chapters four and five. It reflects on the policy implications of an increased use of modeling, by identifying the stakeholders and their expectations, and by suggesting ways to incorporate more modeling practices in a company.

Chapter seven concludes this paper with hypotheses on the development of this study.

Fig.1. LFM EMR Structure



Chapter II
MANUFACTURING SYSTEM DEVELOPMENT

In order to understand the usefulness of modeling and analysis tools in the development of a manufacturing system, it is first necessary to determine what the objectives and the performance measures of the development process are. Four main performance measures are usually considered in manufacturing strategy: cost, quality, delivery and flexibility (Fine and Hax, 1985.) The same objectives are used for the design and development of a manufacturing system, with the addition of another one: risk control.

Some of these objectives are obviously conflicting. Trade-offs must therefore be made between them. Each company will choose where to focus and how to gain competitive advantage depending on its overall strategy. The weights of each of these performance measures thus vary from company to company. Yet all the companies consider the objectives mentioned above as fundamental ones.

This part describes how these most fundamental objectives are evaluated by some of the companies participating in the project. It also presents several methods used at the companies to meet these objectives. It finally describes other practices encountered for the development of a manufacturing system.

II.1. Risk Control

Any design and development work contains an inherent portion of risk. The future behavior and performances of a manufacturing system being built cannot be predicted and guaranteed before the actual system is completed. Risk cannot be completely avoided, because any new complex system is associated with unknown characteristics, and because no process is entirely reliable.

Undesirable and unexpected outcomes may thus occur, which may cause the schedule not to be met, the costs to increase beyond estimates, or the quality of the system not to be satisfactory. Risk underlies all the fundamental objectives mentioned above, and can therefore be considered as the most important one. In general, unexpectedly bad outcomes will translate into a longer time to complete the development of a new manufacturing system.

Although risk cannot be completely eliminated, it can be controlled. Several practices have been identified at the participating companies to achieve this objective:

II.1.a. Variability Minimization

One way to control risk is to minimize variability. Several companies use a similar approach which attempts to reduce variability by introducing as little change as possible in a new manufacturing system compared to existing ones.

Intel insists on this approach. Processes are transferred from the process engineering group to a manufacturing facility according to strict procedures that guarantee little modifications. The philosophy that underlies this transfer is that as few changes as possible should be introduced. Also, the experience of previous factories is taken into account for the development of a new one. Things that can be standardized and do not really need to be changed will remain the same. Thus several factories end up being built the same way, with the same process. In this case, the similar factories can work together - and sometimes have to work together - to improve their similar process.

To reduce variations, standard solutions have been created in terms of automation and equipment at some divisions at Kodak as well. They are believed to remain technologically competitive for another ten years approximately. Whenever possible, a new plant will be developed using these standard solutions, which consist of four standard modules that can be combined together to build the desired automation system. If a new factory can accept them as fit enough for its requirements, it enables a great cost reduction because of the quantity already used, and an important lead time and risk reduction because of the standard process. In the future, these standard modules may impose some constraints on product designs, but the trade off shows that it makes sense to use these standards in more than 80% of the cases at the moment. The features that are specific to each application of these standard solutions are the end tooling, feeding systems and programs. These are usually tested and verified in laboratories. As a result, the system being implemented has a known behavior, and risk stemming from it is considerably reduced.

A similar approach is used at Square D, where there is an attempt to use the same equipment as much as possible in new lines in order to reduce variations. This also has the advantage of reducing and facilitating the ramp-up phase, since the new factory starts with a partially known process.

II.1.b. Experience

A second way to control risk by reducing variability is to use experience. In addition to using known equipment or production processes, one can also focus on the development process itself and how it can be improved by taking advantage of previous experiences. Because manufacturing systems are getting more and more complex now, being able to retain and formalize experience is more and more important. Experience indeed plays an active role in the development process at most companies.

Relying on experience can have two drawbacks if followed too thoroughly. First, people may tend not to question themselves and why things are done the way they are, and take the old practices for granted. Second, if no system is in place to retain this experience, a lot of knowledge is lost when people leave. This second issue brings us back to ways of retaining expertise.

To retain experience and document it, several solutions have been found.

- A few expert systems have been built at Kodak for example, as well as some corrective action tools.
- A common approach has been defined for the development process at Square D, built on the experience accumulated with former development projects. It is recorded in a manual, the Product and Process Development manual. It harmonizes the different practices at each unit, and provides guidelines for the different steps. Yet each unit has its own tools and even its own strategy, which is determined by local characteristics and design standpoints. There is thus a common road map for the development process, which translates into specific practices.
- In order to formalize experience and to ensure more consistency between the different development processes, a road map is also being developed at GM. It aims to capture some of the best practices for each step and each function, and to harmonize the interactions between these functions.
- Similarly, attention is paid to documenting lessons learned at Boeing. This habit has proven very useful in the development process.

II.1.c. Prototypes

A third way to control risk is to build physical prototypes of parts of the system. This method is used for parts that present the most risk and whose future behavior is particularly unknown. It can be combined with the first methods: existing processes and equipment are used whenever possible, and new ones are physically tested before their implementation. This method is obviously expensive, and can be replaced by simulations as we will argue later on. It is however extremely efficient, and several companies still use it:

- Line prototypes are sometimes built at Square D and Kodak prior to their implementation.
- Physical prototypes of parts of the manufacturing system are also built for test at Intel. A mockup of the automation and materials handling system is constructed. It is used to prove the feasibility of new concepts and to understand the behavior of new systems. It is also used concurrently with discrete event modeling tools. There is a two way exchange of information to improve the material handling system. Simulation is used to help evaluate different concepts and design the new system. In return, the physical mockup provides more accurate data that improves the model.

II.1.d. Simulation

As we show in the following chapters, simulation is a very useful way to successfully control risk and to understand the behavior of systems before their development and implementation.

II.2. Delivery

The time it takes to develop a new system is considered as one of the most important performance measures. For the development of a new system to accommodate a new product, it can be understood as the new-product-to-market time. For the development of new processes or for the improvement of an existing system, it can be understood as the time between the beginning of the project and its completion. The time it takes to develop the new system is often translated into two objectives related to the date of completion of the project. The first objective is to be able to set a closer delivery deadline. The second objective is to meet this deadline.

Having a shorter completion time means being able to deliver new or improved products faster and thus gain market shares. It also means being able to use an improved system earlier and thus reduce costs. It finally means using scare resources for a shorter period of time during the development process, which is often a critical issue.

Attention to delivery has often been mentioned at the participating companies:

- Time to build a new factory is a main concern at Intel. One way to reduce this time, as we explained above, is to control risk by reducing variation from a known behavior to a new factory. The result in doing so is to maximize the chances of achieving output on time.
- Time to market is very long for an airplane. One of the goals at Boeing is to reduce it as much as possible. Time to market is a key strategic objective at HP. To achieve this speed to market, the following practices are used at both companies:

II.2.a. Forecasts

Early predictions are made using forecasting techniques, although they are not very precise and associated with the following difficulties: uncertainty, risk, and forecast fluctuation. The time allowed at Boeing between the placement of an order by a customer and the delivery of a plane is often less than the time required to build the airplane. Predictions are therefore necessary, even if they cannot be very accurate. The forecast at HP is currently based on a combination of historical analogy, regression, conjoint modeling and judgment, and a combination of secondary research source estimations as the market size forecast baseline. Decentralized forecasts are performed, which are then consolidated.

II.2.b. Focus on the Early Phases

The early stages, the conceptual phases are often critical and receive a lot of attention at both companies as well as at all the other companies. Planning and interface coordination are considered as the most critical phases in the development process at Square D. The manufacturing system components require high levels of interaction with each other to bring about the desired transformations. As there is less and less human intuition in their operation to deal with ambiguities, careful planning of such relationships is becoming increasingly critical (Wu, 1992). However, there is a conflict between the need to make an analysis as early as possible, when little data is available, and the need to have an acceptable level of detail and accuracy. It is usually dealt with by trying to understand the behavior of the system without going into much details. What is sought in the early phases is a general understanding of how different elements interact, how they work together.

II.2.c. Systemic Approach and Simplicity

Achieving simplicity in the design of new systems can greatly reduce the time it takes to develop them. Dividing the whole into sub-systems which can then be managed through a coordinated approach, and setting standards for each of the sub-systems breaks up the complexity inherent in manufacturing systems (Wu, 1992.) It is important here to maintain a coordinated approach, a global view. First, the interactions between different sub-systems must be carefully examined , because they may radically change the behavior of the whole. Second, setting goals for sub-systems may lead to sub-optimization. An integrated approach is necessary to avoid this problem. Thus, combining an effort towards simplicity as described above with a systemic approach can lead to a reduced delivery time.

II.2.d. Simulation

As we show further down, simulation in all areas of the development process can help reduce the time to build the system.

II.3. Flexibility

It is commonly thought that the rapid changes in technology and the increasing demand for a greater variety of products lead firms to restructure more frequently than ever before. A plant may typically have to accommodate several generations of products over its life time. Being able to switch from one to the next without difficulties is a requirement. Achieving flexibility is therefore extremely important for manufacturing. Flexibility can be measured by the capability of having a large product mix at low cost, or by the lead time to introduce new products

Most companies consider flexibility as one of their priorities.:

- A new plant is being built at Square D so that it can accommodate several types of products.
- Flexibility is one of the main objectives at Boeing and GM, where manufacturing systems are never developed from scratch, but mainly consist of

modifications of existing ones. Achieving flexibility is therefore one of the top priorities, defined as the ability to accommodate more design changes in the product with minor manufacturing system changes.

Having flexible factories is often translated into having flexible equipment and flexible capacity.

II.3.a. Reconfiguration

Several companies focus on the reuse of equipment:

- At GM right now a significant portion of the assembly process is usually redesigned, and much of the equipment in the body shop is changed. The goal for the future is to keep the same equipment and to redesign only the dies and tooling in order to achieve more flexibility.
- At HP there is an effort going on to have easily transferable equipment, but most of the time products change so much that it is not possible to use exactly the same equipment. Reconfigurable equipment and factories are viewed as the answer to flexibility.

II.3.b. Capacity

Regarding capacity flexibility, the main concern is to find a factory size that can fit fluctuations in the demand for the product. Important decisions include how to deal with cyclical demand (for example by holding excess capacity), whether to add capacity in anticipation of future demand or in response to existing demand, and how to use capacity decisions to affect the capacity decisions of competitors (Fine and Hax, 1985.) A main concern at HP is space: HP has limited available capacity in its plants for planned production. Thus, there is a focus on the efficient use of space. At the same time, there is a need to allow flexibility. A trade off must thus be found between space utilization and flexibility. To deal with this issue, capacity is planned to be able to accommodate peak demand at HP. A cost/benefit analysis of capacity buffer is then undertaken. It is however thought that it would be useful to be able to better evaluate the required flexibility, the optimal buffer space, and to quantify the value of space. Some sensitivity analysis is performed, but it is not systematic.

II.3.c. Trade-offs

There is another trade off to find between time to market and flexibility. Is it better to build a small plant that will be operational soon or a bigger one, more complex but offering economies of scale and expansion abilities? Factories at Intel are typically built as flexible as possible, with cost constraints, as they will need to run more than one product technology over their useful life. Usually, the generation of a product-line lasts less than four years. Each factory is thus built to accommodate at least two or three generations of technology, and its primary goal is to ramp the designated technology as fast as possible. At the same time, a given product technology is developed in several factories which are built sequentially to meet a growing demand for that product over time. Depending on the stage of the product life cycle at which a factory is built, its design criteria will be different:

- the first one has the objective of adapting the new technology. Limiting variation from experience is therefore the main goal. Time to market is critical and the objective is to maximize the output as quickly as possible. Therefore, the first factory will start with an organization similar to the one of existing factories and a work force trained at these existing factories. Only part of the technology will constitute the unknown. This limits the risk associated with the start up and thus decreases time to market.
- factories built shortly after the first one will have to plan for low costs, because the market turns into a commodity type. Their objective is to start up with the first factory's performance right away.
- factories built later in the product life cycle will have flexibility as a main objective, because they will quickly face a decreasing demand for the product.

However, as we pointed out, all three types have to develop a new generation of product technology at some point. They thus all have flexibility constraints and must all be able to quickly market new products.

II.3.d. Simulation

We show in chapter III that high level models, such as enterprise models, can be used to analyze the trade offs between flexibility, time and cost. We also show how simulation (mainly discrete event modeling) can help in the transition from one factory configuration to another, and thus be a useful tool to implement flexibility.

II.4. Quality

Quality is also considered as an important objective. The quality of a manufacturing system, as the quality of any product, is its ability to meet "customers" needs and to be delivered on time. It is measured by customer satisfaction over the entire life of the manufacturing system. The quality of the design and development process often translates into two major objectives. First, the quality of the final manufacturing system is considered. Second, quality of specification or quality of design is aimed at. It is the ability of the designer to translate his vision into a system design that can be implemented in practice without major difficulties. It can be measured for example by the number of corrective engineering change orders.

To assess whether customer requirements can be met, without having to wait for the factory to be built, simulation is now almost necessary. We will examine how throughput modeling tools play a decisive role in that respect.

II.5. Cost

Cost is obviously a fundamental parameter. Cost objectives are measured in terms of facility costs, equipment costs and engineering resources. They therefore interact with all the other fundamental objectives: facility and equipment costs are linked to flexibility and simplicity, engineering resources are linked to development time. Most development projects are evaluated in terms of the bottom line, and profit is the ultimate goal. Yet cost is not really an objective in itself. It is more exactly a performance measure and a constraint. Indeed achieving any of the other objectives will translate into cost savings. On the other hand, increasing spending can help achieve any of the other objectives. Cost is thus an enabler and a constraint, a resource and a performance measure. Although all objectives are evaluated in the perspective of cost and profit is the ultimate goal, no company stressed cost as an objective in itself. Cost manifests itself in the way the other objectives are considered and dealt with.

As a result, tools that can help the analysis of the development costs are important. We examine in chapter III how cost models can be used effectively to forecast the cost of different alternatives.

II.6. Other Practices

The objectives presented above were all stressed to some extent at each of the companies visited. In addition to these, others were mentioned by several companies and are worth receiving attention.

II.6.a. Environmental Impact

The environmental impact of factories has been mentioned several times and seems to be gaining importance. People at Intel consider it as an important objective, and energy conservation has been defined as a concern at HP. Yet this issue is not one of the priorities in the development process. Considering the environmental impact of new factories shows the importance of a system viewpoint when designing and commissioning a large-scale project.

II.6.b. Systems Approach

It is commonly thought that a systems approach should be viewed as an adequate framework for the analysis of problems which are generated by modern manufacturing operations. The actual process of systems design which must create a manufacturing system capable of fulfilling strategic objectives is often a structured problem. A systems approach is therefore very well suited for the development of a manufacturing system. Unlike the functional approach, the systems approach encourages the analyst to consider activities in their entirely, focusing on their relationships and on feedback structures, and understanding the objectives of the whole (Wu, 1985.) It is believed at each company that it is important to have a systemic approach, a system view, an understanding of the interface points and of the relationships between different elements.

As we discuss later, several models try to capture this systems approach: from static models to dynamic ones, and from continuous to discrete depending on the corresponding characteristics of the system.

II.6.c. Development Process Road Map

The companies visited present a large variety of manufacturing types: from building airplanes to small parts assembly, from lot sizes of one to mass production.

The practices in the development of a manufacturing system therefore differ from one company to the next. They also differ within each company from one division to the other. As we have already pointed out, there is an attempt in several companies to document experience and develop a standardized road map for the development of a manufacturing system. This can be considered as a necessary preliminary step before the standardization of the tools used for each activity (we discuss this issue later.) This road map would be used by all divisions. Yet some adaptations to specific conditions or strategies would customize it into division specific practices, as is the case at Square D. While common milestones can be defined, some specificity must be retained.

II.6.d. Product and Process Development

(i) Concurrent Product and Process Development

An important issue is the interaction between product and process development. A common practice at most of the companies visited is to have cross functional teams including engineering, manufacturing, marketing, finance, personnel... Concurrent engineering between product development and manufacturing is promoted:

- New products and new lines are developed concurrently and implemented at the same time at Square D. Product and process development are closely linked together. There is no distinction made in theory. Manufacturing is involved early in the product design process, and a cross functional team is responsible for the entire development process. The same guide (Product and Process Development) is used for both, illustrating how closely they are linked.
- A similar approach is being developed at GM. The interactions of different departments are examined and a systems approach integrating the different functions is followed. A recommended course of action is developed in a manual, setting goals that the different divisions have to reach. Each project is conducted by a team with the same leader from beginning to end, although different people may participate along the project. Within each functional area, a person is determined as responsible for the interfaces with the environment.

(ii) Product vs. Technology Driven Development

The way technology changes and influences the manufacturing system, and is then implemented, varies depending on the type of product and the company attitude. Following are some practices encountered regarding the leading driver of technological change:

- There are not many changes in the production process from one generation to the next at Boeing. Most of the changes are related to the plane design. The assembly process remains similar and the tooling philosophy is very conservative: as many tools as possible are retained from one plane to another. Most of the effort has therefore been devoted to improving the design of planes, and less to the manufacturing side, until now. Both have been dealt with separately, so as to minimize risk. Great improvements have been achieved in design. Changes in manufacturing have been postponed on purpose to limit innovation complexity.
- The development process is product driven at GM and Kodak. New technologies or processes are a result of new product requirements, and both are often introduced simultaneously. This may introduce more risk for the new production. Only a close interaction between them as early as possible in the development process can help control this risk.
- The development process is mainly technology driven at HP and Intel. New technologies lead to new manufacturing systems. They also determine most of the constraints of new products. The timing of the decision to go is considered as critical at Intel. It is necessary to ensure that the organization has the capability to support the new technology.

II.6.e. Development Methodology

The development process is from top down with iterations for the design phase, starting with a global picture and going to more details as time goes by. It is from bottom up in the execution and validation phase.

Chapter III
TOOLS USED DURING THE DEVELOPMENT PROCESS

A great variety of tools and methods used for the development of a manufacturing system has been identified during the field visits. Depending on the system that is being analyzed, different types of tools can be used. This chapter classifies these types of tools in several ways. It also presents the main "families" of tools that are most commonly used at the participating companies. Each family is described in a general, high level way with an input/output overview of the tools that it covers. The advantages of using tools from these families are stressed in light of the fundamental objectives of the manufacturing system development examined in chapter II.

III.1. Usefulness of Modeling and Analysis Tools

Several benefits are perceived with the use of modeling or analysis tools:

- they have the advantage of helping the understanding of systems analyzed. With the advances of technology and the size of manufacturing systems, it is more and more difficult to grasp problems with a mere sheet of paper. To be able to make decisions faster, and in a rigorous way, modeling and analysis tools are more and more needed. Faster solutions to more complex problems are the main benefits of the use of modeling and analysis tools.
- they have a rationale, objective decision making process. They are thus less subject to personal feelings and may lead to better decisions, although "soft" parameters are sometimes reflected in the way a model is built or should sometimes be included in a model.
- they have the advantage of backing up decisions. Most engineers are positively inclined towards an opinion justified by an analytical support.
- they can be used as means of communication. When performing the analysis, they help focus the effort of a team. After the analysis is performed, they help present the results.
- they can be used to document decision processes.

We come back to the advantages of modeling and analysis tools more specifically when we describe the different types identified, and we detail the advantages of dynamic models in chapter IV.

II.2. Classification of the Tools Identified

A classification of the different tools encountered during the field visits can be made using a classification of the types of problems or sub-systems that they address: static vs. dynamic, continuous vs. discrete and deterministic vs. stochastic.

III.2.a. Static and Dynamic Tools

This distinction is built on the activities that are considered in the system being analyzed. A static system is one that has a structure, but no activity that evolves over time. A dynamic system combines structural components with activities that evolve, so that the system changes states over time (Wu, 1992.)

(i) Static Tools

Most of the tools currently used at the participating companies are static. Examples are all analyses using spreadsheets, which are very commonly used. Other examples include models that take a snapshot at a system and describe it at a given point in time, in accordance with some logic patterns.

The system analyzed is divided into inputs, outputs and a process linking them. Two approaches can be followed:

- A first type of analysis focuses on the relation between inputs and outputs. The outputs are used as performance measures, to evaluate characteristics of the system which are entered as inputs. An example is a capacity analysis using a spreadsheet. The relation between, for example, desired capacity (output) and number of machines (input) is examined. One can determine the desired value for the inputs by varying them until one reaches the desired output.
- The input/output analysis also contributes to an understanding of the process at play in the system analyzed. In this type of analysis, the input/output relation is used to understand and rate the process itself. It may be used to choose between different systems associated with different input/output relationships. An example of this type of tool use is a static throughput analysis of a production line. Depending on the choice of the elements constituting the system (machines and flows...),

the relation between input (orders) and output (production rate) varies and can be evaluated to choose the most desirable process.

(ii) Dynamic Tools

Dynamic tools or simulations are used interchangeably in this paper. A simulation consists in the imitation of the operation of a real world process or system over time. It uses a model, which can be defined as a representation of reality, of the different elements constituting the system at hand and of their interactions. Two fundamental characteristics of a system are incorporated in the model that describes it in a dynamic tool: the concepts of control (feedback control) and communication (information theory). A simulation results in a description of the behavior of the system over time, behavior which is similar to that of the real system under the same conditions. Examples of dynamic tools are all types of simulations that are performed to understand the behavior of a system from that of a single machine or robot to that of an entire factory.

In all companies, there seems to be a transition from a spreadsheet mentality to a simulation approach in the manufacturing system development process. GM is probably the most advanced in that direction among the participating companies. People at each company recognize the importance of simulation, although they admit that is not fully developed yet. Several acceptance problems still sometimes stand in the way to a wider use of simulation. We discuss these issues in further detail later on.

III.2.b. Continuous and Discrete Tools

Dynamic tools can be further classified using the way variables change over time. In continuous systems, variables change in a continuous way. In discrete systems, they can only take discrete values and change in a stepwise manner. To describe continuous systems, differential equations can be written, that may eventually need to be solved numerically on a computer. Discrete event systems cannot be described in a standard way and must be analyzed using discrete event simulation methods. The way they are transcribed using a simulation language depends on the programming approach of that language. Thus a same system can be turned into different structures once it is translated into a model because of the different languages. This can be of importance when deciding on a tool and evaluating the way it fits a specific operation or strategy.

Continuous dynamic tools can be used for continuous processes, such as the analysis of an injection molding process. Other examples include system dynamics tools.

Discrete dynamic tools are more common among the ones that we identified. They are used for problems such as the flow of material or parts in a production system (all the companies visited had a discrete production process.)

III.2.c. Deterministic and Stochastic Tools

Deterministic systems present unique and direct cause and effect relationships between the inputs and outputs, and between the initial conditions and the final state. Stochastic systems on the other hand are characterized by random properties. Although the principle of causality still applies to stochastic systems, variability is introduced so that results can only be analyzed in probabilistic or statistical ways (Wu, 1992.)

Most of the tools identified were deterministic (all spreadsheets are for example.) They can be associated with a specific problem analysis method: sensitivity analysis. With deterministic tools, "what ifs" can be performed to examine the implications of possible scenarios. By varying one or several parameters, the behavior of the system under different conditions can be studied.

Few tools were stochastic. The main ones are throughput simulation tools. They include the variability of machines for example. Analyses using stochastic tools examine statistical distribution of output variables in response to statistical distribution of input variables.

III.3. Main Families: Brief Description

Another way to categorize the different tools identified is by the analysis that they perform. While the classification used above is useful to understand how tools work and are related to various types of systems, the following type of classification is more useful for an application of the tools. It focuses on the "what" rather than on the "how" or "why" of tools. Several families grouping the most commonly used tools have thus been identified. Within each family one may find tools of the different types described above. See Table 1 for a summary of the families identified.

Families	Classification
Project Management	Static. Deterministic
Cost Analysis	
Facility Cost	Static. Deterministic
Product/Production Cost	Static. Deterministic
Interaction with Product	Static. Deterministic
Tooling Design	
CAD	Static. Deterministic
Tooling Process Simulation	Dynamic: Continuous. Deterministic.
Robotics	Dynamic: Continuous. Deterministic
Throughput Analysis	
Spreadsheets	Static. Deterministic
Queuing Formulas	Static. Deterministic
Simulation Packages	Dynamic: Discrete. Stochastic
Management of Materials	Static. Deterministic
Ergonomics	Static. Deterministic
Organization and Process	Static. Deterministic
Information System	Static. Deterministic
Enterprise Modeling	
IDEF0	Static. Deterministic
System Dynamics	Dynamic: Continuous. Deterministic.

Table 1. Main Families of Tools.

III.3.a. Description Format

In the LFM EMR, each tool is described with:

- a mapping to four dimensions:

1. Phases in the manufacturing system development process: System Analysis, System Design, System Implementation
2. Functions of the manufacturing system development process: Cost Analysis/Project Management, Interaction with Product, Management of Materials, Production, Equipment, Human Resources, IS and Control Systems
3. Level in the manufacturing system: Factory, Line, Cell, Workstation
4. Company participating in the project.

This mapping creates four coordinates for each tool. Using the LFM EMR structure, each tool can be reached using any of its four coordinates. Thus, if one is looking for tools corresponding to a given value of one dimension (e.g. tools used "for Management of Materials", or "at the cell level"), one can directly have access to them only

- a brief description of the tool, indicating what it is used for and including its inputs and outputs
- its main advantages related to the objectives described in chapter II
- its characteristics of use: people using it, training required, time required for an analysis, platform, and cost
- a comparison with similar tools when applicable.

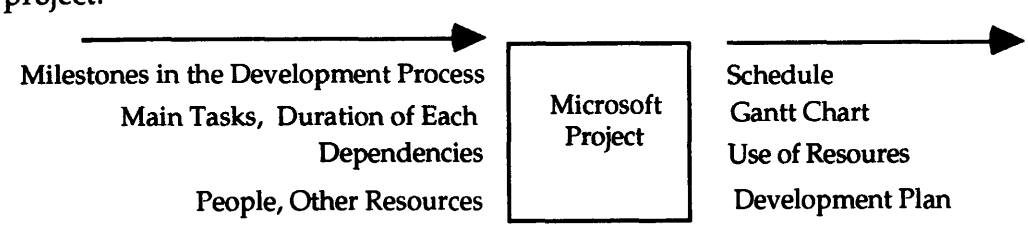
See Appendix2 for the format of the presentation of the tools in the LFM EMR. What was looked for was a general description of each tool and of its main characteristics. The exchange of more information was left to the companies at their discretion.

In this paper we present a summary of the descriptions of tools pertaining to the main families. To avoid redundancies with the LFM EMR or disclosure of confidential information, we limit ourselves to a brief description of each family, the main types of tools that it contains with an input/output definition of them, and their main advantages related to the objectives of chapter I. Some comments are added to evaluate their usefulness. See also Appendix3 for a list of all the tools examined.

III.3.b. Descriptions

(i) Project Management

The most typical and commonly used tool is Microsoft Project: all companies use it. It is a static deterministic tool used to assist the scheduling and management of a project.



Main Benefits:

- it helps focus the effort and mobilize resources when needed;

- it raises flags on potential problems;
- it helps divide the project into parts in which people know what they are expected to do and how they are expected to do it;
- at the same time it keeps the whole project in perspective
- it helps focus on the interface points between the different parts of the project

It may however introduce a false confidence in the project: because a schedule is determined on paper does not mean that it is followed.

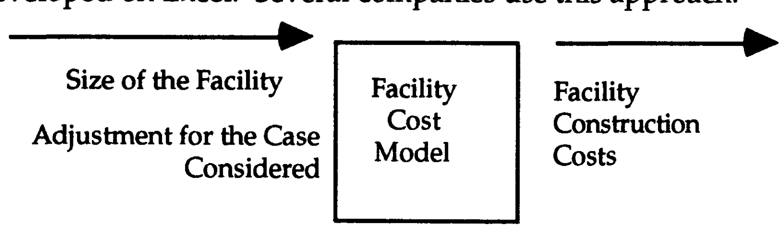
Another very common method for project management, which has already been described above, is the use of road maps for the development process.

(ii) Cost Analysis

Two main types of cost analyses have been identified: facility cost, and product/production cost.

- Facility Cost Tool:

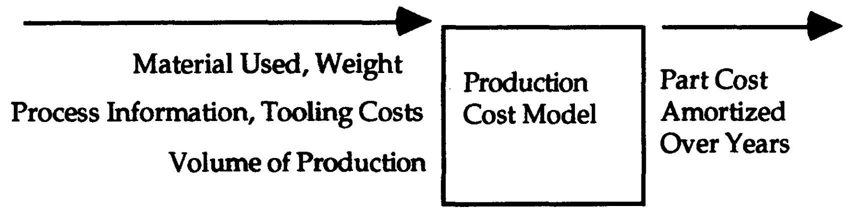
It is a static deterministic model intended to assist project teams in preparing cost estimates during the feasibility and schematic stages of manufacturing facility construction projects, when few or no detailed drawings are available for detail quantity takeoffs. It uses calculations performed on existing factories with a similar design. It is developed on Excel. Several companies use this approach.



Main Benefits:
- it enables a high reduction of the development time: it speeds up cost estimates and assists in credibility for estimates, thus accelerating the decision to go;
- it provides risk control by using the experience of existing factories for future ones.

- Product/Production Cost Tools: Cost Model Using a Spreadsheet

It is a static deterministic tool used to evaluate the cost of a fabricated part, using a process specific approach. Many companies use this type of approach. It is developed on Excel, with several similar sheets for each type of process. It incorporates the experience of existing manufacturing costs. It can be used for make vs. buy analysis, or for material or tooling selection.



Main Benefits:
- it permits an interaction with design, and a manufacturing cost evaluation early on in the design process;
-it reduces the cost of the manufacturing system.

There is however a trade-off between a simple spreadsheet flexible enough but not very accurate, and a more complex one but difficult to modify. Since simplicity is often favored, this type of tool is most useful in the early phases, to get a good estimate.

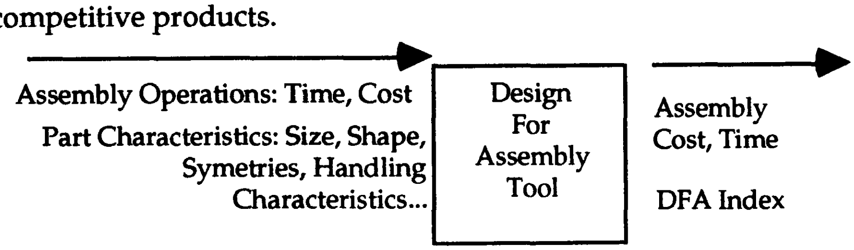
Based on the Activity Based Costing methodology, cost models can also be built using discrete event modeling tools: the cost of material is an attribute of the part, the labor cost is associated with the people who are represented in the model, the overhead costs are included in a burden station.

(iii) Interaction with Product

The most commonly used tools for that purpose are Design For Manufacturing tools. They are not widely used though. Rather, the DFM methodology is followed without the help of any tool. The DFM methodology consists of an interaction between product engineering, production designers, manufacturing and cost accountants aiming to reduce the cost of manufacturing a product. It estimates the manufacturing costs associated with a product design and modifies this design so as to reduce the costs of components, of assembly, and of supporting production, while considering the impact of DFM decisions on other factors (Eppinger and Ulrich, 1994.)

Example: Design For Assembly Tool:

It is a static deterministic tool which enables a product development team to improve the designs of parts to optimize the assembly of a product. It is used to make design comparisons, to choose between concepts or to benchmark existing and competitive products.



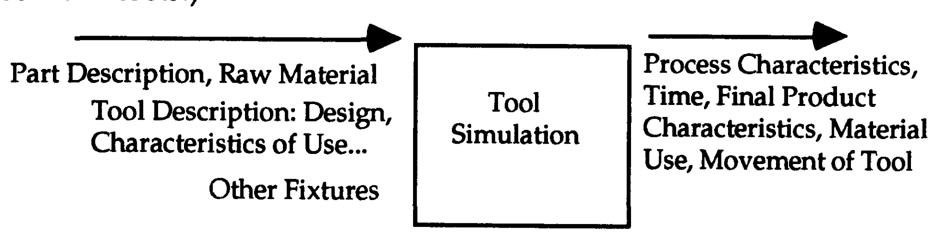
Benefits:
- it enables a high reduction of the development time of the product;
- it enables a high reduction of the cost of the product;
- it enables product design simplifications, it leads to an improved quality of the part;
- it captures and retains a technical memory about the product design
- it provides the benefit of the DFM methodology, the team work.

(iv) Tooling Design

- Tooling is designed using Computer Aided Design systems. The most important aspect of tooling design is the fact that most companies take advantage of Parametric Design. Parametric design consists of having the geometry of the object driven by parameters. These can be linked in such a way that a modification of one of them is followed by updates of all the others linked to it, so as to maintain the desired proportions and interactions between them. If a constraint causes one parameter to change, others linked to it will also have their dimension automatically updated to respect the balance in the design of the whole. It fits well in a manufacturing environment, for tooling design (die design, mold design.) The problem associated with it is that not all changes desired by manufacturing can be accepted once the database is set, because of the way the links are defined. Thus, a close work between manufacturing and engineering is necessary up front.

- Simulation packages are also used to verify the way tools work.

They are dynamic deterministic tools that interactively simulate, verify and display with an animation the process for which a tool is used. Some do not have an animation but only records of the parameters characterizing the process. They are used to verify the way a tool works, or sometimes to modify the design of the product (used as DFM tools.)

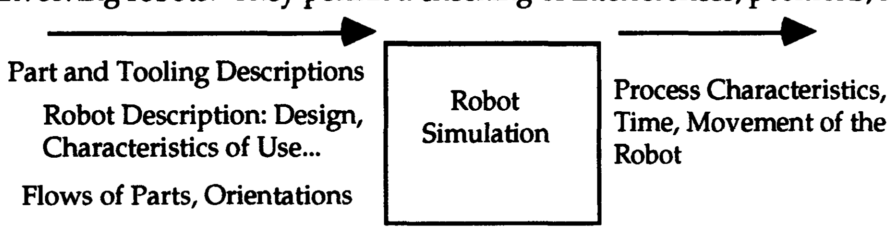


Main Benefits:
- it enables a high reduction of the risk associated with the tool: tests can be performed earlier and tooling issues resolved before implementation;
- it enables a high reduction of the development time: work can be done concurrently with product design to get a shorter time to market;

- it enables a high reduction of the cost of the system being analyzed: it reduces prototyping and retooling; it tests the tool without having to build it; it reduces material usage;
- it enables a high improvement of the quality of the process: lower rejects, higher quality parts, less set-up time, shorter cycle time;
- it is used as a DFM tool and bridges the gap between manufacturing and engineering.
Yet it may lack accuracy for very precise work.

(v) Robotics

Simulation packages are used to verify the way robots work and for off-line programming of these robots. They are dynamic deterministic tools that interactively simulate, verify and display with an animation the movement of the robot. They can be used for dynamic simulations of welding and stamping for example, or other activities involving robots. They permit a checking of interferences, positions, reach.



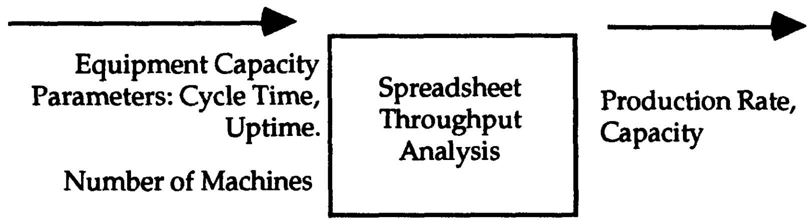
Main Benefits:
- it enables a high reduction of the risk associated with the robot: tests can be performed earlier and interferences or other issues resolved before implementation;
- it enables a high reduction of the development time: work can be done concurrently with product design to get a shorter time to market;
- it enables a high reduction of the cost of the system being analyzed: it tests the robot without having to build it and put it in place;
- it enables a high improvement of the quality of the process: less set-up time, shorter cycle time.

(vi) Throughput Modeling

Throughput modeling tools are the most commonly used modeling tools at the participating companies. Each development project involves the use of them, often of several types. The main goal in throughput analysis is to evaluate the performance of a production system, from a single machine to an entire system, based on throughput related criteria. Three main types can be performed: using spreadsheets, queuing formulas, or computer simulation.

- Spreadsheet Model:

It is a static deterministic tool used to evaluate the capability of individual tool sets, or to determine the number of machines required to meet the desired capacity. Sensitivity analysis is usually performed. Most of the participating companies use this approach in the early phases.



Main Benefits:

It gives rough estimates early in the analysis, without too much time and effort. It is useful as a first pass, and for simple systems. Yet it does not take into account the variability of the piece of equipment and the consequences of linking together several machines. It is too rough to help more than for a quick and early analysis. Simulation is needed as a complement. A spreadsheet analysis can be used as an input for a more detailed analysis using simulation tools.

- Queuing Formulas:

Several mathematical results regarding queuing systems have been developed. They can be used to get quick and easy estimates of utilization, work-in-process, total time spent by a product in the system (throughput time) and waiting and working time.

The main problem with queuing formulas is that they require numerous assumptions, which are not always well perceived or which do not necessarily correspond to reality. Thus, they assume that systems are in steady states: transient behaviors are not well described by queuing theory. Also, a first come first served may not always apply in the factory; considering adequate buffer space or non exponential distributions for service time in the model cannot lead to accurate results but only to rough upper and lower bounds.

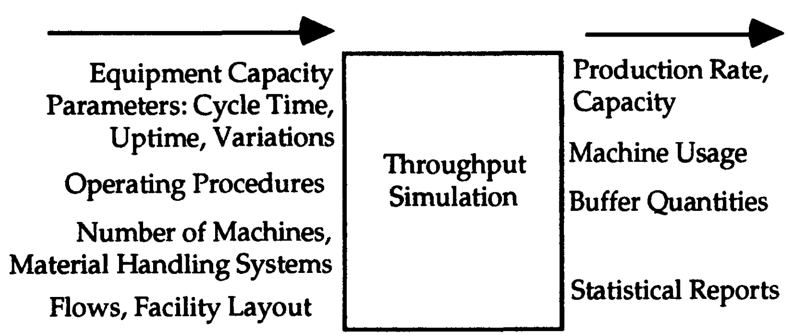
- Computer Simulation:

Throughput simulation packages are dynamic stochastic tools used for a detailed analysis of a manufacturing system, sometimes completing more simple spreadsheets used for planning. Applications include process design or improvements (alternate routings, consolidation of steps, capacity analysis, throughput analysis, part flow time analysis...), operational analysis (lot size, queue sizes, priorities...), human resources requirements forecast, and equipment design. The scope of the models can range from a cell with few operation steps to an entire line. All companies have at least one package.

They can be used at different stages in the development process. First early on for a quick analysis, an evaluation of different possibilities. It is useful to have a crude model that helps you visualize what is going on, and understand the interactions between parts of the system. It is not intended to give answers since the data available is extremely inaccurate, but to give a system view. It helps to play scenarios and examine implications of different alternatives. Second later on for the design of the system. With more accurate data available, it is possible to simulate the system and evaluate its performance. Playing what ifs is again possible. Finally, for operational purposes. With even more data, an existing system can be analyzed to figure out how to improve it by playing scenarios.

Examples of use include the following:

- What-if scenarios (different product mix, process improvements, new machines or layout) to determine how the system will operate under different conditions. Several types of analysis can be performed under this method. First, bottleneck analysis to determine equipment and human resources requirements, and how the resources are likely to be used (dedication of equipment, set ups...) Second, buffer analysis to project floor space utilization and inventory levels. Third, throughput analysis to forecast capacity, production capability, and flow times.
- Material handling system analysis. Some packages have a three dimensional animation which permits the examination of the movements of materials in the plant, and of the interferences between handling systems.



Main Benefits:

- it enables a high reduction of the risk associated with the system being analyzed: simulation helps predict system behavior under different conditions by playing what ifs; it helps to prove concepts prior to their implementation;
- it enables a high reduction of the cost of the system being analyzed: tests can be performed and problems fixed prior to implementation and without having to build the system;

- it improves the quality of the system: bottleneck analysis helps identify the potential problems early enough to solve them; material handling systems can be examined and improved;
- it reduces development time: things can be done right the first time;
- it provides a better understanding of the system being analyzed: unforeseen relationships between different elements of the system and their consequences can be discovered with the use of simulation;
- it can be used as a communication tool, both during the model building phase and for the presentation of the results.

- Comparison of the Three Types:

- Queuing Formulas vs. Spreadsheets:

Queuing formulas constitute a better approach than spreadsheets. They create less chances of error than spreadsheets (consistent assumptions) and are more accurate.

- Simulation vs. Static Analytical Modeling:

The main disadvantage of computer simulation is its complexity. Analytical models have a less expensive and somewhat faster development, a faster runtime, and do not require a statistical background. They enable a quick and easy analysis of different scenarios using sensitivity analysis. They are useful for estimating utilization and production time: for capacity planning. They are useful for early strategic planning.

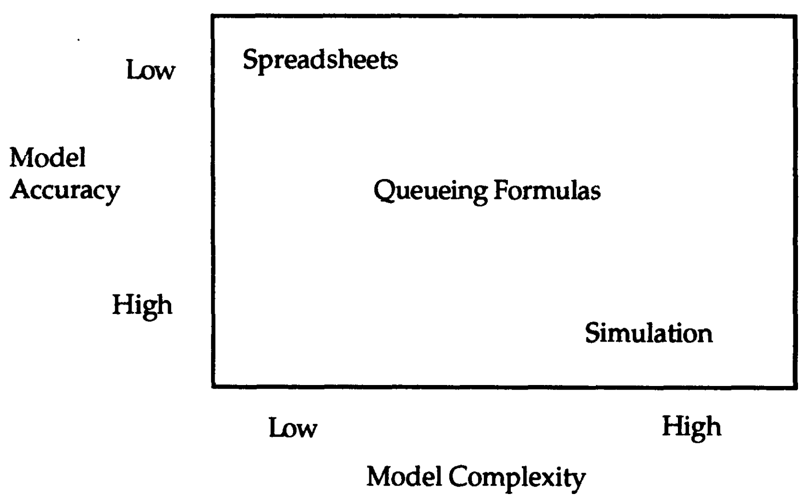


Fig.2. Usefulness of throughput analysis tools.

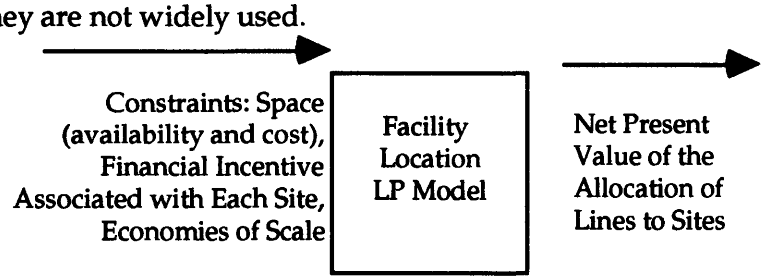
If we define usefulness = perfection x adoption, there is a trade off to achieve between accuracy and simplicity to maximize this usefulness. Indeed, management usually understands spreadsheets better, and has a tendency not to trust too complex systems. It is more difficult to explain the underlying logic of computer simulation.

The main advantage of computer simulation is the possibility to introduce variability in the packages and to get much more accurate results. Because of the lack of variability, static models will typically underestimate the number of machines needed for a new factory for example. For any detailed operational analysis, simulation is necessary.

Simulation packages with animation also present a strong advantage. Animation increases the cost of the software and hardware required and it increases the time to build and run the model. Yet simulation tools with animation constitute better communication tools for management, and their models can more easily be explained to other users. As we will see, communication is often a critical issue. Animation therefore plays a fundamental role, although there is a risk that it might be misinterpreted. Having an animation included in the package is also an advantage for sophisticated analyses: it is useful for verification. Animation finally enables materials handling analysis.

(vii) Management of Materials

Management of materials tools encountered were static, deterministic tools which are used to help determine the best facility location and suppliers locations. Two main types have been encountered. First, spreadsheets for rough estimates of the supply chain in terms of cost or time associated with different options. Some sensitivity analysis can be performed. Second, Linear Programming tools for a more precise evaluation of the supply chain, sometimes completing an analysis using a spreadsheet. They are not widely used.



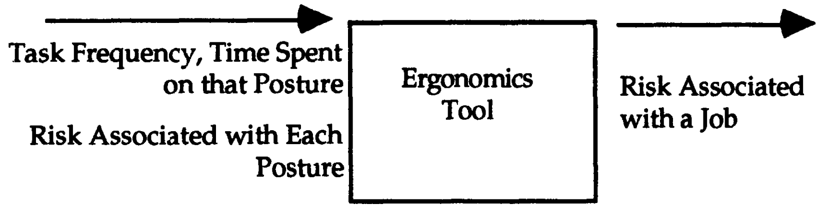
Main Benefit:

- it provides very important cost savings.

Yet it requires some effort to build it.

(viii) Ergonomics

Ergonomics tools encountered were static deterministic tools which are used by several companies to evaluate the impact of line and job designs on people, from a physiological point of view. Two main types were identified. The most commonly used are spreadsheets. There also exist some tools that incorporate graphics for the analysis. They are intended to analyze tasks and job compliance with ergonomics criteria.



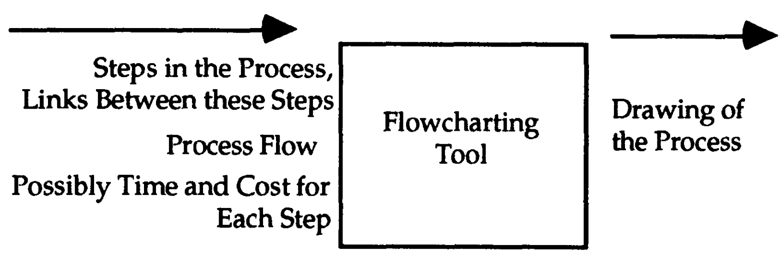
Main Benefits:

- it improves the quality of the manufacturing system. It enables to determine more accurately what people can be expected to do. It creates better working conditions.

No dynamic tools are used yet, although it is thought that they could develop: virtual reality could potentially be used. Mockups of the area would be built, mechanics brought in. There might however be a conflict between cycle time and the necessity to get a lot of data to have a good representation of reality.

(ix) Organization and Process

Organization/process modeling tools most commonly encountered at the participating companies were flowcharting tools. They constitute a static representation of the process flow. They help analyze and understand the process, either an existing one to improve, or a new one to be designed. They also help identify opportunities to improve the process, to reduce cycle time, eliminate unnecessary tasks and identify bottlenecks.



Main Benefits:

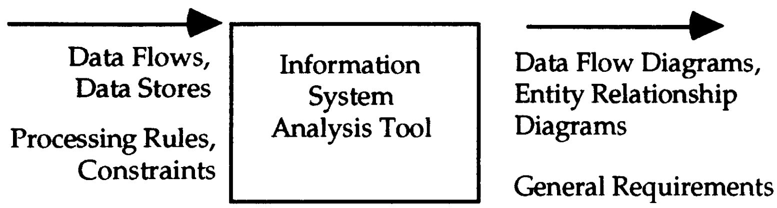
- it enables a reduction of the manufacturing system development time;
- it enables a reduction of the cost of the system being analyzed;
- it documents the process.

However it lacks capabilities that would make it possible to better understand and forecast the need for resources: when, what skills?

There is also a need for a more dynamic tool that would make it possible to evaluate the influence of changes in the process. There is currently no or very limited possibility to play what ifs. It would be useful to be able to include measurement and performance metrics, and to evaluate the impact on these metrics of potential modifications in the process.

(x) Information System

Tools encountered at the participating companies are static tools which are used to determine data standards, data flows, and data storage. They are used to design information systems, to improve the transmission and processing of information in a communication system.



Main Benefits:

- it enables a reduction of the manufacturing system development time;
- it enables a reduction of the cost of the system being analyzed;
- it improves the quality of the system.

(xi) Enterprise Modeling

No entirely satisfactory enterprise model has been encountered, although most companies have expressed a need for it. The tools identified for enterprise modeling are of two types: static descriptive tools based on the IDEF0 methodology, and dynamic deterministic tools based on System Dynamics.

- IDEF0:

It is a technique for the static functional description and specification of a manufacturing system. It produces a structured and hierarchical representation of the functions of a manufacturing system and the flow paths of information and objects which interrelate those functions. It is a top-down approach, starting at a high level and decomposing each element into sub-elements. Basic elements, or function blocks, are linked together through inputs, outputs, controls and mechanisms. This approach is used at different stages: early on or with more details about the process.

Main Benefits:

- it enables a high improvement of the quality of the process. It permits a description of the system at the desired level of detail, and a standardized system communication method

- it reduces the cost of the system being analyzed; in particular, overhead can be greatly reduced after a modeling and analysis;
- it brings a systemic perspective, where the compatibility, interrelationships and interdependencies of different functions are examined. It ensures consistency of all sub-elements with the system as a whole.

Yet it has some limitations. One is the ambiguity often associated with the definition of functions. Another, and probably more important one, is its static aspect. It does not explicitly represent the conditions or sequences of processing. The nature of the relations between different functions in IDEF0 does not allow to visualize the impact of a change in a function: there is no possibility to understand questions such as "what if this function is modified?" As for process modeling, there is a need for a more dynamic tool that would make it possible to evaluate the influence of potential changes in the manufacturing system design.

- System Dynamic Models:

System Dynamics modeling tools are dynamic deterministic tools which are designed to help people have a deeper understanding of how systems and businesses work. They are based on a system dynamics approach which aims at capturing trigger side effects, delayed reactions and interventions by others as a result of our decisions to control a situation. They try to model realistically the delays, non-linearities, feedback effects and hard to quantify variables that influence the behavior of a system. They are used for complex systems or processes, such as market strategy, resource management, and process and organizational change.

Models are built linking different activities, and defining by mathematical equations or graphical relationships how these activities interact. After computer simulation, they provide graphs of variables over time. Sensitivity analysis can also be performed. The modeling and simulation process leads to a better understanding of system behavior, an identification of relationships, of consequences of decisions, and of leverage points.

Examples of use include the following:
- What-if scenarios to determine how the system will operate under different conditions and determine what the leverage points are. First, strategic analysis: for example, for pricing strategy. Second, manufacturing analysis: for example, to understand the impact on manufacturing resources of the introduction of new products. Third, production and distribution analysis: for example, to understand the impact on inventories of different policies. Finally, safety and environmental analysis: for example to understand the impact of more regulations and the policy towards more compliance.

- Throughput analysis for continuous processes: forecast capacity, production capability, and flow times.

Main Benefits:

- the main benefit is a better understanding of the system being analyzed: unforeseen relationships between different elements of the system and their consequences can be discovered with the use of this approach. The main goal in following it is to gain some insight, not to make predictions. It is to produce learning, to reorganize the existing knowledge into an integrated framework, a system view. Much of the benefit takes place during the model building phase;
- it enables a high reduction of the cost of the system being analyzed: simulation helps understand system behavior without having to build the system, by playing what ifs;
- it enables a reduction of the development time: things can be done right the first time.

Yet it presents some difficulties. First, it is difficult to build a complex system and be sure that links that may have a fundamental effect on the behavior of the system have not been forgotten. Second, it is difficult to explain the results and to quantify the benefits.

III.3.c. Modeling Needs

Most of the areas of manufacturing system development have tools. Mapping the tools identified to the different steps in the development process showed that some tasks or areas benefit from more analysis than others: capacity and throughput analysis, cost estimates and project management tools have been encountered at all the companies, and often in various ways. On the other hand, several weaknesses have been identified.

- The early phase, which is considered as critical, is not supported by many tools apart from spreadsheets. Tools are needed to support strategic decisions: they could help managers understand the implications of choosing between policies such as Just in Time, Theory of Constraints or others, based on specific strategic metrics and objectives of that company. Throughput modeling tools are hard to program to perform such an analysis, or sometimes have a language that already embeds an underlying strategy. Similarly, tools could help evaluate different quality decisions and choices between different approaches, by translating them into manufacturing implications that would be more easily measured. No tool was encountered at the participating companies to help make such quality control decisions as "where to measure", "when to measure", "what and how much to measure", "what to do with the data collected", "what to do with the results." Finally, tools could help understand how different policies work together and can be integrated. At the moment, no commercial tool easily allows such an analysis.

- Enterprise modeling is the most commonly quoted area were tools would be needed. There are attempts at most companies to develop enterprise modeling, but it is thought that improvements could be achieved with better suited tools. These could focus on the entire life of a product and on the different functions that interact with it within the company (analysis of timing decisions and risk, interactions between functions, training required...) They could also focus on the company and its environment: customers, suppliers, competition, and regulations.

III.3.d. Simulation and Expert Systems

Only once have expert systems been mentioned as tools used in the manufacturing system development process. This is somewhat surprising given the amount of literature published on that topic in the past years. It may show that major breakthroughs and implementations have not been achieved in this area. It may also mean that this is currently a "hot" topic that companies are not willing to discuss.

As Wu (1992) notes, "it is evident from literature that the integration of computer simulation and artificial intelligence has been regarded by many as the next natural step in this particular area of computer technology. (...) Simulation generators can assist system analysts or managers in model creation and model updating, as well as in the analysis of alternative scenarios. (...) They have the potential to allow manufacturing systems to be evaluated and analyzed under various design changes, alternative control actions, different procedures and new policies with a minimal need of expert intervention."

Yet, it can be argued that the design process is too creative in nature to be well suited for expert systems. Also, as Wu further notes, "one major disadvantage of using expert systems in a manufacturing environment is the diversity of manufacture. This implies that there may be few situations where the same expert system will apply to different companies."

Chapter IV
SIMULATION

As we have seen, a great variety of tools is used at the participating companies. In this chapter we focus on dynamic models. Simulations, or dynamic models (both will be used interchangeably), are widely used in some areas such as materials handling analysis. Yet they are not very well developed in most other areas, and not equally at all companies. This chapter examines the main benefits and disadvantages of simulation, related to the objectives of chapter II. It then presents an approach that can contribute to a wider use of dynamic models and to a better acceptance of them.

IV.1. Status of Simulation

IV.1.a. Companies Attitudes Towards Simulation

At all companies simulation is said to be considered positively. Yet, although some efforts are under way, simulation is generally at its early stage at most companies for the design and development of manufacturing systems. There is some confidence in it, but projected in the future rather than completely perceived and translated into action in the present.

- Simulations at Boeing have been mainly devoted to design and product development so far. Since process has not been the main focus and is not changing much from one generation to the next, simulation is not considered as much needed and is not used much in manufacturing.
- There is a much greater use of spreadsheets than of more sophisticated simulation packages at Intel. Simple modeling tools that do not require too much time (e.g. spreadsheets) have the advantage of providing quantitative results to help make quick decisions and back them up, even if these results are only rough cut. They are widely used, for all sorts of analyses.
- Similarly at HP what is used is mainly spreadsheets for capacity, people, and capital requirements forecasts. They are efficient and effective enough for what is required. Yet spreadsheets are somewhat rigid and difficult to modify. They must be used carefully, because they may sometimes be misleading.

- Analytical queuing formulas are often used at Boeing for throughput modeling, because there is no need for more sophisticated information for capacity analysis. Back of the envelope results are often sufficient to have an understanding of the process. The advantage of analytical methods is that they give more flexibility, they allow you to make more customized templates. They are not as expensive and have a faster learning curve. Similarly simulation is not extremely developed at Intel for throughput analysis.

Simulation is however widely used for material handling systems, at all the participating companies. All have and frequently use discrete event modeling tools for that purpose. It is also desired for enterprise modeling, and several companies use dynamic models based on System Dynamics for that purpose. More and more emphasis is put on simulation at all the participating companies in different areas.

- At HP most people now agree on its advantages, although some still have overly demanding expectations: they expect dynamic tools to be "turn the key", and wonder about the time to develop a model and about its cost. It is perceived that there is not enough use of simulation yet, and there is a desire to increase it.
- There is a shift at Kodak from physical validation to more understanding and predictions thanks to dynamic models. Analyses are considered as particularly useful up front in the planning phase. Although confidence in the predictions of simulations is growing, there still is concern about their validity , robustness and accuracy.
- Simulation is used to evaluate the feasibility of a project at Square D. Spreadsheets are used early on, when it is not necessary to overuse more complex simulation packages. Then, during the design phase, simulation is used to make sure that some relations have not been overlooked. There is more and more trust in it, even if it is not homogenous throughout the company. It is sometimes even considered as a requirement in the development process.
- Dynamic models are very widely used at GM. In all functions and for all types of analyses, they are elaborated and trusted. For example, throughput simulation is well developed. Also, robotics simulation is considered as extremely valuable. It is given more and more importance and recognition.

IV.1.b. Main Drawbacks of Simulation

Summarized, here are the main arguments against simulation:

(i) It takes time and money:

With the current state of the art, it is very often a valid argument. As we have seen in part II, time to market is a critical issue in the development process. What often happens however is that models are long to build, validate and implement, even though simulations are intended to shorten the time to market by providing an understanding or prediction of systems behaviors before the actual system is built. As a result, it is often faster and more efficient to use cruder tools such as spreadsheets, and to possibly build physical prototypes to prove concepts. In addition, simpler tools require much less efforts and investments. Yet with the development of computational capabilities and simplified tools, these issues are becoming less and less true.

(ii) Simulation tools are not well fitted to the needs:

Commercial simulation tools have a general purpose and a large public. They often do not address specific issues. As a result, some commercial tools have to be force-fitted with a lot of effort, or they cannot correctly tackle the desired problem. For example in the area of throughput analysis, it is felt at Intel that there are no really satisfactory simulation tools that fit the process. Most packages are for assembly type operations. They do not fit process type operations very well. However, it can be hoped that tools will be developed to address more specific issues as simulation in general develops.

(iii) Simulation tools are sometimes difficult to use:

There is some learning associated with simulation tools, some expertise that is required to be able to take advantage of them. Also, gathering the data, testing and validating models are often extremely painful tasks. It is true that modeling often requires some commitment. Yet most of the tools need less than a month training, and most of them are now rather user friendly.

(iv) Data is difficult to obtain:

First, data that is required by some models may not be available. At Intel for example, factories do not always operate with clear operational rules. It makes simulation for throughput analysis hard to perform. Second, models often require data that is not available until late in the development process, when the results of simulation are not needed anymore. Before obtaining this data, simulations can be meaningless. Yet models can first be built to have a broad understanding of the behavior of the system, of the interactions of different elements. Then, when more data becomes available, a more predictive approach may follow and complement the early analysis.

Third, data sometimes changes too often and until late in the development process. Simulation is therefore made difficult. For example at Intel some decisions regarding the process may be changing and are not known at the time of performing simulation. It is difficult to gather and maintain relevant data in an environment of rapid change.

(v) Models are too complex:

Models for simulations may be overcomplicated, so that important parameters or relations may be left out while those included are hard to follow. Yet, a rigorous approach, starting with the model boundaries and developing sub models, can overcome this difficulty. Also, the very complexity of the systems at hand justifies the use of simulation to help understand their behavior. There often remains a problem of communication because of this complexity. At the time to present the results of the analysis and to translate them into decisions, the apparent extreme complexity of some models makes them hard to trust. Tools that have communication enhancements such as animation can help in this respect as we mentioned earlier. Also, including the decision makers in the development of the model is often key for its success. We discuss this issue later.

(vi) Experience is lost:

It is often difficult to appropriately incorporate all the knowledge and non quantitative factors. For the design of a manufacturing system, simulations do not incorporate policies, which in real life have a huge impact on the performance of a system. The way that these policies are included is through the simulation code, in a simplistic way that is highly different than reality. It is true, because of this, that simulations to predict accurate results may in fact be subject to inherent approximations. Yet, if one understands and takes these assumptions into account, and looks for predictions of the behavior rather than precise results, one can get a good understanding of how the system might operate.

IV.1.c. Main Advantages of Simulation

Now more than before, simulation is aimed for. Several factors contribute to a change in mentality that is currently taking place and making the benefits of simulation seem more accessible. First, increased computational capabilities enable to build more and more accurate models while reducing the time required to run simulations. Second, improvements in the friendliness of simulation packages makes them more attractive and promotes their use. Third, a greater variety of tools addressing more problems is now available. Fourth, with the development of information technology and a rationalization of data gathering and storing, there is a shift towards more easily accessible information and data to build models. Models are thus easier to build. Finally, a change in mentalities is slowly taking place. Trust and confidence in the results of simulation are increasing.

Going back to the objectives in the manufacturing system development process, we can see that simulation helps to achieve all of them. The way simulation permits to meet these strategic objectives more easily can be described as follows.

(i) It controls risk:

The most important characteristic of simulation is that it permits to control risk by providing an understanding of the behavior of the system being analyzed before this system is built and implemented. Before the new system is implemented, much of the unknown and uncertainty are dissipated. As a consequence for example, equipment and people are now brought up to speed a lot faster than before at Intel. Equipment capacity used to be considered as the main limitation during ramp up. It was installed incrementally, looking at the bottlenecks before deciding what new investments to make. Most capacity requirements are now bought and installed up front. This is partly a consequence of the ability to understand the system better without having to build it, through the use of simulation. Improvements can be started when not everything is in place.

(ii) It saves time:

Simulation enables to perform experiments faster than in real life. Scenarios regarding an entire line for example, which may take months to set up in real life, can be tested with the use of models and simulations in only several weeks. Simulation enables to test part of a system without having to wait for its elements to be built. Furthermore, once the model is built, it is easy to slightly modify it or to modify some parameters in order to run different experiments, thus saving time. Finally, simulation enables to perform some tasks concurrently, without having to wait for some other milestones in the development to be completed.

(iii) It saves cost:

Simulation permits to solve problems during the design phase rather than during implementation. It permits to try different scenarios before implementation, to get the most desirable one beforehand. The earlier changes are made, the less costly they are.

Simulation thus saves money. Furthermore, systems can be tested without having to actually build them. Although some cheap prototypes can be built for simple systems, there often is a huge gain associated with the ability to test the system without having to build a physical prototype. Finally, simulation gives the ability to perform a larger number of experiments at a much lower marginal cost. With a physical prototype, these experiments might cost a lot more.

(iv) It provides flexibility:

With simulation, different scenarios and conditions can be experimented to achieve flexibility. These scenarios would be impossible to perform in a real plant. The influence of a greater number of variables can be tested. Future potential changes can thus be examined to evaluate the flexibility of the system and achieve the desired one.

(v) It improves quality:

As we just pointed out, potential problems can be resolved during the design phase rather than during validation. This is important because decisions regarding the design of the product or of the manufacturing system may be more difficult to modify late in the development process. Thus being able to identify weaknesses earlier means increasing the ability to solve them. This results in a better quality system. For example at Boeing, regarding Design for Manufacturing issues, the design of the plane gets locked by the time it gets to manufacturing. It is therefore necessary to involve manufacturing early enough.

(vi) It creates a systems view:

The simple process of building a model often gives a lot of insight on a system, uncovering unexpected relationships between various elements. The model development phase thus helps create a systems view. Furthermore, models can handle more complex situations than we can, once the structure and the key variables are entered. They may thus lead to a better understanding of reality, by enabling us to extend the boundaries of the system and to include all important relationships.

IV.2. Effective Use of Simulation

Two different approaches to simulation can be defined.

(i) The first one views simulation as a way to get an accurate prediction of a future situation. Several dynamic models are used with that philosophy: models that display the tool path of an NC machine for its verification, or models of robots developed to check interferences. What is aimed for is a point prediction, a description of the behavior of the system considered under certain conditions. The objective is to verify the way a system will behave and possibly modify the design of the system to get the desired behavior. It stems from a desire to be proactive, and results in a forecasting mood. The efficiency of a model is then measured by its accuracy in terms of precision and close prediction of reality.

Yet there is an inherent contradiction in this approach: to get an even more accurate prediction, one has to have a shorter time horizon. In this case, there is a lesser need for predictions. Also, all models are built on assumptions and make simplifications. Instead of trying to avoid these assumptions, one can try to incorporate them in the analysis of the results.

(ii) This leads to the second approach. Simulation is merely viewed as a way to better understand a system. This type of simulation usually deals with larger systems, such as models at the enterprise level. In this approach, simulations are used for insight rather than for precise predictions. What is aimed for is not an exact answer, but a better understanding of the system. The interactions of different elements, the implications of some decisions are the object of the simulation. The goal is not to obtain a point prediction, but to understand patterns. One can discover unexpected relationships and useful leverage points. Several analyses can sometimes be performed to get a range of potential outcomes and behaviors. As much learning occurs with the result as with the modeling process.

The way these two approaches are translated into the dynamic models used at the participating companies can be illustrated with the figure below: Fig. 3.

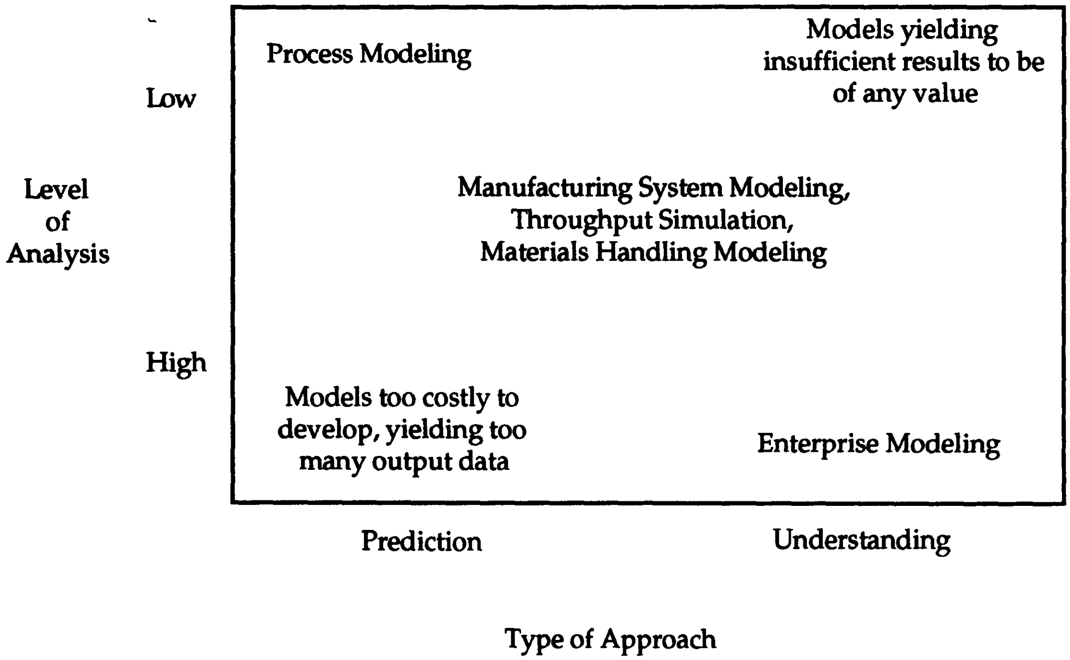


Fig.3. Applications of different simulation models

The description of these two approaches also shows that simulation can be used for a limited number of problems. The types of analyses that are well suited for the use of dynamic models are described in Fig.3. It is not useful to develop models at the workshop level that will only provide a broad understanding of the system at hand. Rather, what is needed at that level is an accurate prediction using a continuous simulation. It is also not possible, or not reasonable, to hope to be able to develop accurate predictions of a complex system at the enterprise level. Rather, what is useful at this level is a model helping to understand the relationships and interactions of different elements. In between, at the line level, the two approaches can be used. An early analysis can be performed with little data to understand the system behavior. Later, when more data becomes available, a more precise simulation with predictive purposes an be undertaken. In both cases, sensitivity analysis plays a fundamental role.

The main types of simulation that were encountered at the participating companies can be summarized with the following table:

Type of Analysis	Example of Application	Level in the Factory	Approach	Type of Model
Process Modeling	Injection Molding	Low	Prediction	Continuous, Deterministic, Detailed Data
Modeling of Physical Entities	Robots/ Materials Handling	Low/ Medium	Prediction/ Understanding	Continuous Deterministic, Detailed Data
Manufacturing System Modeling	Throughput Simulation	Medium	Prediction/ Understanding	Discrete Stochastic, Varying Detail
Enterprise Modeling	Strategic	High	Understanding	Continuous Deterministic, Aggregate Data

Table2. Summary of Observed Model Types (adapted from Wu (1992))

Chapter V
TECHNIQUES AND PRACTICES FOR THE USE OF TOOLS

This chapter examines methodologies encountered at the companies for the development and implementation of the tools identified. It first recommends a technique to better integrate different modeling tools. It then analyzes criteria for the selection of these tools, as well as practices for their implementation. It finally suggests an efficient model development process based on current methodologies.

V.1. Integration of Different Tools

V.1.a. Current Practices

There is currently very little or no interaction between different tools. When modeling is developed for various applications, there is usually no attempt to link several models. It leads to the existence of islands of modeling, which deal with problems independently and cannot communicate. Developing models without an organized framework for interactions has several drawbacks.

- It creates communication problems. Examples of attempts of interactions between tools have been encountered. Some of these attempts were between spreadsheets, i.e. between technically compatible systems. Yet language problems lead to difficulties: there was no uniform definition of different concepts or parameters used, making interactions a lot more difficult than expected. There was no consistency between the various models, which led to confusion. More communication between users of different models is therefore necessary to prevent such a situation.
- It creates redundant work, thus unnecessary cost and time. Because of this lack of communication, limited advantage can be taken of previous analyses. Portions of models may thus have to be recreated to compensate for this situation, both between different functions and different phases in the development process. For example, there is usually no link between throughput modeling tools and plant layout tools, although both have to draw a layout of the machines and of the flows of products. There is thus some avoidable effort spent.

- it may lead to sub-optimization. Dealing with sub-systems independently goes in the opposite direction of the systemic approach that is recommended. This may result in conclusions that are not optimal for the whole.

V.1.b. Interactions

It is thus important to incorporate into analyses the necessary interactions between sub-systems and to identify possibilities of interactions between tools. A simple method has been devised at Kodak to identify improvement opportunities for CAM utilization through the interactions of different tools. The method can easily be extended to different area of modeling. It is an eight step process:

1. Identify the major functions (or tasks) carried out in manufacturing operation

2. Identify the tools in use to accomplish the identified functions. A matrix [functions, tools] is built, in which tools are ranked for each function according to their primary, secondary... utility to perform this function.

Example:

	tool A	tool B	tool C	tool D	tool E
task 1	1	2			
task 2			1		
task 3			2	1	3
task 4			2	1	

3. Determine the necessity of functions to interact. A matrix [functions, functions] is built, in which the desired ability of functions to exchange/share data is ranked from low to high (low means a high level of data sharing is necessary)

Example:

	task 1	task 2	task 3	task 4
task 1	0			
task 2	1	0		
task 3	3	2	0	
task 4	4	4	1	0

4. Determine the actual ability of tools used for functions to interact. A matrix [functions, functions] is built, in which the actual ability of primary tools used for each function to exchange/share data is ranked from low to high (low means an excellent ability to share data)

Example:

	task 1 (tool A)	task 2 (tool C)	task 3 (tool D)	task 4 (tool D)
task 1 (tool A)	0			
task 2 (tool C)	1	0		
task 3 (tool D)	4	3	0	
task 4 (tool D)	4	3	0	0

5. Compare the desired ability of functions to interact with the actual ability of functions to interact through their primary tools. A result matrix [functions, functions] is built, in which each cell is the subtraction of the score in the corresponding cells from the matrices built in steps 3 and 4 (matrix4 - matrix3)

Example:

	task 1	task 2	task 3	task 4
task 1	0			
task 2	0	0		
task 3	1	1	0	
task 4	0	-1	-1	0

6. Interpret the results and identify improvement opportunities (the higher the value in a cell of the result matrix, the larger the problem.)

7. Prioritize improvement opportunities.

8. Improve.

Variations on these matrices could be introduced to evaluate the interaction capabilities and opportunities for different tools:

- One could for example include the possibility of using secondary tools as primary ones in order to increase the overall compatibility. Several options can thus be tested by varying one or several of the tools that can be used for different tasks, and examining the result matrix. The set of tools chosen as primary ones that minimizes the sum of the non negative coefficients of the result matrix is the one that presents most interaction leverage.
- A more proactive action can also be taken that aims to choose tools according to their ability to interact, and to build models with this necessary interaction as an objective. The matrices presented above could again be used for the selection of new tools. Comparison of the sum of the result matrix cells under different possible new tool acquisition could be a criteria for new software selection: the tool leading to the lowest value presents the most interaction possibilities.

V.1.c. Integration

Beyond the achievement of interactions between different tools, one must aim to achieve a full integration of those tools. Integrating means going one step further. Instead of transmitting data from one tool to another, typically using the output of a model as an input for another one, integrating means building several models together, in an interconnected way. Several models covering different areas must be made to work together. One example of such integration has been encountered at several companies. It is an integration of throughput modeling and cost modeling: the cost of material is an attribute of the part, the labor cost is associated with the people who are represented in the model, fixed and variable costs are associated with machines, and the overhead costs are included in a burden station. Such integration enables to examine different options for the manufacturing system along more criteria. A non integrated methodology would examine throughput to decide on factory configuration, and then estimate costs and eventually require modifications in the factory configuration. Instead, the integrated approach can focus on several criteria concurrently, cost and throughput, and achieve the best mutual outcome. Only through integration of several tools can leverage be fully gained.

Following are potential integration of different modeling tools:

- integrate several tools with cost models: throughput analysis can be integrated with cost analysis as we mentioned earlier;
- integrate layout, capacity, and throughput analyses;
- integrate tools to determine requirements in terms of capacity, people, and equipment concurrently, and over time: what type and when;
- integrate people requirements, ergonomics, tooling design and throughput analysis;
- integrate ergonomics with facility layout.

Ultimately, it can be thought of a model of the whole manufacturing system that would consist of hierarchical sub models for the different subsystems.

V.2. In House Development vs. Commercial Tools

At almost all the companies visited, tools are acquired off the shelf. It is admitted that some of the commercial tools do not exactly meet the specific environment and requirements of the firm. Some customization is then necessary to adapt commercial tools to the specific needs of the company. The main reason for acquiring tools off the shelf is that most companies do not have the internal capabilities to create most of their own tools. Furthermore, they do not want to develop these capabilities, having rather focus on their core competencies. Thus, even B.C.S., the computer services company affiliated to Boeing, develops few in house tools. Their role is mainly to understand the requirements stemming from manufacturing, and to translate them into specifications for outside software vendors. B.C.S. is responsible for software evaluation and acquisition. Similarly, even though HP laboratories develop some tools, for enterprise modeling for example, HP usually buys commercial tools that it customizes rather than develops some in house.

A distinction comes from GM. There is a central organization, the Manufacturing Center, responsible for manufacturing engineering capabilities for the entire company. It is linked to counterparts at each division and can be solicited by a division to perform an analysis. A tool will thus be developed in house at the demand of a division. There are advantages in having a central Technology Center developing tools:

- It develops a competence in analysis and simulation, and takes advantage of the size of GM to leverage efforts for modeling. In developing its own tools, it is able to control all the assumptions that have to be incorporated in models.
- It remains close enough to the real problems thanks to a strong communication with the divisions for each analysis performed, and is able to address very specific needs that these divisions may have. Off the shelf packages can be less expensive up front but are not always best suited for the desired analysis, whereas in house tools can be exactly customized to the needs. The trade off depends on the capabilities of commercial software.
- Having unique tools finally provides a competitive advantage.

However, having the desire to retain capabilities in most modeling and analysis areas achieves autonomy but possibly at the expense of cost (cost figures were not available).

V.3. Cost/Benefit Analysis of Tools

All the tools identified represent costs and benefits. Both the questionnaire that was sent and the visits that were made tried to quantify them. Even though people at all the companies could evaluate in rough terms the benefits of the tools used and the requirements to implement them, they could very rarely associate figures with them. Most of the time the benefits were presented as largely exceeding the costs. Can a rigorous cost/benefit analysis be performed to better evaluate the usefulness of existing tools and the opportunity to invest in new tools?

It is often difficult to measure the benefits of using a tool. However, a simple evaluation can give a rough idea of what is required to make a tool worth it. The most important elements to determine the cost of a tool are the following: (i)the purchase price, (ii)the training required to use the tool, (iii)the cost of adapting the new tool to the company environment and of integrating it with other tools, (iv)the cost of model development, (v)the cost associated with the maintenance of the tool. Those costs are usually easily available, except for (iii) which is harder to quantify, and (iv) which depends on the system being analyzed. Given these costs, the expected lifetime of the tool, the number of times it is likely to be used per year and the average size of projects it is supposed to tackle (in terms of dollars), any financial analysis such as a Net Present Value calculation can provide an idea of the savings that should be expected to make the tool worth it.

Although a purely financial analysis is necessary and gives indications, it seems difficult to focus only on it because several models bring advantages that are difficult to quantify financially: learning of the process, better understanding of the system. risk control or time saved. Soft variables have to be taken into account as well. It is thus recommended that each improvement in the development process resulting from the use of models be recorded to facilitate the evaluation of modeling tools.

The decision to acquire a new tool or the timing of this decision is made difficult because of the lack of precision of a financial analysis. After evaluating whether a tool is worth it as indicated above, other considerations should influence the decision to go. A first preliminary step is to have a standardized development process, which will ensure an easier implementation of the tool. A second one is to have people believing in the use of modeling tools, especially decision makers. A third one is to feel a need for a change in practices. We develop these issues later on.

V.4. Selection Criteria, Corporate Standards

V.4.a. Centralized vs. Decentralized Selection

(i) Current Practices

At all the companies the selection process is extremely decentralized, and almost no corporate standards are set. The main reason is that a tool is more easily accepted if it is requested, if it responds to a need than if it is presented as a possible useful system, if it tries to create a need. Therefore, tools are chosen by their users according to the specific needs and requirements they feel. Furthermore, as we pointed out, there are often important differences between different divisions within each company. For example at Kodak there is a great variety of manufacturing system development types: some new products require the development of entirely new systems (for example the point and shoot camera), others lead to minor modifications of existing ones (for example sensitive goods); some are technology and process driven, while others are product driven. In these conditions, it is difficult for a central group to understand the specificity of each division. It makes more sense for each different process to have different tools. Thus at HP someone in each unit is responsible for the evaluation of commercial tools, their selection, and for training. There is no central organization coordinating these activities, which leads to more flexibility for each unit.

Also, there is often a tendency to give more autonomy to each business unit. This is the case at Boeing where each unit is moving towards a specific process, and consequently towards the use of its own tools. Although some leverage may be lost, it is thought that there really should not be a "one size fits all" computing. This is also the case at Intel, where the modeling process is very decentralized. There are no corporate guidelines about how to handle model development or about which tools to use. It is believed that it would be useful to have a central group to manage these activities. A Modeling Working Group has been created and is being further developed to address this issue.

(ii) Advantages of More Centralization

Indeed, being too decentralized may lead to a loss of leverage. At a time when modeling and analysis tools are not well developed and implemented yet, there are advantages in having a central organization. First, it can devote more efforts to the evaluation and selection processes. Secondly, it can be efficient in promoting, encouraging and facilitating the use of modeling. Thirdly, it can provide necessary training. Finally, it provides a way for different users to remain up-to-date or to find help and information when they need it. These are some of the reasons for the usefulness of the Manufacturing Center at GM. Even though each site acts somewhat independently and chooses its own tools, the Manufacturing Center and the Knowledge Center are used for evaluation, selection and training for various tools that are part of the central library. In spite of that, even though some efforts are underway, the Manufacturing Center does not always set corporate standards for all the tools. Corporate standard have been established in some area, such as throughput simulation and robotics simulation, but not for all types of tools.

Being too decentralized may lead to communication problems. In some areas at Square D the selection process is also specific to each unit. Tools selected for molding analysis, for example, are thus different in several plants, even though the use and process are similar. Although it results in an immediate positive effect because it fits the users' needs and preferences, it may lead to longer term difficulties because of incompatibility of tools, inability to compare results or methods, and too specific training. Some exchange of information and potential leverage is thus lost at the company level. One of the goals at Kodak is thus to have less tools that can perform more, and to standardize those tools, while at the same time there is a concern about the compatibility of those tools.

A central simulation group must make sure that it remains close enough to the real problems thanks to a strong communication with the divisions. A trade off must be found between a strong central group that may be disconnected from the real users needs, and completely independent factories developing their own tools without taking advantage of the leverage of others. An example of how this balance may shift is illustrated by the experience of Square D. In some areas, for example for discrete event modeling tools, there was a centralized evaluation and selection process at Square D. Then the selected package was presented to the different units, and potential needs were identified. Training and guidance was provided to new users. Now, although there are attempts to institutionalize the use of this selected package, people in each unit can decide to use a different one.

V.4.b. Selection Criteria

As we just mentioned, at all the companies visited the selection process is very decentralized. It is therefore not a surprise to note that tools are often chosen on the basis of their perception by the user, of their influence on the morale. People at Boeing explained that the ease of use, the confidence and happiness with the tool are fundamental criteria, especially for tools such as throughput simulation packages which have similar capabilities. In several other companies as well throughput simulation tools are chosen mainly according to the user's preference.

More objective decision criteria identified at the participating companies for modeling tools selection, especially for dynamic modeling tools, can be summarized as follows:

(i) User interface:

This criteria is still along the lines of perceived satisfaction with the tool that we mentioned above. User friendliness is critical to promote and facilitate the use of modeling: most of the initial apprehension and distrust can be overcome with a user-friendly tool. Thus, the user interface, the ease with which inputs are accessible are important characteristics. GM for example considers user interface as a fundamental objective when developing its own tools.

(ii) Ease of model development:

Tools are implemented more easily within a company if they are easy to use: less training is required, more people may be able to use these tools, and benefits are reached faster. One of the criteria for the selection of throughput simulation tools at Square D was for example that there be as little programming required as possible, so that people would accept them better and quickly get up to speed. Similarly, there is an attempt at HP to select tools that are simple enough so that people who need them for an analysis can perform this analysis themselves, without having to ask an "expert". Also, the easier the model development, the less expensive the use of the tool in terms of training and time spent using it.

(iii) Modeling flexibility:

The ability of commercial tools to be customized, to extend, is considered as very important. Indeed it is thought that most of them do not exactly meet specific needs and must be adapted. Being able to easily define in the model an environment corresponding to the company's one is critical. A lot of attention is paid at Kodak for example to the capabilities of commercial software and to their assumptions and limitations. Open architectures are regarded as fundamental features. Also, as we have seen, several manufacturing types may exist within a same company. If a tool is to be considered as a corporate standard, it must be flexible enough to adapt to different environments.

(iv) Maximum model size:

One of the advantages of simulation packages is that they enable to perform an analysis of systems that get so large that they are difficult to grasp simply by reflection. With the progress of computing power, tools can now handle more and more complex systems. Yet limitations of some tools still exist, and can be used as differentiation factors. Kodak thus paid attention to maximum model size for the selection of throughput simulation packages.

(v) Execution time:

One of the drawbacks of simulation tools is that they take time to develop and to run. Linked with the maximum model size that a tool can handle is its speed. Again, the advances in computing power lead to more and more powerful tools. This is particularly useful when the analysis involves performing "what ifs". The ability to perform sensitivity analysis is often considered as a fundamental feature. A faster tool often means a more thorough study. Execution speed is therefore a characteristic that is considered.

(vi) Understandable outputs:

As we already mentioned, acceptance of the results of simulation is a critical issue. It is thus extremely useful to have understandable outputs. For these communication purposes, animation is considered as a fundamental feature for simulation tools. Although it is sometimes felt that management can misinterpret animation or focus excessively on it, it is generally thought that having it greatly improves communication. It is also useful for debugging and verification. Also, a glossary to allow the user to identify the package with the company language is welcome. Indeed language is often a major issue in the sharing of results, both within a unit and with other functional departments in the company.

(vii) Customer support and documentation:

The ease with which a commercial tool can be used and the support that it may receive in the future are important criteria. This is particularly true for new packages that are just released. There is a high risk associated with the decision to go with them, and a belief that support is very likely to be needed. Thus the size of the vendor, its survivability, and potential upgrades are examined. Also the documentation and training available are viewed as important.

(viii) Compatibility with other packages:

As we have already mentioned, it is an important issue. This is one of the criteria already considered at Kodak and at GM. We discussed above a method that can be used to rate the compatibility of a new tool with ones already acquired.

(ix) Other users to network with. Company experience with a similar product:

We develop in chapter VI the importance of having other users with whom to share modeling experience. This facilitates the learning process. It also provides useful ways to use tools. Often, having several modelers working together on the same simulation may lead to more robust and useful models. This issue is sometimes considered in selecting a new tool, although we described an example showing that it was not a priority.

(x) Platform:

For obvious reasons, the hardware is fundamental. There are still a great number of tools running on workstations, and some on the mainframe. There is however a desire at most companies to move towards the use of PC's.

(xi) Price.

As we mentioned earlier, the cost of modeling tools, although currently not taken fully into account, is a fundamental characteristic. This cost involves not only the purchase price, but also the cost of training that will be required, of using the tool, and of integrating it in the company's environment and with other tools. We suggested above a way to handle this cost.

V.5. How to Develop and Implement Models

V.5.a. Characteristics of a Successful Model

Following are several characteristics that are necessary for a model to be successful. They are required to ensure that the model developed will be used in an effective way and really aid decision making.

(i)The model must be goal or purpose oriented:

Several questions need to be asked (and answered) before deciding on a type of analysis and model. What decision will you be making with the results of the analysis? What is the objective? What are the performance measures? How will you measure the performance measures? People at GM stressed the importance of these issues when developing their models.

Also, the future use of the model must be taken into account when deciding on the type of analysis. This means that the stakeholders must be clearly identified, and that the time when the analysis needs to be performed must be completely accepted.

(ii) The model must be simple:

One of the great difficulties is to find the necessary level of detail. It should be clear that one only needs to build the simplest model that will answer one's questions. One must start simple and evolve towards more details, in order to always control the complexity of the model. To determine the level of aggregation, Wu (1992) defines a link between this level and the time horizon and hierarchical level of people who will make decisions with the results of the model. He notes that aggregate models are usually employed to study the policies of long term planning at the corporate level. At the other extreme, there are the very detailed models for short-term planning problems down to the workshop level. For models in between, he suggests a reduced set of data approach. This approach uses a Pareto analysis to determine the set of variables that are vital for the sub-system considered. Since these variables determine to a large extent the performance of the sub-system, it is sensible to use the same set for the modeling effort.

(iii) The model must be complete on important issues:

Although the model must be kept as simple as possible, it must of course contain all the important variables. An important step in the development of a model is the determination of the model boundaries. Jay Forrester explained (1968) that "the boundary implies that no influence from outside of the boundary are necessary for generating the particular behavior being investigated. From this it follows that one starts not with the construction of a model of a system but rather one starts by identifying a problem, a set of symptoms, and a behavior mode which is the subject of the study. Without a purpose, there can be no answer to the question of what system components are important."

A model's data requirements can often represent the major impediment to its implementation. The data need of a model is one of the most frequent model-based factors that leads to failure of implementation according to the participating companies. The ease to gather data may depend on a company's attitude towards modeling. A company that is accustomed to the use of models will focus on the approach that it implies, the decisions that need to be taken, the way to record data and make it available. It will thus make the data collection effort much easier. A good information system in place helps facilitate the development of a model.

Also, one must make sure to look for the appropriate level and quality of data. One can define three main types of data. The first is data from a mental database . It usually has low quality. It is extensive and difficult to gather. The second is data from a written database. It has a better quality because of its consistency. It is usually large, although not as much as data from a mental database. It is easier to gather. The third is data from a numerical database. It has an even better quality and less redundancies. Yet it of course inherently lacks quality, because of any of the following fundamental causes: it can be just plain wrong, poorly defined, purposely disguised, inconsistently measured, or there can be errors in measurement. Because of these properties, numerical data is the most commonly used. Yet, non numerical data is extremely important, both for building the model and evaluating its validity. System Dynamics, which looks at all three databases and tries to integrate them, provides examples of the usefulness of incorporating all three.

(iv) The model must be robust and valid:

Robustness and validity can only be tested once the model is built. A model is robust if its results remain reasonable for any set of data. Validity is often viewed as accuracy, i.e. the ability to describe and predict reality with a lot of details and with a very small margin of error. A model is considered as valid if is both complete and precise. This can lead to models that are highly complex but do not necessarily improve the usefulness of their use. There is a trade off to find between a longer time to build the model in order to include as much detail as possible, and the decision making motivation which requires results as quickly as possible. To find the right balance, it must be borne in mind that a model must be kept as simple as possible. The required level of detail is determined by the purpose of the model. The validity of a model is no more than its usefulness in addressing the problem. It includes its accuracy, but also its appropriateness and its flexibility, which is often the opposite of its complexity. The validity of a model truly lies in its physical validity and its decision-aiding utility. The physical validity of a model is determined by its physical and structural fidelity to the system at hand. The decision-aiding utility depends on the purpose of the model. Robustness and validity are necessary to build trust in the model and to be able to use it for analysis. Sensitivity analysis can then be performed to evaluate the impact of some changes of parameters on the behavior. It can only be performed once the model is known to be robust and valid.

(v) The model must be adaptive:

Having a model incorporating the physical structure of the system at play is key for its adaptation and modification. The model structure should be easy to modify, to maintain and to update. Documentation of a model therefore plays a fundamental role. It ensures that results can be understood, replicated, criticized and extended by others. This is particularly important for two reasons. First, because of the high mobility of people, some models may be interrupted before their completion or may have an ongoing use after the people building them have left. Therefore documentation is necessary for subsequent users and for updates. Second, in order to facilitate communication and training, documentation is extremely valuable.

(vi) The model must be compatible with other tools:

We have already discussed the importance of this issue. As a first step, to deal with the problems of consistency, data integrity, process confusion and sub optimization, one must strive to have compatible models, which can interact. It is therefore necessary to have a common language between the different tools. Protocols to receive inputs would be useful, to precise what is included or excluded. It is for example considered to move towards a database format at HP, with central data manipulated by individual models. It would save time and ensure data integrity. But one must be careful with the management of a huge database: it is necessary to have a data dictionary, a good maintenance, updates and to make sure that there is compatibility between the different data elements. A move towards client server architecture is considered.

As a second step, one must aim to use several models concurrently and in a complementary way.

V.5.b. People Involved in Modeling

The critical factor in the success of a model however lies in the people, their approach and their opinion. Three key players can be identified for the development of a model: the person(s) with a knowledge of the system, the model builder, and the user of the model or decision maker. All have a role to play in the success of the development and implementation of the model.

(i) It is obviously necessary to involve the persons with a knowledge of the process in the model development phase. Two approaches can be followed, with different success.

- The first approach is the expert consulting approach. The model builder, or the "expert", is responsible for gathering data and building a model. He tries to obtain as much information as possible from the person with a knowledge of the system, without directly involving that person in the model development. Once enough data is gathered, the model is built and presented to the person with a knowledge of the system for potential improvements and for "validation." It seems that efficiency is lost with this approach.
- The second approach tries to involve the person with a knowledge of the system in the model building process. This has two positive results. It has a positive effect on the model being developed, greatly improving its validity both in terms of physical validity or conformity to the actual system, and in terms of the ability of the model to meet its desired use. It also has a positive impact on the person with a knowledge of the system, who often learns during the model development phase, discovers unexpected relationships in the system and possibly leverage points to improve that system.

At the moment simulations at all the companies are often performed by "experts" asked to perform an analysis by manufacturing people, the "clients". This is the case at all the companies, and is best illustrated with the example of GM, where the experts belong to the Manufacturing Center and may be asked by clients from the divisions to perform analyses. This requires an important exchange of information between both during the model building phase. Although this is still the case at HP as well, there is a desire to have simple enough tools to be able to move the analysis process to multiple agents close to the problems they want to model.

The persons with a knowledge of the system are often going to be affected by the model. It is therefore important to involve them as much as possible in the model development phase. Having their feedback improves the model and transforms them from skeptical and suspicious, even possibly hostile, to fully participating and supportive once their input is incorporated in the model. It is highly important to get their desire to share their vision, both for the development of the model and for its implementation.

(ii) The serious dedication of the decision maker to the model, his trust and commitment to its results are fundamental for the success of the implementation of the model. The decision maker must have a vision, an aspiration.

Also, the implication of the decision maker in the model building phase will lead to a two way benefit. First, as we described above, it will contribute to the acceptance of the results and to their translation into actual decisions. The most successful models are often the ones that show unexpected behaviors of the system being analyzed. These challenging models tend to be trusted and believed when it is easy to verify that they make sense, or when the system at hand is not too complex. Yet, for more complex ones dealing with a system from a high level, disbelief and doubts about unexpected and bothering results are more common, unless people have been involved in the model building process. Second, more than being able to improve the model, the decision maker can learn from the model building process. Much of the benefit of a model can be the learning that occurred during the building process.

(iii) As a summary, all three must be involved and participate in the development of the model. The decision maker and persons with a knowledge of the process are necessary to improve the model, to ensure their involvement and guarantee a better implementation, and to produce learning. The "expert" is necessary for technical assistance. During the model building phase, all three will have to share their assumptions, their views and their thinking. This may lead to even more learning.

To get more leverage from modeling, a team approach is extremely useful. This team must include the three stakeholders identified above. Involving several modelers has also been found to improve the success of model development.

V.5.c. Development Steps

Most companies follow a similar model development process. A mix of their different modeling process flows, including the main successive steps, is presented in the attached pages (Fig.3.) Boeing presented the most structured approach, and the attached figure builds on the process flows used by the simulation group. Yet all companies follow a series of steps, which have been taken into account to elaborate the attached "best practice". The following definitions are used in this figure:

- modeling approval is the procedure that gives a decision to go to the modeling project, based on the analysis of the purposes of the model and the intended way to reach these purposes;
- modeling qualification is the procedure that evaluates whether the model being designed has a structure and data in conformance with reality;
- model verification is the procedure that tests the functioning of the model, its technical correctness (program debugging);
- model validation is the procedure that verifies that the model is a close representation of reality, and that it will meet its objectives.

Fig.4. Steps in Model Development

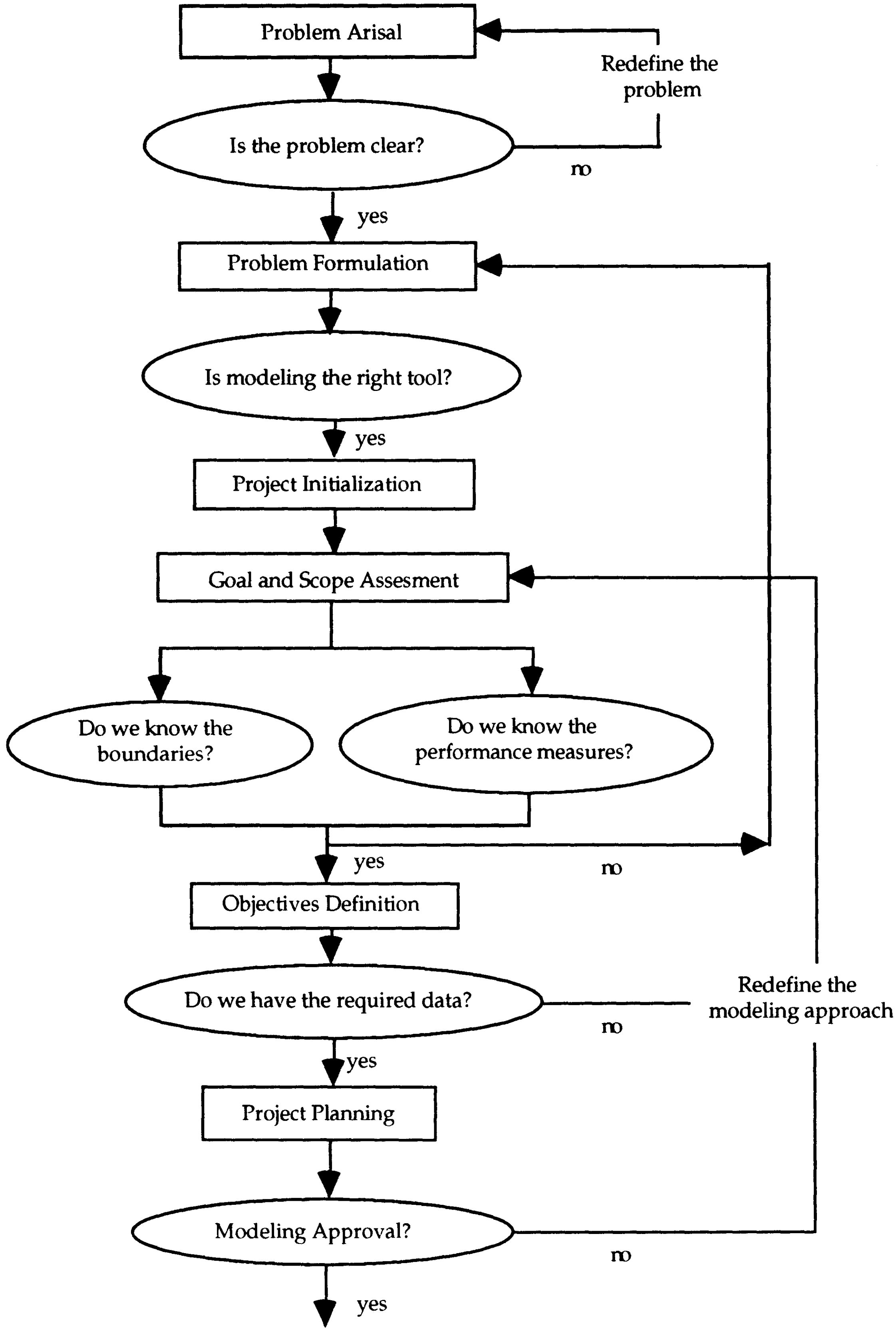


Fig.4. Steps in Model Development (Cont'd)

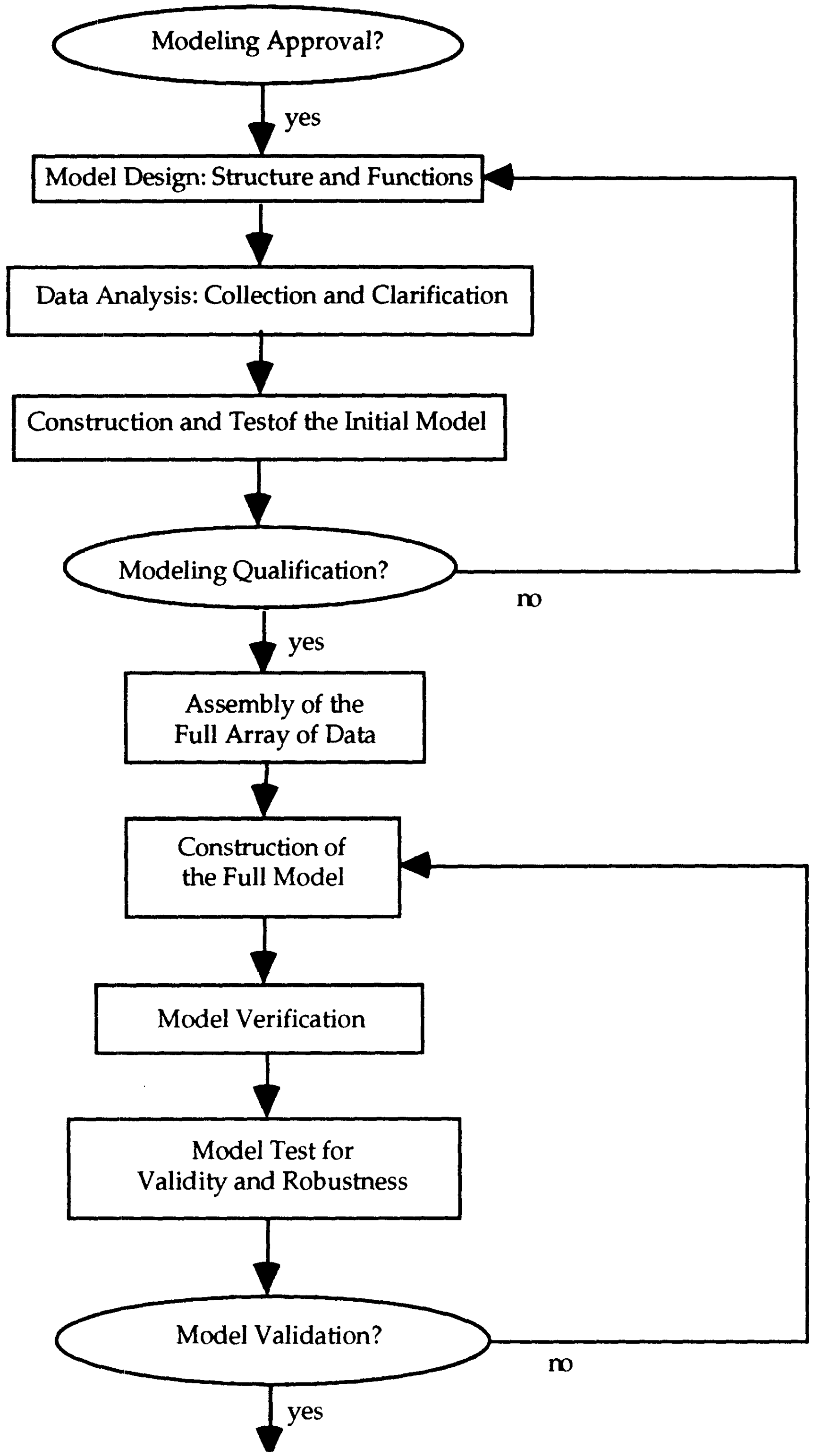
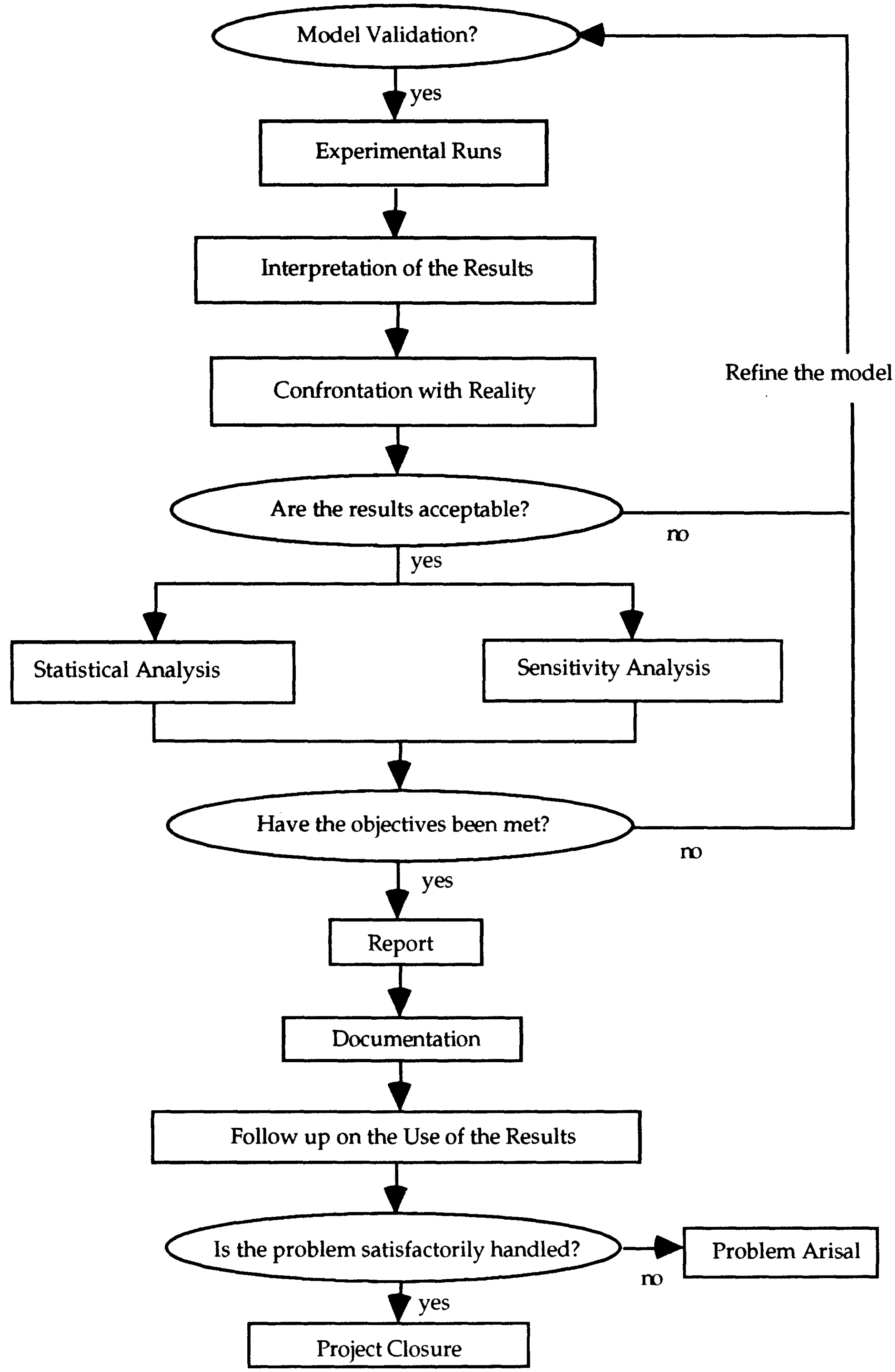


Fig.4. Steps in Model Development (End)



Chapter VI
POLICY FOR THE IMPLEMENTATION OF AN EFFICIENT USE OF MODELING

This chapter summarizes some of the recommendations presented in chapters IV and V. These recommendations address the effectiveness of the use of modeling and analysis tools in manufacturing system development, with a focus on simulation tools. This chapter identifies possible ways to implement these recommendations. Its focus is on the policy side of the use of modeling in manufacturing system development. It analyzes what can prevent or facilitate a wider adoption of modeling tools, particularly dynamic models, in a company. It uses the framework developed by Tucci (1991) for this policy analysis. It starts by determining the factors that influence technology and modeling adoption at a company. It then suggests strategies that a firm can use to promote the adoption of modeling.

Two main criteria can be considered when examining technology adoption within a firm: the people affected by the technology or the technology change, and the organization of the firm.

VI.1. People Affected

As we mentioned in chapter IV, there are often three stakeholders in the modeling area: the "expert" or model builder, the "client" or decision maker, and the "system owner" or the person(s) with a knowledge of the process. These three people have a different appreciation of the models:

- the expert pays attention to the "beauty" of the model. The main objective is to build a model as accurate as possible, that behaves in the most satisfactory way. Once this goal is achieved, a considerable trust is placed in the model and in its results. New modeling tools are usually considered with excitement.
- the client is interested in the results of analyses, and in the speed and cost to get them. The more complex the system gets, the less confidence is put in its results because of a misunderstanding of the functioning. Similarly, the longer it takes to get results, the less satisfaction for the client. In any case, the trust and confidence of the decision maker in modeling is the key to the development of the use of models.

Clients view new modeling tools as potential ways to improve the decision making process. They are likely to promote them, as long as they are not too complex nor too expensive. As we mentioned before, cost and return on investment are critical issues, although it is often hard to fully quantify the benefit of using tools.

- the system owner is also likely to be affected by the modeling. He often views models with suspicion, in part because of their complexity, in part for fear that they might impact his power.

The attitudes of these stakeholders towards modeling thus widely differ. They all have different interests in technology adoption. A way to reconcile them is to include them all in the model building phase. This will increase their understanding of modeling, thus their trust and confidence in results of models. It will promote the introduction of new modeling tools and facilitate their acceptance. We stressed the importance to involve decision makers and process owners as much as possible in the model building phase. This leads to benefits both for the model which can be improved and whose results can be better accepted, and for the decision maker who learns during that process. It should be understood that some types of simulation have benefits other than point prediction. They can create learning and a better understanding of the system.

To further change mentalities and promote the use of simulation, two main means of action can be followed:

- Communication is important. Full advantage should be taken of communication capabilities between geographically remote people to develop the use of simulation. Advertising using success stories through newsletters on-line for example can be very useful in disseminating some ideas. The LFM EMR could also contribute. Two groups of people should be the targets of this communication: users and decision makers.
- Training is important to get people to use simulation. Conferences or training sessions should be developed. It is also extremely useful to have practice fields where people can use models at no risk, and learn from their mistakes. One should try and redesign the practice environment so that people may have an opportunity to "rehearse", to step out of action, think about the way they make decisions, and find about tools and ways to use them.

VI.2. Organization

As Tucci observed (1992), the impact of the organizational structure on technology implementation can be defined along two lines: orientation and autonomy. Orientation is the organizational emphasis on input or output. Autonomy is the measure of centralization of decision making. Along these two characteristics, all the companies visited can be considered as divisional organizations: the hierarchy is present, but groups are divided into product divisions. The number of people performing the same function and working together is less than in other types of organizations. The employees are focused on the product or business. The disadvantage of this structure is a lack of technical critical mass, and a lack of perceived dependence between different divisions.

VI.2.a. Communication

The lack of communication between users of modeling tools is one of the most striking weaknesses identified at all the participating companies. This is probably also the area with most leverage. This lack of communication appears in two ways. First, people do not know about other users of similar tools in the company, and do not share their knowledge or experience with others. Second, people do not focus on the compatibility, even less on the integration of different models. These two factors result in islands of modeling, extra time, effort and cost spent during the development process.

We already examined the lack of interaction between different tools. We suggested in chapter V a method that helps identify improvements that can be achieved through more interactions of different tools. We also recommended that more attention be paid on compatibility of tools during the selection of new ones. It is indeed difficult to change current uses and force shifts to compatible modeling tools. On the other hand, it is much easier to act now on tools that are being selected and that will soon be used. A set of tools that can work together and fit the specificity of the company can be determined at each firm. These tools can then be strongly recommended and considered as a first choice when models have to be built. Also, a real integration of several tools should be aimed at in the longer term. Reflection and interactions between users of different tools should be encouraged for that purpose.

As we have already noted, at all the companies there is a lack of communication between the different users of models, resulting in islands of modeling. The units are very decentralized and autonomous at Square D, Kodak, HP and Intel. Although there is some exchange of information between the units and knowledge of what other people do, there is little coordination of effort between them. Each has its own process and its own tools. Although this provides more flexibility, it misses opportunities of leverage. There is however a re engineering effort going on at Kodak to try and have common processes, starting at the high level. The next step will be to share common tools associated with common best practices. Similarly, the Modeling Working Group that is being set up at Intel will focus on this sharing of information and on the communication of best practices between different divisions. Even at GM, although there is communication between the Manufacturing Center and the divisions for a given project, there is little outside these boundaries. Some divisions may thus not take advantage of what is done elsewhere in the company. Some analysis undertaken at the demand of one division may not be used to the maximum possible extend by others. Efforts are in progress to share best practices across divisions using cross divisional groups. This would ensure a more efficient use of the resources devoted to modeling by the Manufacturing Center.

Several practices can improve the communication between users of similar tools:

(i) Common packages should be used in all divisions as much as possible, i.e. as long as differences in the process do not prevent this harmonization. Before moving towards commonalty in the tools used, it is necessary to achieve commonalty in the development process. A first step before the standardization of modeling should be the establishment of a road map for the manufacturing system development process. First, the development process should be simplified. Second, some standard procedures for this development should be developed. Third, these standard procedures should be documented and distributed. They should then be considered as goals to achieve by all the divisions. Once some commonalty in the development process is achieved by all divisions, the use of identical tools across the divisions could be promoted. This would make easier and more efficient the transfer of people between divisions or the transfer of knowledge and experience with the tools between users.

(ii) Communication between users of similar tools should be encouraged. More communication could help the development and acceptance of modeling tools, and could help users and modelers. A newsletter between users of a common tool could be created, that could be sent on-line. The advantage of a newsletter is its regularity, periodicity and its openness to all users. Such an initiative is said to have had a positive impact on the development of System Dynamics for example. More information about experiences, practices, success stories or problems could be sent on-line to the users' group. The only danger with this type of organization is that too much time be spent on the network helping new users or conversing with existing ones.

(iii) A library or another repository of practices with the tools, improvements found and examples of problems addressed could also be set up. It could take advantage of the LFM EMR that already exists, and extend internally on it. The documentation about each tool could be augmented. It is felt that it could include the following items:

- An executive summary, containing a non technical introduction to the model, examples of use, information to assist a potential user in deciding whether to use the model, and details about how the computer program can be obtained.
- A description of the model input and output, of the assumptions used for the model, its main requirements and limitations: flexibility, type and size of problems that can be addressed, type of approach (prediction vs. better understanding of the system)
- A technical description to provide potential users with an understanding of the theoretical underpinnings of the model and of its advantages. A description of the computer program to enable customizations if desired
- A description of its computer characteristics and of the capabilities required for the user: computer platform, training required
- A user's manual describing step by step how the model is operated once it is installed on a computer: model creation (editor, graphic, menu)
- A list of the tools with which it can be integrated
- A list of users with a way to reach them

(iv) A central group could be responsible for the evaluation and selection of the modeling tools. It could also help setting up the users' groups, and facilitate the activities of these groups. A forum for the exchange of technical and application information between users of throughput simulation has been developed at Boeing with success four years ago. It is still being active, periodically publishing an assessment of the different packages and a description of their applications at Boeing. Appendix4 presents the charter of this group.

VI.2.b. Selection and Development

It is useful to have a central organization responsible for the evaluation and selection of tools as we just mentioned. This is particularly useful during the acquisition of a new tool and its dissemination, when little is known about it. Once it is acquired, it should clearly be publicized to all the potential users, via on-line information or presentations. Then, it is important to have a central group to facilitate communication between different users. It is also necessary to have one to ensure the commonalty of tools across the company for similar analyses, and the compatibility of different tools used for different analyses.

It is however extremely important that this group be sufficiently aware of the exact needs of different users. An important communication should take place between this central group and users, so that it is understood how users utilize modeling tools, what they expect from them and what they would like to change. Satisfaction of the user with the tool is a condition for success. A feedback mechanism from the user is therefore necessary.

The central group could also provide training for the tools recommended. It is important to quickly get up to speed with a tool to feel confident with it. A central group could help for that purpose, as well as a users network.

VI.2.c. Mobility

A point of leverage in a policy aiming to promote the introduction of modeling is the resolution of the independence of the groups. Favoring mobility among the different divisions may be a way to handle the issue:

- it will stimulate the introduction of tools equally in the entire organization. Mobility of people is a way to create information exchange and advertising about techniques and tools that can successfully be used in the development of a manufacturing system.
- it will also contribute to more standardization of the practices and tools used.
- it will finally reinforce a feeling of mutual dependence between the different divisions, which may lead to more communication between people.

As a result, the adoption of modeling can be made easier.

Chapter VII
FUTURE DEVELOPMENT, CONCLUSION

This final chapter examines potential developments of the project that was initiated with the present study. It also evaluates this study in the perspective of the benefits expected by the participating companies.

VII.1. Extension

VII.1.a. Maintenance and Upgrade of the LFM EMR

The first possible development is to maintain and upgrade the LFM EMR.

The objective of doing so is to have a useful and lively communication tool which creates interest and knowledge about tools, increases awareness, changes mentalities, and communicates best practices.

The goal in doing so is to identify weaknesses in the current version of the LFM EMR, to correct them, and to keep the document up-to-date while technology is changing. The LFM EMR is in its first version. It therefore necessarily contains several imperfections. Its presentation can be improved to take full advantage of the user friendliness of Mosaic and to make it an easier and more enjoyable tool to work with. The information that it contains can be augmented. Some tool descriptions are limited to the minimum and could be developed. More tools could also be added to the database and old ones removed.

The requirements to do so can easily be achieved. The physical maintenance can be performed by an undergraduate student at MIT. The participation of each company is the critical point. It should be made easier by the fact that each one can have examples of what is expected. Geographically dispersed tool users can be included in the development of the LFM EMR and easily brought up to speed thanks to information technology. The template for new tools descriptions should also facilitate the broadening of the LFM EMR. What is important is that each company commit to contribute to the development of this tool, and act accordingly. If each company does so, each will receive more than it gives. It may seem first for a tool user that the marginal utility in cooperating is small. A person who uses and appreciates a tool will find at the very outset little interest in letting others know about it. Yet the addition of all these marginal advantages leads to the greater benefit of all. Most of the success of the development of the LFM EMR thus lies in the companies' hands. It will develop as much as they want it to.

VII.1.b. Deepening of the Tools

Another natural development of the project is to focus on a part of what has been dealt with and go more in depth.

One way of doing so is to focus on selected companies. Three main groups can be identified in the LFM companies that participated in the project or intend to: the Automobile/Aeronautics group (with Boeing, Chrysler, Ford and General Motors), the Semiconductors group (with Digital, Hewlett Packard, Intel and Motorola), the Small Parts Manufacturing group (with Hewlett Packard, Kodak, Polaroid). Comparisons of different tools used for similar purposes could be performed. The advantage is that there are more similarities between these companies and more chances of being able to make comparisons. Yet there are also more concerns about confidentiality that will need to be overcome.

Another way is to focus on a function. Enterprise modeling for example seems to be a good candidate. It is not well developed yet. It could improve decisions made early on, i.e. with the most leverage. It belongs to the type of simulation oriented towards the understanding of a system and the learning aspect. It could focus on the enterprise along two lines: along the entire product life cycle, from product design to delivery and recycling, or along the whole factory and its market.

A final possibility would be to focus on a given phase of the development process. On the implementation phase for example.

VII.1.c. Extension to the Operation of a Manufacturing System

The project focused on the development of a manufacturing system and on tools used for that purpose. The operation of a manufacturing system shares lots of tools with the development process. A similar study could thus be performed for operations. In addition to a direct contribution to operations, it could also improve the integration of tools between development and operations.

VII.1.d. Integration of Modeling Tools

Still focusing on the development of a manufacturing system, a lot can be gained through the integration of different modeling projects.

A first step would be to study how different tools can interact. The interaction of the underlying activities for which they are used, and the compatibility of their outputs could be examined. The complementary aspect of these tools would also be considered. Given all the existing tools and the objectives in the development process, one could develop a set of tools that can be used together.

A second step would be to go beyond compatibility and interaction to reach full integration. A modeling approach that would incorporate and interconnect the different modeling types in a hierarchical framework could be aimed at.

VII.1.e. Policy Determination of Modeling Tools

Another problem that could be addressed is to try to understand how a manufacturing philosophy (Just In Time, Theory Of Constraints...) influences and affects the way models are built or tools are constructed.

VII.2. Conclusion: Benefits of this Project

One of the immediate benefit is the database that has been developed using the Mosaic tool: the LFM EMR. It contains information about tools used by different companies, and therefore provides some benchmarking and information that can be used to develop each modeling group.

The presentation of the results in a Mosaic format also gives an example of how to use information and communication tools to share ideas and spread knowledge. The user friendliness of the software can be combined with the advances in communication technology to allow transmission of information and sharing of practices across geographically dispersed users. One of the main improvements that can be achieved to facilitate the use of simulation in the manufacturing system development is communication within the company. The LFM EMR is a powerful tool to develop communication between users of similar tools who can benefit from each other's experience, or between users of complementary tools that need to be integrated.

Another less obvious benefit is the cooperation that took place. Each company accepted to provide information that it could consider as proprietary to some extent, in the hope that each one would play the game fairly. The leverage comes from the higher information that is received than given. It lies in the assembly of these pieces of knowledge, in the sharing that is taking place. In the modeling area that is still burgeoning and growing fast, each company can learn from the others and benefit from this cooperation. We hope that the LFM EMR and this document have contributed to some learning for each company. We also hope that this project will lead to further cooperation on the area between the participating companies, with even more trust that can lead to more learning.

APPENDIX1: LFM EMR Home Page

The Leaders For Manufacturing Electronic Manufacturing Resource
Version 1.0, November 10, 1994

The Leaders for Manufacturing Program (LFM)
Massachusetts Institute of Technology

Welcome to the Leaders For Manufacturing Electronic Manufacturing Resource. It is a tool designed to enable simple and rapid discovery and retrieval of information about tools and methods used for the design and development of manufacturing systems (you can look at the definitions of these concepts and the precise focus of this project by clicking on the underlined word.)

This document is presented in a Mosaic format: it is a web of information with links on selected words. Anywhere in the text you can have access to more information about an underlined word by simply clicking on it.

The content of this document is the result of a research project conducted by the LFM program in 1994. The tools and methods presented here are the ones identified at the participating companies.

This document was initiated by Pierre Brunet under the guidance of Prof. Kevin N. Otto. We welcome any feedback that you would like to make. To do so, you can send an e-mail to one of the addresses mentioned below.

You can search this hyperbase and have access to identified and analyzed modeling and analysis tools and methods by

- Phases in the manufacturing system development process (System Analysis, System Design, System Implementation)
- Functions of the manufacturing system development process (Project Management/Cost Analysis, Interaction with Product, Management of Materials, Production/Process, Equipment, Information and Control Systems, Human Resources)
- Level in the manufacturing system (Factory, Line, Cell, Workstation)
- Company participating in the project.

You can also directly access the list of all the tools that have been identified, arranged in alphabetical order.

You can finally submit new additional tools to increase this database.
Also, there is information on how to freely obtain Mosaic on the Internet.

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pbrunet@mit.edu knotto@design.mit.edu

APPENDIX2: Description Template

Tool Name:

We want to map this tool with the activities of the manufacturing system development it is used for. Please identify, for each of the three following "dimensions", the "coordinate(s)" that best correspond to the application of the tool.

1. Phases in the manufacturing system development process:

System Analysis	System Design	System Implementation

2. Functions of the manufacturing system development process

Interaction with Product	Management of Materials	Production
Equipment	Human Resources	IS, Control Systems

3. Level in the manufacturing system

Factory	Line	Cell	Workstation

Tool Description:

Input:

Output:

Examples of Use:

Main Benefits/Drawbacks:

• Cost reduction:	high	medium	low
• Time reduction:	high	medium	low
• Quality Improvement:	high	medium	low
• Better Understanding of the System:	high	medium	low
• Other			

Integration with Other Tools:

Characteristics of Use:
- Person using it, training required:
- Time required to use it:
- Hardware:
- Cost:

Openness About it. Other Remarks:

APPENDIX3: List of All the Tools

Following are all the modeling and analysis tools and methods that have been identified through the survey that was sent to the participating companies in June 94, and through one week visits that were made to some of the participating companies during the summer 94. Please note that this list is not all inclusive of the tools and methods used at the participating companies. It contains selected robust and simple modeling and analysis tools and methods that can successfully be used in the design and development of a manufacturing system.

If you want to go back to the main menu, please click here. To have access to the description of any of the following tools and methods, simply click on it.

Accrapath
ABC Flowchart
Act
Activities Modeling
Activity-Based Costing (ABC)
Autocad for Facility Layout
Autocad for Tooling Design
Automod
Autosched
Autosketch for Process Modeling
Autosketch for Line Layout
BDI Design For Assembly
BDI Design For Manufacturability Toolkit
BDI Injection Molding Estimator
Computer Vision Cadds5
Catia
C_Mold
Computer Aided Process Planning (CAPP)
Coordinate Measuring Machine Data Analysis (CMMDAna)
Data Standard/Data Dictionary
DEC Model
Design For Machining
Design For Manufacturability: Machine and Tool Design
Design For Serviceability
Digital Program Methodology (DPM)
Echip
EDA for Piping Design
Elecdas
Eplan
Equality
Ergo
Ergonomics Checklists
Error tracking in Software
Excel to Estimate Production Cost
Excel to Estimate the Facility Construction Cost
Excel for Ergonomics<
Excel for Environmental Impact Analysis
Excel for Project Planning
Excel for Capacity and Space Requirements
Excel for Capital Requirements
Excel for Equipment Requirements
Excel for Staffing Requirements

Excel for Presimulation Analysis of Steady Flows
Excel for Balance Efficiency Requirements
Excel for Static Throughput Modeling
Excel to Analyze the Supply Chain
Excel for Assembly Capability
Excel for Failure Mode and Effect Analysis
Extend+BPR
Factory Simulator
Factoryplan
Flowchart
GMForm-2D
GM-Toxscreen
GPSS
Icad
Idef0
Igrip
Intergraph
Ithink
Joint Application Design (JAD)
Kepner-Tregoe
Lead Time Reduction Charting (LTRC)
Linear Programming to Determine the Location and Relocation of Assembly Lines
Mannequin Designer
Manufacturing Assembly and Installation Data System (MAIDS)
Manufacturing Shift and Sequence Planner (MAAP)
Manufacturing System Qualification Manual (MSQM)
Machinery Equipment Design and Development System (MEDDS)
Metis
Milestones
Microsoft Project
Modeling of Behavior towards Change
Moldflow
On-Line Planning (OLP)
Operation Description Sheets (ODS)
Optima
Optimizer
Primavera
Producibility Automation and Cost Estimate (PACE)
Production Part Approval Process
Productivity Plus
Promis_e
Promodel
Quality Function Deployment (QFD)
QFD/Capture
Quest
Repairman
Request for Application Program Change
Robcad
Schedule Requirements and Order Analysis (SROA)
Siman
Single Task/Multiple Task Job Analysis
Static Strength Prediction Program
Service Level Agreement (SLA)
Systems Diagrams
Task-System Matrix Analysis

Taylor II
Techfiles
Technical Memory System (TMS)
Top Down
Valysis/VSA
Vensim
Vericut
Via Schematic
Virtual Numerical Control (VNC)
Visio
Wire EDM Machining Expert System
Witness
Worksite Analysis

APPENDIX4: Boeing Simulation Forum Charter

1. Simulation Technology Forum Charter

November 12, 1992 (Revised from July 17, 1990)

Purpose, Goals and Objectives

PURPOSE:

To increase the benefits Boeing can derive from simulation by efficient sharing of ideas and resources.

The purpose of the Boeing Simulation Technology Forum is to provide a platform for the exchange of technical and application information between the various simulation professionals in the company to foster the Continuous Improvement of simulation systems and expertise.

GOAL:

Continuously improve simulation hardware/software tools and modeling and analysis expertise.

OBJECTIVES:

1) Exchange of information on the techniques, equipment, software, and applications related to simulation.

2) Provide a vehicle for education and training of both simulation providers and customers.

3) Provide management with a source for consolidated information on the current activities of simulation in Boeing.

4) Provide a forum for evaluation of simulation software and hardware.

5) Provide a database of simulation providers and systems.

6) Present a unified position to simulation vendors to influence future enhancements and product support.

7) Develop recommendations for simulation methodology and systems.

8) Development of centralized resources such as:

   - Reference books
   - Journal articles & reading lists
   - Library of routines & procedures

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