Integrating Discrete-Event Simulation into the Manufacturing System Development Process

A Methodological Framework

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Abstract

Today, after more than four decades of presence in the manufacturing industry, we can conclude that simulation as a technology has become extremely powerful, that simulation software – although not entirely adequate – still appears very capable, and that methodologies for performing simulation projects are reasonably well-developed and documented. Turning to the context and scope of this thesis, we see that discrete-event simulation (DES) can be applied to a wide range of manufacturing system development activities. As evidence of what this technology can do, successful cases from various industrial sectors abound. In brief, DES use can have significantly positive impacts on the quality, cost, and time aspects of manufacturing system development (MSD) and the product realization process (PRP).

Despite a seemingly rosy picture, however, this thesis argues that several problems associated with the adoption and use of DES still exist in industry.

First, a majority of companies do not use simulation at all, and many of these do not have enough belief in what simulation can do for their organizations to even consider using it in the future.

Second, companies that use simulation do not seem to have realized the full potential of this technology. In the terminology of this thesis, they have not fully *integrated* simulation into their MSD process. Often, simulation is used on a *one-shot* basis only, troubleshooting specific problems such as bottlenecks, usually in late stages of the manufacturing system life-cycle, or as a *stand-alone* tool, both of which reflects a low level of *simulation integration*, a concept introduced here.

Despite that reasons for this modest and non-integrated use of simulation in the manufacturing industry have been less than satisfactorily explored (empirical studies in particular are scarce), some conclusions can be drawn as to the nature of these reasons. In brief, these have been found to be attributed to *reductionist* views on and *unstructured* approaches to DES integration.

At the same time, it seems that academia is not fully addressing the issues needed to overcome this situation. Simulation research on integration aspects often deals with specific system and application integration, or what can be referred to as functional issues, such as integrating and connecting simulation to other systems and tools, rather than structural, hierarchical, and procedural integration aspects as part of a methodological approach. Finally, and perhaps most importantly, simulation use and adoption often lacks strategic focus.

From a systems perspective, and based on industrial experience and case studies this thesis looks at the activities and knowledge needed to integrate DES into the MSD process, and outlines a framework for a structured approach to integration. This framework rests on three pillars – (i) a holistic view on simulation integration, (ii) knowledge from other disciplines, and (iii) an integration methodology – and it extends over four simulation integration domains; here defined as *strategy*, *operations*, *data*, and *enablers* (DOSE).

It is concluded that both simulation users and non-users could benefit from incorporating such a framework into their simulation integration efforts, but also that several research challenges remain, including further development of the methodology, if the approach is to gain industrywide acceptance.

Keywords

Manufacturing System Development, Discrete-Event Simulation, Integration.

When I read the book

When I read the book, the biography famous,
And is this, then, (said I,) what the author calls a man's life?
And so will some one, when I am dead and gone, write my life?
(As if any man really knew aught of my life;
Why, even I myself, I often think,
know little or nothing of my real life;
Only a few hints – a few diffused, faint clues and indirections,
I seek, for my own use, to trace out here.)

WHALT WHITMAN

Leaves of Grass, 1900

Contents

Acknowledgments

As this thesis sums up my first years as a doctoral student, my thoughts wander off to several people, places and events that in some way have contributed to me getting this far.

First, I wish to thank my supervisor, *Professor Gunnar Bolmsjö*, who introduced me to the world of science and awoke my interest in pursuing the doctoral degree. Professor Bolmsjö has been as much of an inspiring discussion partner and mentor, as a friend and supporter.

Turning again to people here at my own department, my next words of appreciation go to *Lars Randell*. Lars introduced me to the world of simulation, and his friendship, cooperation and encouragement have been important. I am also grateful to *Arne Ingemansson*, friend and colleague, who shares my interest in Japanese production and management philosophies among other things. With his own industrial experience, Arne has provided valuable feedback and discussions on my research. My appreciation also goes to *Dr Johan Ericsson*, who once graduated from our department. Johan is a true scholar on Japanese and Swedish industry and has been a valuable discussion partner and a good friend. I would also like to thank my other colleagues here at the department for contributing to a stimulating and positive work environment.

In further acknowledging people, experiences, and impressions that during these years have had a significant influence on both my research and private life, my thoughts soon go to a country far away, yet always close to my heart. That country is Japan, which through its people, history and culture has been a major source of inspiration and happiness on both a professional and personal level. Dating back to the 1980s, the Department of Mechanical Engineering here at Lund University, through Professor Bolmsjö, has had an exchange program with the *Department of Mechanical and Systems Engineering at Gifu University, Japan*, through *Professor Hiroshi Fujii*. Through this programme I and *Robert Pozgaj* got the chance to spend four months in Gifu during 1996/97, which resulted in a Master's Thesis on Small and Medium-Sized Enterprises in Japan. I have since returned to Japan for two research visits. All through my stays in Japan, Professor Fujii has been my supervisor, devoting a considerable amount of time and interest to my studies and research. This alone would have been much more than anyone could

have asked for. Fujii-sensei, however, also introduced me to Japanese culture, history and society in a wonderful way for which I will always be deeply grateful. My thoughts and gratitude also go to *Mr Itaru Tōmei* of *Tōmei Engineering*, Gifu; a man whom I also greatly respect and admire. Tōmei-san took great interest in my research, and with his family made me feel very much at home in Gifu. I am also indebted to *Mr Hiroshi Mearashi* at *Nihon Unisys*, *Professor Toshihiko Mori* at the *Department of Mechanical Engineering at Nagoya University*, *Mr Toshihiro Sugai* at *Melco Brains*, Tokyo, and *Professor Etsuo Yokoyama* at the *Department of Education at Nagoya University*. They all helped me and my colleagues out in several ways, and from them I learned many things about Japanese industrial and cultural practice that I will always carry with me. During my time in Japan I also received support from and enjoyed the discussions I had with *Dr Antanas Daugela*, *Dr Naoki Sase*, *Dr Inga Skiedraite* and Professor Fujii's colleagues and students. In the end, however, my studies of Japan's manufacturing industry would not have been possible without the support from all the Japanese companies that welcomed me and my colleagues to visit them. To you all I would like to extend my sincerest *dōmo arigatō gozaimashita*.

The two research visits to Japan, in 1999 and 2000 respectively, were made possible by scholarships from *The Swedish Institute* and *The Sweden-Japan Foundation*. Their support is most gratefully acknowledged.

Moving on to another great country in East Asia, I would like to thank *Professor Kyo-Il Lee* at the *Department of Mechanical and Aerospace Engineering at Seoul National University* for widening my research horizon, and introducing wonderful Korea to me.

Industrial relevance in the kind of research described in this thesis is nothing less than crucial. The continuous exchange of scientific and technical information is of particular importance in a time of rapid and complex changes in manufacturing environments around the world. I owe my gratitude to a number of companies in the Swedish manufacturing industry for having enabled cooperation and bidirectional dissemination of research results and industrial practice. Here, I would like to thank *BT Products* in Mjölby, *Segerström & Svensson* in Eskilstuna, and *Volvo Car Corporation* in Gothenburg for stimulating and rewarding cooperation. My special thanks go to *Mr Jörgen Norgren*, *Mr Oliver Pallman* and *Mr Hoa Hai Gieng* at BT Products, *Mr Jan Andersson*, *Mr Per-Erik Bergström*, and *Mr Mikael Jansson* at Segerström & Svensson, and *Mr Ulf Eriksson*, *Dr Pär Klingstam* and *Mr Bengt-Göran Olsson* at Volvo Car Corporation's Manufacturing Simulation department. I am also indebted to *Delfoi* and *Establish*, and their offices in Gothenburg/Malmö and Lund respectively. Me and my colleagues have had fruitful discussions with a number of individuals at these consultancies, especially *Mr Torbjörn Danielsson* at Delfoi and *Mr Jörgen Möller* at Establish. Delfoi has also been a partner in a number of simulation projects, and has supported us with software issues.

I have also very much enjoyed working on the PROPER team consisting of my fellow researchers *Mr Peter Almström* at the *Department of Production Engineering at Chalmers University of Technology*, *Ms Elisabeth Sagström* at *The Swedish Institute for Production Engineering Research (IVF)* in Mölndal, and *Mr Ulf Eriksson* and *Dr Pär Klingstam* mentioned previously. Here, I would also like to send my appreciation to the entire PROPER network of researchers and industry practitioners (please see below).

Moving on to those who ultimately made this research possible, I would like to acknowledge the financial support from *The Swedish Foundation for Strategic Research (SSF)* through the Programme for Production Engineering Education and Research (PROPER), and *The Swedish National Board for Industrial and Technical Development (NUTEK)* through the research programme VSOP for CONSENSUS, part of the national research programme Information Technology in the Manufacturing Industry.

Thank you.

Preface

For the past years, I have tried to explore as many aspects as possible of what I believe to be one of the most exciting and promising technologies in the manufacturing industry: discrete-event simulation.

To this end, I gathered knowledge through reviews of literature, empirical studies, and cooperation with industry. In doing so, I became overwhelmed by the potential of this technology, but at the same time a picture emerged that spoke of less than a fully realized potential of simulation. I thus came to the initial conclusion that something was missing from the picture, but I could not see exactly what. Then something interesting happened. I discovered an anomaly–a discrepancy between theory and the observed reality. It appeared as a lack of *integration* of DES in manufacturing system development, which seemed to be due to not taking a holistic view on simulation issues as well as to the absence of structured guidelines for *how* to increase this integration.

So I tried my best to address and highlight the wide range of issues facing companies that wish to integrate simulation into their operations, and I then set out to synthesize these issues into a formalised set of tasks and a structured approach to carrying these tasks out. In other words, I tried to develop a methodology.

Did I succeed? Not really. As I hope this thesis will show, the topic I have chosen cannot be confined to a single discipline nor can the inherent problems be solved with any speficic solutions. In fact, it is likely that even thousands of years of research would not produce a complete and fair coverage of all the underlying issues. Not only because of the size and complexity of the task, but because the context of the task is constantly changing. In fact, and as the subtitle to this thesis suggests, what I present here is merely a framework, and even as such it has theoretical and practical knowledge gaps that need to be filled.

So what can be concluded from this? One thing, I would say, above all: That as always, the continuous quest for more knowledge must continue. After all, as a reliable source once stated, the truth is out there somewhere. It is our job as scientists to find it.

LARS HOLST
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Knowing is not enough; we must apply.
Willing is not enough; we must do.

– Bruce Lee

Explanatory Notes

SIMULATION – Unless otherwise stated, the term *simulation* alternates between denoting discrete-event simulation (DES) and simulation in general. If other specific simulation techniques are referred to, they will be explicitly stated. Also, when speaking of simulation in general terms it is usually understood that the simulation is done with the aid of a computer, i.e. *computer simulation*. Furthermore, simulation in this thesis is referred to both as a *technique* and a *technology*. Both are true; the context should make it clear which of these that apply.

PROCESS – The term *process* is referred to in literature with several different meanings. Unless otherwise stated, process in this thesis refers to the manufacturing system development (MSD) process, hence an important distinction is made from the more common understanding of process as the production process.

REVIEW OF LITERATURE – Explicit *review of literature* chapters have been left out. Instead, the findings from literature reviews have been incorporated into their appropriate sections throughout the thesis, particularly within the frame of reference chapters.

REFERENCES – All references that point to a Uniform Resource Location (URL) were checked for availability during the period of June–July 2001, and unless the access date is explicitly stated in the form of [accessed…], to distinguish the access date from the year the referenced text was authored or published, the letters "www" have been used instead of the year to indicate that the reference is a world wide web site.

APPENDED PAPERS – All papers have been appended without any changes of their original text. For typesetting reasons, the font style and page margins have been adapted to fit the style of this thesis. As a result, the number of pages and position of page breaks will differ from the original versions. In addition, the reference style in Paper I has been changed from the original to comply with the Harvard style reference system used throughout this thesis.

Part I

INTRODUCTION

1

Context and Motivation

1.1 The Basis for Economic Growth

Manufacturing, as one of the most basic, yet wonderfully complex activities undertaken by man, deserves our attention for several reasons, three of which will be brought up here: (i) manufacturing always has been, still is, and within the foreseeable future will remain, both directly and indirectly, the basis for economic growth of nations; (ii) the manufacturing industry is constantly exposed to change and uncertainty which threatens prosperity and quality of life in all countries; and (iii) it is fascinating.

In retrospect, the manufacturing industry, throughout its history, has always faced significant challenges: in the form in which it came to economic ascendancy as part of the industrial revolution it had to deal with basic technological challenges, growing demand, and inherent inefficiencies; as it shifted to mass-production of standardized products for mass markets, issues related to organization, quality, and natural resources were put on top of problems related to already existing inefficiencies, declining rates of productivity growth, and changing demand patterns, thus giving way to novel Japanese approaches to manufacturing, and the resulting Western paradigm of lean manufacturing. Still, the manufacturing industry now faces problems related to customer demands, environmental legislation, competition on a massively global basis, the use of information and communication technologies, over-capacity, inflexibility, and so on, in a never ending chain of events characterized by two things: change and uncertainty.

For the past twenty years the pace of change and the amount of uncertainties have been steadily increasing, and today the threat to manufacturers appears massive and relentless. Indeed, the new information and communications technologies (ICTs), and the thereby associated process of globalization have forever changed the face of manufacturing. It is now widely agreed upon that today's manufacturing industry is best characterized as *global*, *integrated*, *customer-driven*, and *dynamic* (Wang et al., 1997).

It is *global*, in the sense that an increasingly wider range of functions from R&D and marketing to production and distribution are undertaken on a global basis, including new players on the supply side, the emerging or newly industrializing economies (NIEs), and subject to various cultural (corporate and social), legislative, and infrastructural environments; it is *integrated*, in that the coordination of these functions makes extensive use of electronic networks and of virtual and geographical clusters of expertise, be it through strategic alliances, restructured organizations resulting from mergers & acquisitions, or extended enterprises, and in that many of these processes, particularly final production, are controlled by advanced computer systems which need to work together with human beings; it is *customer-driven*, in that methods of production must allow for detailed customization of products to meet the needs of individual markets and individual consumers, shown by the emergence of concepts such as customer relationship management, first to mind, make to order and market-in vs. product-out; and it is *dynamic*, since all this is increasingly driven by time, as evidenced by the focus on terms such as time to market, time to customer, product life-cycle, first to market, market window, lead time, throughput time, and so on.

Looking at the market situation of manufacturers today, a majority of the customers now demand high-variety, small batch volume products of high quality, available on time, fast, and everywhere, at a lower cost.

With all this focus on manufacturing, however, it is in place to acknowledge the presence of other forces. Here, a diverse combination of factors – from greater productivity arising from technological innovations in industry, a shift of demand in high income industrialized countries from goods to services in spite of declining relative prices for goods, and increased global competition – is leading to a decrease in the share of gross domestic product (GDP) arising from goods production in all developed countries.

In the emerging so-called *knowledge-driven* economy, there is a shift from goods industries to knowledge and intellectual capital industries in terms of the composition of GDP and employment. But it is not that one group of industries is replacing another, as, for example, cars replaced horse-drawn carriages. Rather, although there is some increased demand for services as final products, activities related to the development, production and distribution of goods still lie at the heart of advanced economies. But those activities are becoming increasingly knowledge and service intensive, so that there is growing convergence between traditional goods industries (including, of course, manufacturing) and service industries.

For example, a majority of manufacturing firms rely heavily on services, both from within the firm and from the outside, and sell both goods and services, as exemplified by truck manufacturers such as Scania and Volvo. In addition, many service sector firms have specialized in providing services to manufacturing firms, or to firms producing other types of goods. In fact, one can argue that companies no longer offer products but rather *functions* that are part tangible – products – and part intangible – services (Teknisk Framsyn, 2000).

In other words, there is considerable evidence of a large scale *integration* of industries. But what good does manufacturing do? Next section will try to answer this.

1.2 Manufacturing System Development: Improving Quality of Life

The previous section claimed that manufacturing represents one of the most *basic* activities undertaken by man. It is not hard to see why: for almost as long as our species has existed, we have been forced to *manufacture* objects just to survive. From the simple artefacts our ancestors used for making fire and killing prey more than 100,000 years ago, to contemporary life-saving devices such as cars and helicopters, our survival has relied on inventing and producing things.[1]

However, apart from such obvious necessities, manufacturing not only provides what we need to survive, but holds an enormous potential to improve quality of life for people all over the world. Just as affordable cars, low-cost housing, and cheaper sea- and airfare have changed life for millions of people in the industrialized world, the lives of hundreds of thousands of people in developing countries are also improving thanks to clever inventions and the cost-efficient production of goods. And there are billions more whose hopes of attaining a decent standard of living to a great extent depend on how we succeed in our manufacturing operations. This holds particularly true in a time when the gap between the rich and the poor is rising, even in industrialized countries (The Economist, 2001*b*). We must thus recognize not only the technological aspects of manufacturing, but also its economic and social significance.

Here, one might think that all that stands in the way of creating a better world is a lack of political will, capitalists reluctant to redistribute wealth, or other seemingly non-manufacturing related issues. This is wrong. First of all, politics is very much related to manufacturing since it partly defines the environment in which manufacturers must operate. This insight alone does not make things easier, but rather shows the need for manufacturers to be adaptable. Second, it is not a matter of redistributing wealth, but to create it. And this is what manufacturing does very well.

Yet other problems remain. Scientists and engineers may come up with the most marvelous and fantastic inventions that in various ways make our lives better. They may then sit down and transform these inventions and ideas into real products which on paper have all the quality characteristics that customers desire. But if these products cannot be efficiently and effectively *manufactured*, they will be made available only to an elite group of consumers that are willing and able to pay the premium that comes with inferior manufacturability. This certainly speaks against the view of manufacturing as having the potential of improving the quality of life for people everywhere and increasing the wealth of nations.

When speaking of prosperity and quality of life, one must also remember not only the real or potential end-users of finished products, but as suggested in the previous section, all those whose employment or income in some way depends on the successful operations of single manufacturing enterprises. In this sense, it becomes both economically and ethically necessary for every manufacturing company to deliver products at the right quality, cost, and time.

More than this, it is necessary to recognize the need for "quality of working life", which depends on social issues such as man-machine interaction and stimulating work tasks in the organization and operations of manufacturing systems (Hitomi, 1996). This is particularly true in times when it is becoming increasingly difficult to attract young people to manufacturing jobs, as a result of a lingering reputation of these work tasks being dirty, hard, non-stimulating and dangerous.

What we have learned from history is that, if anything, manufacturers must never cease to strive for continuous improvements of their operations, an imperative nicely epitomized by the Japanese concept of *kaizen*.

In summary, it should be clear from the above that manufacturing is characterized by three things above all: *complexity*, *dynamics*, and *change*.

What, then, if there was a technology that was particularly well suited to handle exactly this? As it happens, there is.

1.3 Discrete-Event Simulation in Manufacturing System Development

In a world where complexity, dynamics, and change dominate, it becomes vital to understand systems behavior and the parameters that affect performance. This is particularly true in the development and operations of manufacturing systems; activities in themselves characterized by complexity and change.

To represent, analyze and evaluate this complex, dynamic reality, the need for *models* has long been recognized. As Askin and Standridge (1993, p. vii) state, "models address a wide range of manufacturing system design and operational issues and are therefore essential tools in many facets of the manufacturing system design process." As we have seen from ample empirical evidence and as this thesis will show, one of the most powerful modeling techniques in the manufacturing industry is discrete-event simulation.

In fact, discrete-event simulation is fundamental to the assessment of a new manufacturing system design or operations management policy since many of the measures used are dynamic in nature. Its purpose here is simple: to support correct decisions throughout the development process, thereby increasing the quality of those decisions.

Discrete-event simulation thus provides analysis, description and evaluation capabilities of systems, and if successfully applied can support collaborative work across organizational boundaries and thereby improve information and communication. In addition, it can be used for training and educational purposes. By these means, simulation can significantly improve system knowledge, shorten development lead time, increase utilization and productivity and support decision making throughout an organization. The author has also found that simulation increases the awareness of performance measurements and emphasizes the importance of those measures to the people involved in the simulation projects.

By the virtue of these qualities, simulation has become one of the most powerful decision support tools available in the manufacturing industry today, helping managers and planners analyze the effects of a large variety of policies with a high number of alternative combinations of different parameters. A manufacturer of some medium complex product wishing to increase its throughput might ask itself a number of questions: what happens if we introduce a new product into the existing production line? Can we meet our production targets? Are the real bottlenecks in our current system where we assume them to be? Should we increase the number of machines, and if so at what stage in production? Would we be better off changing the layout or routing instead? Or should we look at the batch and buffer sizes? What about the shifts? Would it be economically viable to invest in a new material handling system? Or do we just need more fork trucks? Or some combination of these policies?

Not only can simulation answer such questions, but it can answer them without disrupting or in any way affecting the real world business processes in the company. In addition to saving cost and time and increasing customer satisfaction by helping to assure the right quality, price and delivery time through better informed decisions, a large part of all simulations are justified because other means of experimentation (e.g. with the real world) would not be possible. The reasons for this may be *practical*, such as not wanting to disturb or change some existing system, like a running factory; *physical*, as in the case of simulating something that does not yet exist, like a new production line; *ethical*, when real world experiments are possible but considered unethical; *legal*, such as trying out the effect of yet to be implemented changes in legislation, e.g. working hours for truck drivers; and *risk-eliminating*, when real world experiments would be dangerous or hazardous, such as testing the failure of a production line. The real world in turn can go about its business as usual, without even noticing it is being simulated.

Despite these outstanding credentials, empirical research shows that discrete-event simulation use in the manufacturing industry is not as widespread as one would think. Several companies do not use it at all, while some of those who do seem to have mixed emotions about the potential of this technology. Several researchers also agree that the full potential of discrete-event simulation has not been realized in the industry as a whole, although some companies have come a long way. In other words, there are clear indications that a number of problems remain for the simulation community to solve.

So what is missing then, if these problems are to be overcome and the full potential is to be realized? The next section will sketch a few suggestions.

1.4 Integration Through a Structured Approach: The Missing Concept

Although much has been said of dynamics, complexity, change, and uncertainty as characteristics of manufacturing in the 21st century, one thing has remained notoriously static and certain for the last decades: the manufacturing industry's need to meet *quality*, *time*, and *cost* objectives. At any given time and for any given company, this fact holds true for both products and processes, albeit that the weight attributed to each of these objectives differs depending on product type, market conditions, etc. What certainly *has* changed though, and what continues to change over time and across industries, are the *means* of meeting these objectives. Despite a somewhat chaotic picture, recent years have seen a focus on activities labeled under one or more of the following headlines:

- leanness,
- flexibility,
- total quality,
- cost management,
- information management,
- operations management,
- supply-chain management,
- business-process reengineering.

There is one thing missing from the above however. Representing a concept that is affecting hardware, software, and people and transforming business practices and processes to the extent that it may almost be thought of as a paradigmatic shift, the keyword missing is *integration*. From all the above perspectives, technology innovation, particularly in information and communications technologies, has created both needs for and possibilities of far-reaching integration in many different areas of business, on several strategic and operational levels, and of various kinds of information, objects, and processes. So it is not surprising that integration, given the increased complexity, dynamics, and globalization of operations, has become harder to manage and carry out. In other words, although there are vast integration *possibilities*, industry seems to have had less success with realizing the full potential of its integration *capabilities*, be it of computer integrated manufacturing systems, enterprise resource planning systems, or discrete-event simulation.

The reasons can be sought after in many areas, including of course technology. However, this thesis argues that problems with integration are not so much related to a lack of technology, as they are to the lack of knowledge of and capability to use that technology and related standards, methods, models, and tools in a structured way and with a holistic view on the systems and processes concerned. In other words, intense use of advanced technology is not a unique trait of certain individual companies in the industry: a majority of companies that want to stay competitive already use such technology to a great extent (and to their best abilities). Porter (1999) puts it like this:

> Productivity is really independent of the type of industry or sector. There was a view some years ago that you had to be in certain industries to be productive – that idea has hopefully been discredited for there is no industry that cannot produce higher value products, there is no industry that cannot exploit high technology. All industries today are high tech, all industries use information technology, new materials, new kinds of technology to dramatically improve the way they do things.

The missing parts here are decision support and methodological support. When companies decide to go from lower to higher levels of integration, they are faced with a number of questions: How do we change our practices? How do we reorganize our processes? How do we spread awareness of the need for integration throughout the organization? How do we facilitate communication? What kind of informational infrastructure do we need? What about hardware and software? How do we organize our development teams? How do we ensure the quality and reliability of input and output data? Who has the responsibility for supplying that data? Do we involve customers and suppliers? And if so, how? Do we have all the necessary competence in-house or do we need consultants? Should we have this competence ourselves? What are the cost-benefit trade-offs when going from lower to higher levels of integration? And, in the end, *how much* integration do we really need?

It should be obvious that to answer such questions, companies must follow *structured approaches*. Today, however, they do not. The need for such approaches is no less true for the application areas of discrete-event simulation in the manufacturing industry, which as will be showed later on, are just as global, complex, dynamic and subject to change and uncertainty as the manufacturing industry itself. In support of this view, several analysts agree that today DES is used on a *one-shot* basis only, troubleshooting specific problems such as bottlenecks, usually in late stages of the manufacturing system lifecycle, or as a *stand-alone* tool, both of which reflects a low level of integration.

Just as a *simulation methodology* is the decision support needed when developing manufacturing systems, so there is a need for decision support when integrating simulation into the development process, or in other words, an *integration methodology*.

In final support of the need for structured approaches, it also has to be recognized that DES is no *panacea*; no universal cure for all ills or difficulties facing a company (any serious simulation specialist will point this out just to speak in the next sentence as if it was). Rather, DES is but one of many technologies that management is faced with in their strategic and operational decisions. They need simple yet powerful methodologies that can support and guide their decisions on how to integrate this particular technology into their business processes.

Regarding integration of discrete-event simulation into the manufacturing system development process, we can therefore say that the challenge now is to move from theory to practice and from technology to methodology. This is the focus of this thesis. One of the concepts that seem to share this view is enterprise integration (Kosanke et al., 1998), the context in which the contributions of thesis should be seen in.

1.5 Industrial and Academic Relevance

At least one thing is reassuring in the uncertain world of manufacturing and simulation – we are not alone. In other words, the herein presented research area has considerable support in both the scientific and industrial communities.

Starting with local support, part of this research has been funded by *The Swedish Foundation for Strategic Research (SSF)* and carried out within the Programme for Production Engineering Education and Research (PROPER), a long-term national research effort involving all the major Swedish technical universities and aiming to achieve excellence in areas of strategic importance for Sweden. One of these areas is “Methods, Models, and Tools for Analysis and Development of Manufacturing Systems”, where it is stated that (Bolmsjö, 1999):

> For many years, specific research projects and programs have been focused on modeling the different processes within a manufacturing system. However, there is a lack of knowledge in the field of integrating such research work together with a holistic view on the manufacturing systems development process and how this can be modeled and implemented in simulation tools to represent the system as a virtual model. For this work, a scientific approach that focuses on methods, models and tools is needed which includes interdisciplinary teams…

The remainder of this research was funded by *The Swedish National Board for Industrial and Technical Development (NUTEK)* and carried out under the national research program “Information Technology in the Manufacturing Industry” and the sub-program Coordinated and Structured Development of Manufacturing Systems (CONSENSUS). Here, this research was performed as part of the Visualization, Simulation, Off-line Programming, and Production (VSOP) project where the overall objective has been to integrate market, design and production activities by supporting and increasing the efficiency of the exchange and sharing of information through the use of advanced simulation tools (Bolmsjö and Gustafsson, 1998).

Both the above projects are supported by and involve a large number of firms from the Swedish manufacturing industry.

Remaining on home ground, *Swedish Technology Foresight* is a national project aimed at finding the best ways of promoting long-term interplay between technical, economic and social processes. As part of Swedish Technology Foresight, 130 representatives of the academic, business and research communities have identified Sweden’s weaknesses and strengths in various fields of technology. In eight areas, panelists have looked ahead toward the year 2020. Technology Foresight does not predict what *will* happen, but what *may* happen, and its ambition has not been to plan the future but to plan for the future. One of the eight panels is “Production Systems”, which states that (Teknisk Framsyn, 2000, p. 1) [2]:

> Information technology and globalization will bring forward a radical change of traditional manufacturing systems. These must develop in a way that will adapt for fast changes and be able to take advantage of the increased mobility of and access to information. The competence must develop so that these systems manage the transformation to new products and new manufacturing technologies with significantly increased presence of IT, software, and services. The new information economy will provide a large potential market and increased competition…Simulation and modeling provides opportunities for new working methods in development and in education…Customers and suppliers will in the future be able

> to jointly develop and test products from idea to manufacturing in a virtual world…Results [from these activities] will lead to higher quality and shorter lead times in all stages of development, and will reduce development costs and the need for physical models and testing of prototypes, as well as facilitate education of personnel and ramp-up of production lines.

It should be evident from the above that simulation is seen as strategically important for Swedish industry, in both academia and industry.

Moreover, modeling and simulation (M&S) has been identified as a crucial component in major recent work done on future manufacturing across the world, including governmental and industrial organizations in the U.S., Europe and Japan. Most recently this has included the Integrated Manufacturing Technology Roadmapping Initiative (IMTR) (Integrated Manufacturing Technology Roadmapping Initiative, www), a comprehensive U.S. initiative that builds on results from the Next-Generation Manufacturing (NGM) project (Intelligent Manufacturing Systems, www). Driven by the previously described challenges facing manufacturers in the 21st century, IMTR's overall vision is illustrated in Figure 1.1. Based on this vision, IMTR has identified needed research efforts and synthesized them into four *technology roadmaps*. These roadmaps define strategic directions for future research in manufacturing in terms of six *grand challenges* facing all manufacturers. These grand challenges are then broken down through all the major functional elements of the manufacturing enterprise, suggesting actions that need to be taken in order to meet the overriding challenges within each roadmap (for more details on these challenges, see Integrated Manufacturing Technology Roadmapping Initiative, 1999). The four roadmaps represent closely interrelated areas and are defined as:

- **Information Systems for Manufacturing Enterprises**: a robust communications infrastructure and "intelligent" applications will deliver the right information to the right place, at the right time, and in the right format.
- **Modeling & Simulation**: this will be *the* way products and processes are designed and integrated, providing the foundation for fast, low-cost development, efficient production, and responsive enterprise management.
- **Manufacturing Processes and Equipment**: future processes and operations will leverage a deep understanding of underlying science to radically enhance performance, quality, flexibility, adaptability, and control in response to changing business requirements.
- **Technologies for Enterprise Integration**: all manufacturing enterprise operations will be seamlessly interconnected, radically enhancing efficiency and responsiveness while enabling different partners to quickly "plug together" to pursue new opportunities.

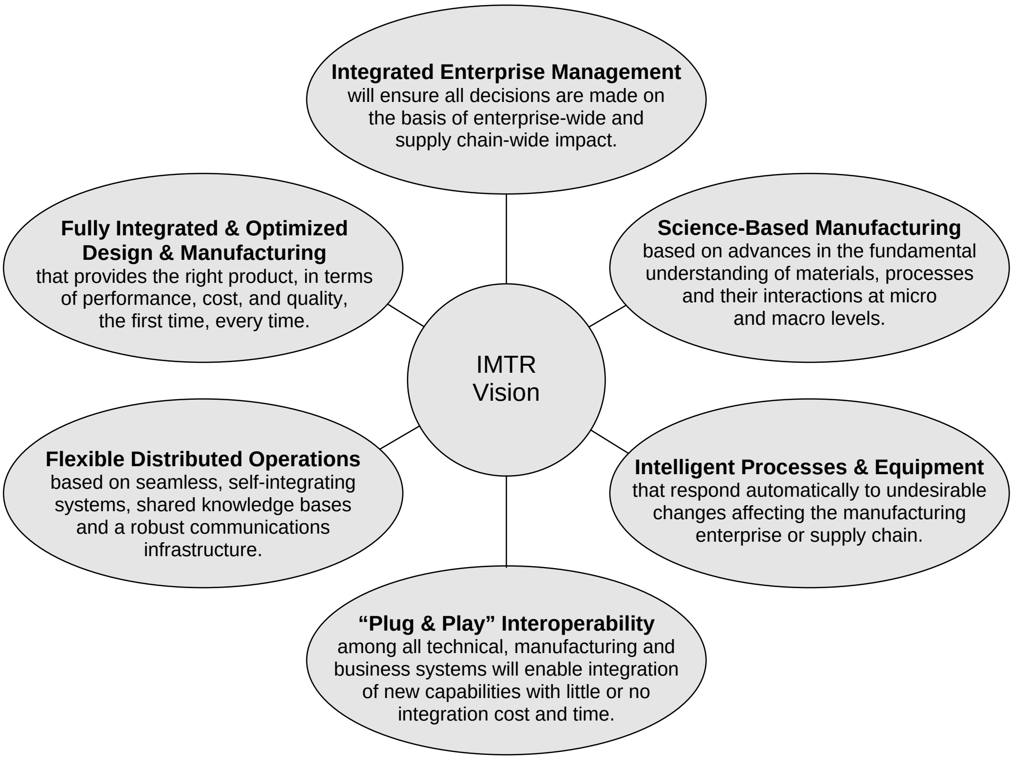


Figure 1.1 *IMTR's vision for manufacturing success in the 21st century. Adapted from Integrated Manufacturing Technology Roadmapping Initiative (1999, Figure 1).*

Regarding the Modeling & Simulation roadmap, NGM envisions the following:

> ...modeling and simulation (M&S) will reflect a new way of doing business rather than a supporting technology. It will make virtual production a reality. All production decisions will be made on the basis of modeling and simulation methods, rather than on build-and-test methods. M&S tools will move from being the domain of the technologist, to being a tool for all involved in the product realization, production and business processes.

In summary, it can be concluded that the industrial and academic relevance of this thesis is high, both from a Swedish and from an international perspective.

Notes for Chapter 1

[1] This refers to the *Paleolithic* period, also known as *Old Stone Age*. It is the earliest period of human development and the longest phase of mankind's history, beginning about 2 million years ago and ending in various places between 40,000 and 10,000 years ago. The most notable feature of the Paleolithic period was the evolution of the human species from an apelike creature to *Homo sapiens*. This development was slow and continued through the three successive divisions of the period, the Lower, Middle, and Upper Paleolithic. The most abundant remains of Paleolithic cultures are a variety of stone tools whose distinct characteristics provide the basis for a system of classification containing several toolmaking traditions or industries (Bartleby.com, www).

[2] The text was translated from Swedish by this author. The original text is provided here for reference:

Informationstekniken och globaliseringen kommer att tvinga fram en genomgripande utveckling av de traditionella produktionssystemen. De måste utvecklas så att de klarar snabba förändringar och kan utnyttja den ökade mobiliteten och tillgången till information. Kompetensen måste utvecklas så att systemen klarar omställningen till nya produkter och ny produktionsteknik med ett kraftigt ökat inslag av IT, programvara och tjänster. Den nya informationsekonomin ger en stor potentiell marknad och ökad konkurrens…

Simulering och modellering ger möjligheter till nya arbetssätt i utvecklingsarbete och i utbildning…

Kund och leverantör kommer i framtiden att tillsammans i en virtuell värld kunna utforma och prova produkter från idé till tillverkning…

Resultat från "tillverkning" och "prov" av produkterna i den virtuella världen ger ökad kvalitet och kortare ledtider vid utveckling och produktframtagning, reducerar utvecklingskostnader, minskar behovet av fysiska modeller och prov av prototyper, samt underlättar utbildning av personal och intrimning av produktionslinjer.

2

Research Objectives

If we knew what it was we were doing,
it would not be called research, would it?

– Albert Einstein

As a starting point for this research, the industrial and academic relevance of discrete-event simulation applied to manufacturing systems was explored based on results from industrial case studies and reviews of literature. A first wondering then emerged:

Have manufacturing enterprises realized the full potential of DES?

The answer to this was a definite *no.* Some firms had come close, for sure, but the industry as a whole had not. The next wondering was then obvious:

How can manufacturing enterprises realize the full potential of DES?

A basic awareness was formed, at an early stage, that the full potential of DES could only be realized through *integration.* In other words, it was realized that there are several benefits to integrating simulation into the MSD process, but that the full potential of these benefits had not been realized.

The next logical step was therefore to look at the different aspects of integration and the problems associated with such integration. Hence, the primary objective of the research presented here has been to answer the questions implied by the above:

- What do we mean by integration of simulation into MSD?
- What are the benefits of integrating simulation into MSD?
- What are the problems?

The overall research question guiding the remainder of the work was then stated as follows:

> *How can manufacturing companies fully integrate discrete-event simulation into their manufacturing system development process?*

This research question lead to the following ultimate objective of this thesis:

> *To suggest a methodological framework for integrating discrete-event simulation (DES) into manufacturing system development (MSD).*

3

Scope and Limitations

The scope of this thesis is limited to production and operations management issues related to discrete-event simulation used for development and analysis of manufacturing systems, more specifically modeling, simulation, and visualization of material flows in production and logistics. The scope is further limited to discrete parts manufacturing.

Moreover, since the potential of simulation increases with the dynamics and complexity of operations, it is assumed that complex products and production systems are involved in some way. However, while these conditions may apply particularly well to certain industries, such as automotive and aerospace, complexity and dynamics is certainly not limited to these industrial sectors. Consequently, the fundamental ideas of this thesis do not limit themselves to any specific type of industry, provided that the above limitations apply.

Furthermore, this thesis does not address the development of *simulation methodologies* per se, i.e. the phases and steps necessary to conduct a simulation study, but rather *simulation integration* methodologies, an important distinction that will be explained later on.

Neither does this thesis look explicitly into what is known as concurrent engineering, or integration of product and process, although these issues certainly constitute important interfaces to the research area presented here.

Even with the above limitations, it should be noted that developing or even outlining a methodology that covers all aspects and phases of manufacturing system development is an enormously complex task. If the result is to be useful and relevant, several different research areas must be integrated, something requires the participation of a large number of researchers and industry practitioners, over a long period of time. For obvious reasons this has not been possible.

Rather, this thesis is but one piece of the giant puzzle that is manufacturing research. As the Integrated Manufacturing Technology Roadmapping Initiative (p. 2) observes:

> No one organization or industry has the resources or breadth of focus needed to develop the wide spectrum of technologies needed for future manufacturing success.

Still, an important purpose of this thesis is that it aims at providing not in-depth research on all these aspects but rather the framework for a holistic view on one of these technologies, namely issues related to the integration of discrete-event simulation into manufacturing system development.

4

Research Methodology

Science is what you know, philosophy is what you don't know.

– Bertrand Russell

If one claims to be in the business of doing research, any kind of research, the theory on which that research rests obviously becomes very relevant. As it turns out, however, there is not one single theory, but rather a set of theories that have evolved over time. Nor are the theories strictly just theories; as the name of the next section suggests, *theory* of science may also be called *philosophy* of science. In other words, there is no universal right or wrong choice of research approach; it is always possible to argue for or against a particular theory of science based on ones own subjective opinions. The question of what theory of science ones work should be based on thus becomes not only a matter of technicality, but a philosophically rooted decision based on individual believes and ideals.

This chapter will outline some major philosophical aspects of science, the author's view on these, and what this implies for the research presented in this thesis.[3]

4.1 Philosophy of Science

Philosophy of science deals with how scientific knowledge is and should be created and tried, as well as its role in society. The subject as such was introduced in the early 20th century when philosophical questions such as “what is knowledge?” and “what are our values based on?” were transferred to the field of science. Early on, the subject also looked at the relationship between science and society – should science be independent and governed by its own values, or should it be guided by the needs of society?

In recent years, much of the discussion in philosophy of science has centered on whether science is a rational activity, governed by methods and rules that objectively try the knowledge obtained, or if science is controlled by what the research community and its inherent power structure finds acceptable, as argued by the research sociologists (Wallén, 1996).

In fact, a definition of science used in sociology is that *science is what scientists do* (Wallén, 1996). This definition makes an important point, namely that the research community can be seen as a closed society, where only the scientists themselves have the competence to decide what good science is, and where all scientific knowledge is evaluated within the group itself (Wallén, 1996).

But what is science really? It seems as if this question still provokes debate, as evident from public reaction to the practice of alternative medicine and the “New Age” movement, among other things. Dictionaries give several alternatives:

> **Definition 4.1** SCIENCE
>
> The observation, identification, description, experimental investigation, and theoretical explanation of phenomena (The American Heritage, 2000); Any domain of knowledge accumulated by systematic study and organized by general principles (Princeton University, 1997); Ascertained truth of facts (MICRA, Inc., 1998).

The key words here seem to be *systematic*, *observation*, *facts*, *knowledge*, and *truth*. The word itself stems from the Latin *scientia*, derived from the word *scire*, meaning “to know”. But how do we know? Can we know anything for sure? And can we prove that we know what we know? These and similar questions date back to Greece at around 600 BC, where philosophers first became aware of the “problem of knowledge”. As these ancient Greeks became the first to explore their world with the help of logic and observation, and even religion in the quest for provable knowledge, they also became the Western world’s first philosophers of science. However, even then not all philosophers agreed that knowledge could be proved to exist. The next section will explore this issue further. First, however, we will look a little closer at different notions of knowledge, as it seems to be such a central concept in the philosophy of science.

Here, there are two basic aspects that have been discussed among philosophers for centuries: *epistemology* and *ontology*. Epistemology is the branch of philosophy that studies the *nature of knowledge*[4], whereas ontology is the metaphysical study of the *nature of reality*. In older philosophy, two main ontological schools of thought were *realism* and *idealism*, which today exist in a large number of varieties, see for instance Wallén (1996, pp. 12-16). As one would expect, neither of these branches can be clearly separated. George Berkely's famous *esse est percipi* – to be is to be perceived, and the even more famous statement by Reneé Descartes, *cogito ergo sum* – I think, therefore I am – deal with questions of both epistemology and ontology.

Hacking (1983) makes a simpler distinction, arguing that since the 1960s the two main issues to obsess philosophers of science have been *rationality* and *realism*. Rationality includes what has traditionally been called logic and epistemology, while realism, also discussed under the heading of *truth*, is a branch of ontology as mentioned previously.

Scientific rationality is thus related to reason, evidence, and method, asking questions such as: What do we really know? What is evidence? What should we believe? It is the subject of the next section.

Scientific realism says that what we observe really exists – the entities, states, and processes described by correct theories are all real, regardless of whether they are industrial machines or black holes (Hacking, 1983). Science thus describes not just the observable world but also the world that lies behind the appearances (Chalmers, 1999). There is also *anti-realism*, which, of course, says the opposite.[5] While this may at first sound like a trivial topic for philosophical contemplation, most philosophers would argue that it is not. Here, the question about theories is whether they are true, or are true-or-false, or are candidates for truth, or aim at the truth. If a theory is believed to be true, does it mean that the entities of the theory exist? Exemplifying with Einstein, who in 1905 explained the photoelectric effect with a theory of photons, it can be said that "the debate between realist and anti-realist is whether the adequacy of Einstein's theory of the photon does require that photons be real (Hacking, 1983, p. 54). Also, the answers to the previously stated questions are not mutually exclusive. As Hacking notes, Bertrand Russell was a realist about theories but an anti-realist about entities. Here, the anti-realist school of thought known as *instrumentalism* denies that theories are either true or false – they are only instruments; intellectual tools for predicting phenomena or rules for working out what will happen in particular cases (Hacking, 1983). As an example of different theories being used to explain the same phenomena, one can consider light. Here, two different theories – particle theory and wave theory – are used to explain (among other things) the photo-electric effect and interference respectively. Another example: several centuries ago the Church accepted Galileo's heliocentric world view as an instrument for calculations, but not as a description of reality (Wallén, 1996).

However, as interesting as it is, the aim of this philosophical discussion falls slightly outside the scope of this thesis, since it studies (what this author believes to be) observable and real entities, states, and processes.

Also, if we look at another distinction in science, namely what Hacking refers to as *representation* – the building of theories that try to say how the world is – and *intervention* – experiment and subsequent technology that change the world, we find that the question of realism applies differently. As Hacking (p. 31) puts it:

> I suspect there can be no final argument for or against realism at the level of representation. When we turn from representation to intervention, [...] anti-realism has less of a grip.

While the research presented here, to some extent attempts to do both – represent and intervene – it can certainly be said to focus on the latter. Next, we move on to the subject of scientific rationality, looking at both epistemological and ontological issues.

4.2 Is Knowledge Possible?

One of the must fundamental questions in the philosophy of science has been if attaining knowledge is possible at all? Among those who doubted or even denied this were a group of philosophers belonging to the ancient school of Pyrrho of Elis, at around 300 BC. This school stressed the uncertainty of our beliefs in order to oppose dogmatism, and its followers were known as the skeptics, hence their school of thought is referred to as *skepticism*. Their doctrine thus stated that absolute knowledge is impossible, either in a particular domain or in general (The American Heritage, 2000; Holmberg, 1987). Even among the skeptics, however, there were philosophers who did not approve of seeing knowledge as a *dichotomy*,[6] where either absolute knowledge or no knowledge was possible, and thus realized that our actions had to rely on more or less probable assumptions of the world.

More certain of the possibility of attaining knowledge are two major philosophical schools of thought – *rationalism* and *empiricism* – although they take rather opposite sides as to what the *source* of knowledge is.

Rationalism is the theory that the exercise of *reason*, rather than experience, authority, or spiritual revelation, provides the primary basis for knowledge (The American Heritage, 2000). According to rationalists, the ability to reason is decided upon birth, and based on this, knowledge is created according to our impressions.

Empiricism, on the other hand, attributes the origin of all our knowledge to *experience*. According to the British empiricists of the seventeenth and eighteenth centuries, knowledge is thus derived not from reasoning but from perceptions of the world. In fact, even some modern dictionaries define knowledge as *understanding gained through experience* (The American Heritage, 2000). Two terms are used to distinguish these views – *a priori* and *a posteriori*. *A priori* is used to identify the type of knowledge which is obtained independently of experience, whereas *a posteriori* means knowledge gained through the senses and experience (Internet Encyclopedia of Philosophy, www).

Positivism, introduced by Auguste Comte in the 19th century, shared the view of the empiricists that knowledge was based on experience, although the positivists took a broader and less psychologically oriented view of what knowledge was.

These two schools further agreed that scientific knowledge is based on *facts*, established by observation and experiment (Chalmers, 1999). In fact, it can be argued that modern science was not born until the early 17th century, when “the strategy of taking the facts of observation seriously as the basis for science was first seriously adopted” (Chalmers, 1999, p. 2). Prior to the 17th century, knowledge was based largely on *authority*, in Europe especially on that of the philosopher Aristotle and on that of the Bible.

When acknowledging that science is derived from the facts, there are two fundamental questions to answer:

- What is the nature of these facts and how do scientists have access to them?

- How is scientific knowledge derived from these facts?

According to Chalmers, the nature of the facts, as seen from a philosophical point of view, is subject to discussion. In brief, this discussion centers on the fact that facts are not sufficiently straightforward to sustain the view that science is special because it is derived from them.[7] Here, we will be content with the observation that what is needed in science is not just facts, but *relevant* facts.

We thus find that all these schools, *skepticism*, *rationalism*, *empiricism*, and *positivism* represent the view that attaining knowledge is possible, but that they differ in their view on *how* this knowledge is gained.

Another difference relates to what Holmberg (1987) refers to as *everyday knowledge* and *scientific knowledge*. Although there are similarities, such as the quest for knowledge, the principal difference between these two lies in *how* knowledge is created. The next section will take a closer look at this process, to answer the second question posed above: how is scientific knowledge created?

4.3 If so, then how is it Created?

Scientific knowledge is derived by applying methods and principles of science, with the purpose of helping us to create *more reliable knowledge* than what would have been the result of simply "living and learning" (Holmberg, 1987). Scientific method thus aims at providing the scientist with:

- control of how our experience and values affect our knowledge creation,
- information of the phenomena we want to gain knowledge of.

In addition, the information must be characterized by:

- the right kind,
- the right amount, and
- the right quality.

Another important difference to everyday knowledge is that scientific knowledge is attained through a *systematic* process.

Scientific work, however, cannot be conducted merely by systematically applying scientific methods based on facts – it is also a creative process, which requires imagination and the ability to think different.

According to Christensen (2001), our understanding is built through a stepwise process, as shown in Figure 4.1. This process starts by observing real world phenomena. In doing so, Christensen notes, the key to doing *breakthrough research* lies in following two rules:

- observe through the lenses of other disciplines, and
- observe the phenomena within the phenomena.

According to the observations made, the scientist then attempts to *classify* these phenomena. This process may be based on a *hypothesis* – a tentative explanation for an observation, phenomenon, or scientific problem that can be tested by further investigation (The American Heritage, 2000). The aim of testing a hypothesis is thus to see how well it corresponds with reality, and the result is either a verification or a falsification of the hypothesis. Here, some argue that a scientific hypothesis must always be based on established theories, while other prefer to judge the quality of a hypothesis by how reasonable it appears. In addition, there are other criteria by which the quality of the hypothesis can be judged, such as simplicity and range[8] (Holmberg, 1987).

In the next step, the classification of phenomena leads to the formulation of a *theory* – a scheme of the relations subsisting between the parts of a systematic whole (MICRA, Inc., 1998).[9] The relationship between theory and phenomena

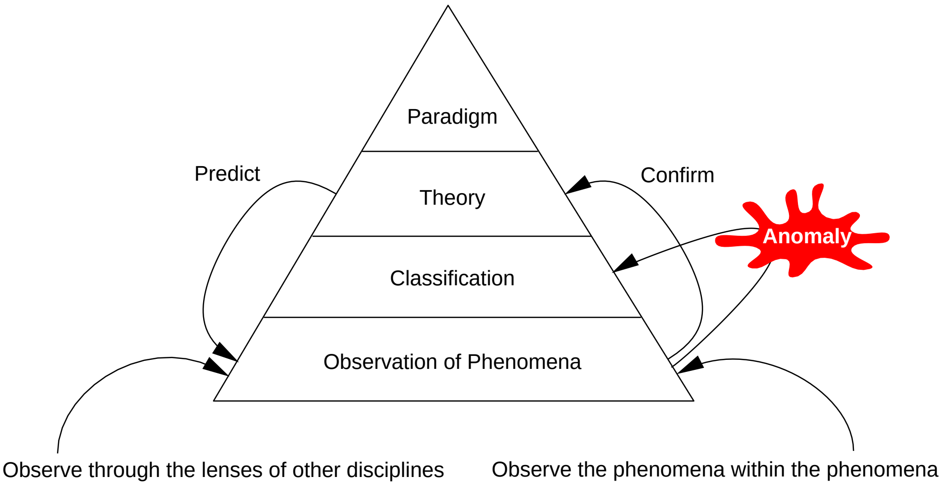


Figure 4.1 *How understanding is built. Adapted from Christensen (2001).*

is strict – to be valid, the theory must predict the phenomena, and the phenomena must confirm the theory. In a sense, there is no sharp distinction between a confirmed hypothesis and a theory. A theory, however, usually covers more than a hypothesis – it can be seen as a system of hypotheses, assumptions, and axioms, including information on how these are related to each other (Holmberg, 1987). In linking theory and reality, it is common in natural sciences to employ a *model*, a concept further explained in Section 7.2.2.

The last step in the process of scientific knowledge creation is realized when a certain amount of knowledge has been created, i.e. when there exists a theoretical framework on which a *paradigm*[10] can be formed, a concept further explored in Section 4.3.4.

Now that we have a basic understanding of how scientific knowledge is created, it is in place to look in more detail at how this process can be classified.

4.3.1 A Basic Classification of Research

Our aims and intentions of doing research may vary greatly. Conversely, there are different ways to classify scientific research, based largely on the following three questions:

1. How is the purpose of scientific research chosen?
2. What are the aims of this research?
3. Why is this research being done?

The first classification relates to the question: *How* is the purpose of scientific work chosen? Does the scientist decide for herself on what topic to do research or does someone else? Does she set her own limitations or are they given by an individual or organization outside the research community? These questions lead to a distinction between *intra-* and *extra-disciplinary* control (Holmberg, 1987).[11] If the research involves the participation of people, they may guide the research by the information they give about themselves, what they do, or how they react in certain situations. This constitutes a special form of extra-disciplinary research, known as *participatory research*.

The second classification centers on the question: *What* are the aims of this research? If the objective is to fill gaps in our scientific knowledge, it is known as *basic research*. Here, the scientific process is not controlled by any immediate benefits of the research. On the contrary, the purpose may just be to satisfy our scientific curiosity (Holmberg, 1987). Hence the knowledge gained through basic research may remain unused for long periods of time, if indeed it ever gets used.

This contrasts with *applied research*, where the purpose is clearly stated as a specific application. Applied research is commonly found in research & development (R&D) departments of major corporations, where some form of theoretical knowledge is required in product or process development. However, it may also apply to cases when organizations are analyzed with the purpose of having the researcher recommend suggestions for improvements (Holmberg, 1987).

There are several terms which are more or less synonymous with basic and applied research, particularly *conclusion-oriented research* and *decision-oriented research*. Conclusion-oriented research relates to basic research, and the conclusions made on the basis of hypotheses and theories. Decision-oriented research relates to applied research and the decisions that need to be made on the basis of the achieved results and progress made.

The above described how the scientist sets her research objectives, and what these objectives may be. The most important question, however, is: *Why* is this research being done? This question strongly relates to our perspective on science. As Tebelius (1987) notes, different perspectives can cover larger or smaller proportions of the real world, as well provide different qualitative knowledge of this reality. In this context, a distinction is made between *assimilation* and *accommodation*, as proposed by the philosopher Piaget. Assimilation means a stepwise increase in knowledge by adding to what is already known, whereas accommodation gives existing knowledge new meaning through a new perspective. This perspective that a scientist chooses is captured in the concept of *paradigms*, the subject of Section 4.3.4.

First, however, the next section will explore in more detail the creation of scientific knowledge by describing two central concepts – induction and deduction.

4.3.2 Induction and Deduction

The previous two sections outlined the general framework in which scientific work is conducted. Given that the scientist stays within this framework, and assuming that appropriate facts *can* be established in science, there are basically two directions to follow – those of *deduction* and *induction*. Both these terms denote ways of drawing conclusions, but they can be seen as guiding the scientist in opposite directions of the same path.

Deduction is the drawing of a conclusion by reasoning from the general to the specific (The American Heritage, 2000). As an example, Albert Einstein stated:

> The grand aim of all science is to cover the greatest number of empirical facts by logical deduction from the smallest number of hypotheses or axioms.[12]

Deduction is well rooted in theories, and is commonly represented as a scientific method in various disciplines and professions, such as psychology and criminology. Here, the English 19th century detective Sherlock Holmes provides us with a good example of deductive logical reasoning. By using general theories to explain particular details and observations, many of which were overlooked by Scotland Yard, Holmes was able to solve a large number of seemingly mysterious crimes.

Induction, on the other hand, is the process of reasoning from a part to a whole, thereby deriving general principles from particular facts or instances (MICRA, Inc., 1998; The American Heritage, 2000). According to the inductivists, it is the process of thorough inductive reasoning that may eventually lead to the formulation of theories. Indeed, Sherlock Holmes was no stranger to inductive methods either. By studying a large number of different kinds of tobacco, Holmes derived general principles on the characteristics of their ashes from which he later on was able to deduce the particular brand of cigarettes that had been smoked.

As we see, induction and deduction are not mutually exclusive. As Holmberg (1987) notes, induction and deduction are characterized by *proof* and *discovery*, both of which are fundamental to good research.

Whether inductive or deductive by character, all scientific work is born out of questions (Holmberg, 1987). When the scientist attempts to proof something by deductive reasoning, she answers these questions herself by formulating her assumptions of the real world in a hypothesis. The validity of the hypothesis is then tested against reality, whereby the answer can be accepted or rejected. This process of testing a hypothesis is stipulated within scientific methodology, and whether or not it will be regarded as *scientific* depends on how well the scientist conforms to the rules of scientific method. Deduction thus implies a focus on *method*.

On the other hand, in the process of discovery by inductive reasoning, producing an answer is the ultimate objective. Although the basic principles of scientific work must still be respected, the focus is much less on method than on the patterns and relations found in the gathered information.

Seeing the distinction of deduction and induction in a temporal sense alone, however, is not enough. As Chalmers (1999) states, no matter what comes first, the facts or the theory, the question is to what extent the theory rests upon the facts. That is, given the facts, can the theory be proven as a logical consequence of them? We thus find that there is a *logical* aspect to the manner in which science is derived from the facts, just as Einstein implied in the previous quote.

Here, the reader is referred to the set of examples of logical deduction given by Chalmers (1999, chapter 4). As those examples show, an argument can be based on false statements and still be perfectly valid. How is this possible? The point made by Chalmers is that logical deduction alone cannot establish the truth of factual statements. All that logic can offer is that *if* the premises are true and the argument is valid *then* the conclusion must be true.

We thus find that logic alone is not a source of new truths on which to build scientific knowledge because logic alone cannot decide if premises are true. As a consequence, in many cases of real world observations there can be no *logical* guarantee that the law or theory based on the observed facts holds true. As an example, it can be shown from a large number of experiments that metals expand when heated. If every experiment is considered a premise in the form of ”metal x_i expands when heated”, and the number of experiments is n, the conclusion that “all metals expand when heated” is not logically valid, regardless of the size of n. Such arguments which proceed from a finite number of specific facts to a general conclusion are therefore known as *inductive* arguments, to distinguish them from logically based *deductive* arguments. Inductive arguments thus go beyond what is contained in the premises. Obviously, general scientific laws invariably extend beyond the limited number of observations that can be made to support them, and thus can never be proven as logically deduced from the facts.

Against this limitation, of course, stands the strength of logic – if we can be sure that our premises are true, then we can be equally sure that everything we logically derive from them is also true. If we cannot be sure that our premises are true, however, but still want to claim that scientific knowledge is to be understood as derived from the facts, then “derived” must be understood in an inductive sense, that is, that our knowledge is based on inductive arguments.

What are the characteristics of a good inductive argument then? This question becomes one of fundamental importance if we are interested in warranting the generalizations that we make based on observable facts, something that is a frequent concern in simulation studies.

According to Chalmers (1999), three conditions must be satisfied:

1. the number of observations must be large,
2. the observations must be repeated under a wide variety of conditions, and
3. no accepted observation statement should conflict with the derived law.

Although the choice of these conditions is easily justified, they all impose problems. With the first condition, one problem is the vagueness of "large" – does it mean a hundred, a thousand, or more observations? Another problem with meeting this condition arises when the demand for a large number of observations can be seen as inappropriate, or unethical.

The second condition has serious problems too. What is a sufficient variation of conditions? The answer to this question is obviously not straightforward, since for most observations the conditions can be varied indefinitely, particularly when something as complex as a manufacturing system is studied. To solve this problem, we must draw on our available knowledge. However, this contradicts with the demand that all knowledge be induced from *facts*, and not from experience.

Even the third condition poses problems, since little scientific progress would be made if there was a strictly enforced demand that there be no exceptions and no conflict with existing observations.

As Chalmers argues, there are further problems. Scientific knowledge of the unobservable world can never be established by the kind of inductive reasoning discussed here, since generalizations from facts about the observable world can yield only generalizations about the observable world. Another problem relates to the inherent inexactness in all observations, making it difficult to justify exact theories and models on the basis of inexact evidence. A final and fundamental problem deals with the justification of induction itself. Chalmers notes that there are only two options on which to justify it: logic or experience. As the above showed, logic will not do since inductive inferences are not the same as logical (or deductive) inferences. The only option left is then to justify it by an appeal to experience. After all, induction has been observed to work on a large number of occasions and under a wide variety of conditions. However, this argument falls on the same kind of premises as the expansion of heated metals example mentioned previously.

Chalmers discusses attempts to avoid this problem, as well as how new problems result from this. He concludes with the following (Chalmers, 1999, p. 53):

> …what constitutes a valid deductive argument can be specified with a high degree of precision, whereas what constitutes a good inductive argument has not been made clear at all.

The reader, who probably agrees, is referred to Chalmers for a more thorough discussion on this topic.

4.3.3 Verification and Falsification

In the 1920s, positivism reemerged as a major school of thought in the Western world. Originating in Vienna, it became known there as *logical positivism*. It attempted to formalize the positivism introduced by Auguste Comte by paying close attention to the logical form of relationship between scientific knowledge and the facts. The main difference to Comte's positivism was that the demand for verification had been eased. It was acknowledged that a statement cannot always be proved to be true as all empiric knowledge is uncertain and may contain errors. However, the logical positivists believed that by focused study on the objectively observable, such as measurable physical objects or human behavior, it was possible to estimate the probability that a given statement was true.

Karl Popper, who began his philosophical career as part of the Vienna Circle, had become disappointed with the prevailing idea that science is special because it can be derived from the facts. As he saw it, empirical support could easily be claimed for almost any theory, but it was much harder to state under which circumstances it would *not* apply. Thus arguing that any theory could be fitted on the real world if it was just flexible enough, Popper rejected the idea that a theory could ever be proven – it could only be *falsified*.

In 1934, Popper presented these thoughts as a radical new theory. It was both a development and a critique of logical positivism and became known as *falsificationism* (Chalmers, 1999). The process of falsification was to go on continuously through a series of *conjectures* and *refutations*. Theories were thus to be seen as built on conjectures that have to be rigorously and ruthlessly tested by observation and experiment. Theories that fail these tests, that is, are refuted, must be eliminated and replaced by new conjectures. This is how science progresses – by trial and error, by conjectures and refutations – "leaving only the fittest to survive" (Chalmers, 1999). In this sense, all theories are to be seen as provisional (Wallén, 1996). Popper (1969, p. 231) explains this himself:

> We prefer this because we believe that this is the way in which we can learn from our mistakes; and that in finding that our conjecture was false we shall have learnt much about the truth, and shall have got nearer the truth.

However, it can never be said of a theory that it is absolutely true, only that it is more closer to the truth than its predecessors in the sense that it has stood up to tests that falsified those earlier theories – a principle known as *verisimilitude*.

So while other influential philosophers of the time, most notably Rudolf Carnap, argued that meaningful propositions must be *verifiable* in principle, or else they tell nothing about the real world, Popper thought that powerful scientific theories can never be verified – their scope is too broad for that. They can, however, be tested, and possibly shown to be false. In other words, Popper argued that a proposition is only scientific if it is falsifiable (Hacking, 1983). This difference strongly relates to the principles of induction and deduction from the previous chapter. As Hacking (p. 3) explains, "Carnap's verification is from the bottom up: make observations and see how they add up to confirm or verify a more general statement. Popper's falsification is from the top down. First form a theoretical conjecture, and then deduce consequences and test to see if they are true". In fact, as explained by Chalmers (p. 62), Popper's approach, which was captured in Einstein's quote on page 29, draws heavily on logic:

> An hypothesis is falsifiable if there exists a logically possible observation statement or set of observation statements that are inconsistent with it, that is, which, if established as true, would falsify the hypothesis.

As an example, consider the statement "it never rains in Lund". Obviously, this assertion is falsifiable because it can be falsified by observing rain to fall in Lund. Now, if we instead claim that "either it rains or it does not rain in Lund", we find that, apparently, it does not satisfy the requirement stated previously, since no logically possible observation statement could refute it.

Based on such arguments, falsificationists argue that it is only by ruling out a set of logically possible observation statements that a law or theory can be *informative*. Therefore it must be falsifiable. If a statement is unfalsifiable, then the world can have any properties and behave in any way whatsoever, without conflicting with the statement. Such statements tell us nothing about the world (Chalmers, 1999). Ideally, however, a scientific law or theory should give us some information about how the world behaves, thereby ruling out ways in which it could behave but does not.

By the early 1960s, these inductivist and falsificationist accounts of science had become dominant. Soon, however, they were to be challenged in a major way by another philosopher and his concept of *paradigms*. This is the subject of the next section.

4.3.4 The Paradigm

In a scientific context, the concept of paradigm was brought forward by Thomas S. Kuhn in his 1962 book *The Structure of Scientific Revolution*. From Kuhn's point of view, a paradigm can be defined as (Princeton University, 1997):

Definition 4.2 PARADIGM

The generally accepted perspective of a particular discipline at a given time.

Until Kuhn published his work, science had been regarded as a more or less continuous process towards better knowledge of reality, where new perspectives grew out of old ones in a harmonious way. Kuhn opposed this, and argued that research is guided by a set of assumptions, concepts, values, and practices that constitutes a unified and restricted framework to viewing reality for the research community that shares them (The American Heritage, 2000; Tebelius, 1987). He further argued that this works fine as long as the quest for knowledge can be satisfied within the existing framework — a state which Kuhn refers to as *normal science*. However, all paradigms contain unresolved problems – *anomalies* – and when questions can no longer be asked and when problems cannot be solved within that framework, a revolution is on its way. First, the new questions and unresolved problems are tried within new conceptual frameworks, resulting in a period of confusion and *crisis* – a preparadigmatic period. As more scientists join in, a *scientific revolution* occurs. A new paradigm is established, and the view on what constitutes normal science is adjusted accordingly. As an example, the perceived crisis of Newton's classical physics revolutionized physics as we knew it in the early 20th century, and brought about a new paradigm – modern physics.

What really became a matter of controversy, and made Kuhn be seen as "the enemy of science", was his argument that within every paradigm, science becomes *monopolized*. Only what takes place within the paradigm is considered "real" science. This implied that scientists with two different paradigmatic views were incapable of communicating with each other, as the thinking, language, etc. within one paradigm was incompatible with that of another paradigm. Here Kuhn introduced the concept of *incommensurability*, the idea that there is no objective "super-paradigm" that can evaluate all other paradigms. Rivaling paradigms, or paradigms replacing other paradigms can therefore not be objectively compared – they are incommensurable. In other words, paradigms are mutually exclusive ways of seeing the world. Kuhn exemplifies such a major paradigmatic shift with the transition from a geocentric world view to a heliocentric world view, that came about as a result of Galileo's observations in the early 17th century (based, of course, on the theory that Copernicus introduced during the first half of the 16th century).

In summary, we can consider the paradigm as the highest level concept capable of being reasoned about (Page, 1994). It addresses overriding normative issues and questions, such "what is worth doing research on?" and "what is good science?" (Wallén, 1996). The next step below a paradigm is *methodology*. Methodology addresses science's "everyday" issues, such as what rules to use, how to work systematically, how to assure reliability and relevance, how to attain generalizable results, etc. Scientific methodology does not stay the same through the change of paradigms, and different normative systems may thus be in conflict with each other.

The next section is devoted to another philosopher's view on paradigms and scientific methodology – a view completely at odds with Kuhn's.

4.3.5 Research Programs

In the late 1950s, the Hungarian philosopher Imre Lakatos moved to England where he become one of Popper's students. Although Lakatos supported Popper's theories, he came to realize that it had some limitations, see e.g. Chalmers (1999, chapter 7). Carrying on from what Popper and Kuhn had in common, Lakatos looked for a way to capture scientific activities as taking place in a framework, and thereby coined the phrase *research programs* in the 1960s. In a sense, this was Lakatos's alternative to Kuhn's paradigms.

As Lakatos saw it, the main problem with falsification was that it did not give any clear guidance as to which part of a theory that caused the falsification. Rather, this seemed to be left to the individual scientist, something that questioned how science could progress in the coordinated and cohesive way that it it apparently does. Chalmers (p. 137) explains it like this:

> The fact that any part of a complex theoretical maze might be responsible for an apparent falsification poses a serious problem for the falsificationist relying on an unqualified method of conjectures and refutations. For that person, the inability to locate the source of the trouble leads to unmethodical chaos.

In addressing this issue, Lakatos suggested that the theories and principles of science exist at different levels. At the core of science are the fundamental theories and principles, which Lakatos referred to as the *hard core*. The hard core is supplemented by a range of supplementary hypotheses, referred to as the *protective belt*, since its role is to protect the hard core from falsification. Assumptions made as part of this protective belt should be modified in order to improve the match between the predictions of the program and the results of observation and experiment. If, on the other hand, a scientist modifies the hard core, then she has, in effect, opted out of the research program (Chalmers, 1999).

With this view, it is the less fundamental components of a particular science that are to be blamed for any apparent failure. A science is thus to be seen as the development of the *implications* of these fundamental components rather than the whole science itself. When scientists successfully modify these more "peripheral assumptions", they contribute to the development of the same *research program*. The defining characteristic of a research program is thus its hard core.

In contrast to Popper's theories, Lakatos emphasized that a research program must be given a chance to realize its full potential, and when it has been developed to a stage where it is appropriate to subject it to experimental tests, it is *confirmation* rather than falsification that is important. Another important difference relates to Kuhn's incommensurability principle. Lakatos, who was dissatisfied with its implications, sought a standard that lay outside of particular paradigms or research programs, which could be used to identify the sense in which science progresses. Lakatos suggested the notion of progressive and degenerating research programs. Progressive research programs retain their coherence and lead to novel predictions that are confirmed, whereas degenerating programs mark the opposite. Progress, then, involves the replacement of a degenerating program with a progressive one, where the latter is an improvement on the former in the sense that it has been shown to more efficiently predict novel phenomena (Chalmers, 1999).

Chalmers argues that one of the problems with Lakatos's methodology, which according to Lakatos himself should be tested against the history of science, is whether there really are "hard cores" that identify historical research programs.

4.3.6 Methodological Anarchy

As noted in Section 4.3.4, Kuhn's theory of paradigms became subject to much criticism. Perhaps most notably, the philosopher Paul Feyerabend claimed that Kuhn's idea of science was immoral because it lacked freedom. Freedom was needed both from an ethical point of view, and because scientific progress occurs when someone breaks with accepted truths and methodological rules, for which freedom is a prerequisite. Feyerabend thus proposed a "methodological anarchy", manifested in his 1975 book *Against Method: Outline of an Anarchistic Theory of Knowledge*. Feyerabend presents several interesting points on how scientific progress has not conformed to the theories of science proposed by leading philosophers, and denies the existence of "theory-neutral" facts. In brief, Feyerabend's main points can be summarized as follows (Chalmers, 1999, p. 155):

> Given the failure of attempts to capture the special features of scientific knowledge that render it superior to other forms, which failure Feyerabend considered himself to have established, he drew the conclusion that the high status attributed to science in our society, and the superiority it is presumed to have not only over Marxism, say, but over such things as black magic and voodoo, are not justified.

Feyerabend defended his anarchistic account of science on the grounds that it increases the freedom of scientists by removing them from methodological constraints, and gives individuals the freedom to choose between science and other forms of knowledge (Chalmers, 1999). Needless to say, Feyerabend provoked (and still provokes) far more criticism than Kuhn ever did. According to Chalmers, however, there is a sense in which Feyerabend's case against method can be sustained, namely the argument that there exists no universal, ahistorical method of science that contains standards that all sciences should live up to if they are to be worthy of the title "science". This becomes especially true if *future science* is included, since it would be hard to imagine that any scientific method could contain the appropriate standards for judging science that is yet to come. Rather than seeing Feyerabend's case as adding to a methodological dichotomy – universal method or no method at all – Chalmers argues that it actually accommodates a "middle way". This middle way or intermediate view would hold that there are methods and standards in science, but that they can vary from science to science and can, within a science, be changed, and changed for the better.[13]

With this we conclude the exploration of the most fundamental philosophical views on science. Once the scientist has dealt with these, a number of other aspects relating to more practical aspects of research remain to be investigated. The remainder of this section will look at the aspect on which significant parts of this research is based – *case study research*.

4.3.7 Case Study Research

The research presented here relies in part on case studies as a means to gaining more knowledge of the real world. A case study can be defined as (Yin, 1994):

> **Definition 4.3** CASE STUDY
>
> An empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.

However, there are several ways of gathering information and knowledge about different social systems for the purpose of research, and conversely this section will briefly motivate the choice of *case study research*.

According to Yin (1994), other ways of doing social science research include experiments, surveys, histories, and analysis of archival information. The choice of strategy, then, depends upon three conditions:

1. the type of research question,
2. the control an investigator has over actual behavioral events, and
3. the focus on contemporary as opposed to historical phenomena.

The type of research question can be stated as one or several questions from the series of *who*, *what*, *where*, *how*, and *why*. In general, research questions of type *how* or *why* make case studies the preferred alternative.[14] Furthermore, case studies should be preferred when the investigator has little or no control over events, and when the focus is on contemporary phenomena.

Case studies can be further classified as (i) explanatory, (ii) exploratory, and (iii) descriptive. Regardless of the type, however, a number of questions need to be answered before starting:

1. how to define the case being studied,
2. how to determine the relevant data to be collected, and
3. what to do with the data.

The actual case study then has to go about in a specific order. These case study *phases* are:

1. design and preparations,
2. data collection,
3. analysis,
4. reporting.

A number of tests can be made to judge the quality of the research design, i.e. the case study. The most common of these are construct validity, internal and external validity, and reliability (Yin, 1994). How and if these are performed will depend on the type of case study. Data collection in case studies has some aspects in common with data collection in simulation studies, which is described in Section 7.3. However, several aspects differ, such as the preparations that need to be made and to some extent the various forms of data collection available. The reader is referred to Yin (1994) for a good description. As a concluding remark, we turn to Yin (1994) who stresses that "real case studies, unlike case studies used for teaching purposes, must present data rigorously and fairly."

4.4 And what do we do with it?

The previous sections described different perspectives on knowledge, and various means of gaining it. But what do we do with this knowledge once we have it? The answer seems to depend on our aims and intentions of doing research, which was explored in the previous sections. A fundamental reason for doing this research is the feeling that unstructured and reductionist views on simulation are the reasons behind its relatively modest dissemination in industry, and the less than fully realized potential of this technology. The perspective that is needed to overcome this situation, as well as to just study something as complex as a manufacturing system, is the *systems perspective*.

4.4.1 A Systems Perspective

Our world is characterized by diversity, and so many of its phenomena that we choose to study appear unique, complex, and almost incomprehensible. To deal with this situation, man has tried to structure, arrange, order, and classify what he sees – he has tried to systematize the world. This need for systematization became stronger with the increased complexity of technology and organizations that marked the 20th century. As a result, some researchers went further and realized that all systems, no matter how diverse, have some characteristics in common. In the 1960s this led to the development of *systems theory*[15] – an attempt to explain the structure and nature of systems in a scientific way (Wu, 1994). This was partly a critique of positivism, and partly an attempt to summarize the general characteristics of the developments in telecommunications, cybernetics, and operations research that emerged during World War II (Wallén, 1996). As a scientific tradition, systems theory can be placed inbetween hermeneutics and positivism, and as such it can be seen as an attempt to resolve the conflict between some of the more predominant scientific traditions' world views (Wallén, 1996).

But what is a system? One definition is the following (The American Heritage, 1996):

> **Definition 4.4** SYSTEM
>
> A group of interacting, interrelated, or interdependent elements forming a complex whole.

This can be illustrated as in Figure 4.2 on the next page. As we see, a system is determined by its boundary, components, and relationships. Relationships exist on both component and system level. For example, at the same time there can be relations between components within the system and between components in the system and in the system environment, as well as between the system as a whole and another system. Components are also referred to as elements, entities, and objects; the terms will be used alternatingly in this thesis.

Seliger, Viehweger and Wieneke (1987) describe a system by its function, structure, and hierarchy, as shown in Figure 4.3 on the following page. Hitomi (1996) uses the terms structure, transformation, and procedure. Here, function and transformation carry the same meaning, while structure is used in the same way in both cases. Hence, the only additional property is procedure, which is exemplified in Section 6.2.1.

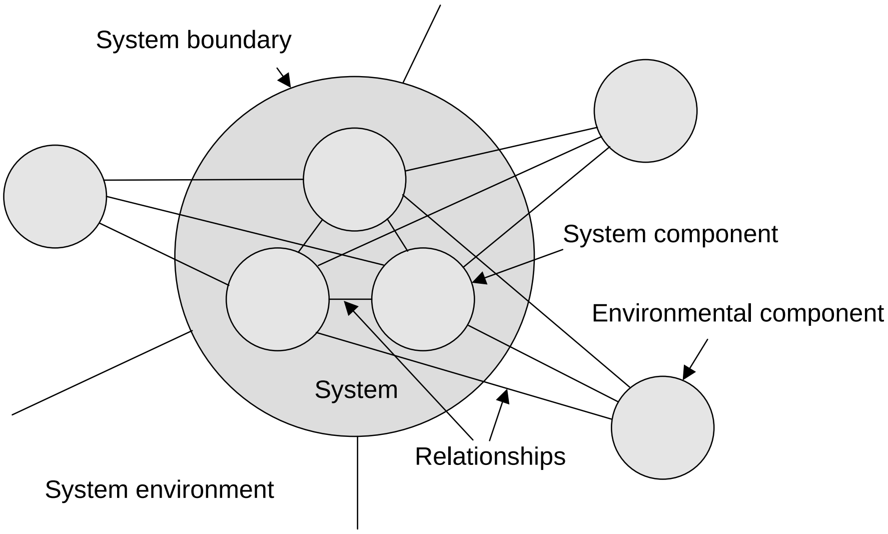


Figure 4.2 *Basic system terminology. Adapted from Bruzelius and Skärvad (1995, p. 61).*

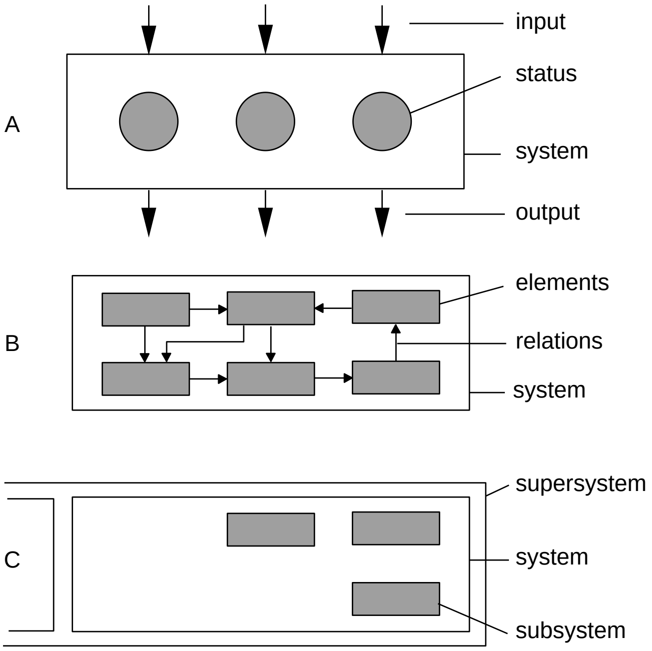


Figure 4.3 *Functional (A), structural (B), and hierarchical (C) aspects of a system. Adapted from Seliger et al. (1987).*

If we combine these two sets of properties, a system can be described with the following properties and terminology (Hitomi, 1996; Seliger et al., 1987):

1. Structure
2. Function
3. Hierarchy
4. Procedure

With this terminology, the structural aspect defines the system by its elements and their relations. The functional aspect describes the system as a black box, where inputs are transformed to outputs, and where this transformation is the function of the system. Hence, function is also referred to as *transformation*. The hierarchical aspect describes the system's relation to other systems, in terms of supersystem, system, and subsystem (Seliger et al., 1987). The procedural aspect refers to the series of chronological, logical stages that the product goes through in the process of transformation (Hitomi, 1996). Procedure is also referred to as *dynamics*, and thus implies a *dynamic* system. A dynamic system combines structural components with activity so that the system state changes over time. This contrasts with a *static* system, which is defined as having structure without activity (Wu, 1994).[16]

As Bruzelius and Skärvad (1995) argue, however, when a particular perspective is taken other aspects may easily be obscured. For example, when seeing a system from a structural point of view, it may be difficult to understand its function. Similarly, for a system seen from its functional aspect, it may be hard to identify the components. One way of dealing with is to work with several system properties simultaneously.

A system can further be separated in terms of its interaction with the environment. An *open* system interacts with its environment, whereas a *closed* system is self-contained under normal conditions (Wu, 1994). Open systems are exposed to uncertainty, constraints, and disturbances.

Regardless of the perspective chosen, a system is to be seen as an organized whole of a number of individual units. The essential sense of the word thereby captures its organic characteristics and implies *synergy effects*, a concept first mentioned by the Chinese philosopher Lao Tze about 500 BC (Hitomi, 1996).

The purpose of a *systems perspective*,[17] then, is to deal with a complex situation by simplifying the problem through a systems theory based perspective. It encourages the analyst to consider activities in their entirety, utilizing system concepts such as *objectives*, *relationships*, and *transformation* (Wu, 1994, p. 29). The systems perspective contrasts with the *functional perspective*, also referred to as the traditional analytical approach, which breaks a problem down into individual functions and attempts to analyze them in their own. The functional perspective assumes that reality is characterized by the whole being the sum of its parts, whereas the systems perspective opposes this by incorporating the notion of synergistic effects.

These two approaches – the traditional and the systems perspective – are also referred to as *reductionism* and *holism*, respectively. From the latter we have become familiar with the concept of a *holistic approach*, which basically has the same meaning as systems perspective.

More recently, the *actor's view* which emphasizes values and actions has emerged. It is similar to the analytical view, in that the totality is understood from the qualities of the parts.

4.4.2 The Chosen Methodological Approach

The research presented here is based on a combination of theoretical and empirical studies. The theoretical studies have been conducted primarily through literature studies, whereas the empirical studies have been performed through case studies (see Section 4.3.7) and industrial visits. The literature studies are based on books, journal, and magazine articles, conference papers and various sources of information found on the World Wide Web. The primary means of searching for this information have been Internet-based bibliographic and scientific databases, such as Emerald Library[18], and IEEE[19], as well as Internet search engines, especially Google[20] and AltaVista[21].

4.5 Analysis and Conclusions

This chapter started with an exploration into different philosophies of science so as to provide a theoretical basis for the research methodology chosen in this work. The first question, then, is: must a particular philosophy or methodology be chosen? The answer is no. Hacking (1983, p. 152) agrees by stating that:

> There is not just one way to build a house, or even to grow tomatoes. We should not expect something as motley as the growth of knowledge to be strapped to one methodology.

In fact, all theories hold interesting perspectives. However, a few seem to be more easily accepted than others by this author. For example, in manufacturing there is much talk about *paradigms*, but they exist on such a high level that the concept as such does not seem to be readily applicable to the context of this thesis. This context is *methodology*, which as mentioned previously exists at a level below the paradigm. Neither does the monopoly theory seem to apply since this author feels he has a high degree of freedom in chosing his field of research and in formulating his research questions while maintaining a scientific approval from the rest of the research community. On the other hand, if one looks at the division of research fields among related disciplines, there may on occassions seem to exist monopolies at the professor level. For instance, when national research teams are formed these constellations are usually based on existing borders of research "territory" rather than unbiased views on what disciplines that should be part of those teams.

Looking at Lakatos's research programs, they appear to be more appropriate models of how research in this field progresses. The reason is that it seems more logical in this context to divide theories into a hard core and a protective belt and to see the protective belt as containing those assumptions that should be modified, rather than to see the hard core as subject to change. Certain laws and theories in the context of manufacturing systems engineering obviously do hold true even from one "paradigm" to another. These may be basic economical or physical laws, or laws that are more specific to manufacturing systems, such as Little's Law.[22]

As for falsification in the context of this research, it seems relevant but difficult. The difficulty lies in the fact that it is easier to confirm an hypothesis based on the absence of something than it is to confirm an hypothesis that claims that this something exists. The classical example in this case is that of swans. A few hundred years ago, one could easily have claimed that all swans are white, since this hypothesis could be reassuringly confirmed with substantial empirical evidence. That is, if the count was made in a country with only white swans. Eventually, of course, someone discovered black swans and that particular theory could be falsified. Conversely, the usefulness of a falsificationist approach in this research can be discussed. This issue seems relevant on a more general level as well, because many researchers motivate their work by the novelty of their particular approach, or on the fact that their perspective is absent in previous research, or similar assumptions. The principle of *verisimilitude*, however, seems more relevant to the kind of research desribed here, since it can never be expected to reach the point where it offers the absolute truth of manufacturing systems, or simulation for that matter. We are only getting nearer the truth.

Regarding case studies, this chapter has focused on giving a basic description of the characteristics of case studies in order to motivate that what is labeled in this thesis as case studies in fact are case studies. While this purpose has been fulfilled, issues relating to the design of case studies have not been dealt with. Ideally, these issues should have been addressed as well.

Moving on to the systems view, it seems relatively safe to motivate its choice based on the fact that the characteristics of manufacturing systems are generally seen as best described with a systems view. In fact, it would be hard to motivate another approach based on the views taken by other resarchers in the field. In addition, this author makes a point of considering simulation from a holistic view since the lack of such views in current simulation research are believed to be a major factor behind several problems in this area. This is not to say, however, that the actor's view is not relevant or useful in certain cases or under certain conditions, or that parts of this research do not take what can be labeled as a reductionist approach. Rather, it seems that an open mind should be kept in future research because all these views complement each other. Conversely, they should be further investigated.

What about methodological anarchy then? It seems to this author that the more time he spends in pursuit of the doctoral degree, the more he appreciates the need to follow structured appoaches provided by methodologies. In addition, he has found this to apply to industrial practice as well, although the degree to which industry has identified this need itself is questionable. Developing methodologies for integrating simulation into the manufacturing system development process is thus the motivation behind the research presented here. And *methodology* is both the means and the end in this case. Still, Feyerabend's theories contain certain elements that appeal to this author. One such element is the denial of the existence of "theory-neutral" facts. Somewhere along the road to universal truth, at least within the discipline of manufacturing systems engineering, the scientist filters his findings through generally accepted or personally preferred paradigms, through his own subjective opinions and values, or through ignorance and prejudice. This is hard to avoid. Oscar Wilde expresses this from a somewhat different but complementary angle:

> The value of an idea has nothing whatsoever to do with the sincerity of the man who expresses it. Indeed, the probabilities are that the more insincere the man is, the more purely intellectual will the idea be, as in that case it will not be coloured by either his wants, his desires, or his prejudices.[23]

Feyerabend's theory of science is not necessarily to be interpreted in a negative way. As Chalmers argues, it may actually be seen as accommodating a "middle way". This middle way or intermediate view would hold that there are methods and standards in science, but that they can vary from science to science and within a science, can be changed, and changed for the better. Let us hope that this is true.

Notes for Chapter 4

[3] This chapter is mainly based on Chalmers (1999), Patel and Tebelius (1987), Wallén (1996), and lecture notes from a course taught by Bertil Mårtensson at the Department of Philosophy at Lund University.

[4] Epistemology is also known as philosophical *theory of knowledge*.

[5] Realist schools of thought include falsificationism (referred to by Chalmers as *conjectural realism*), and materialism. Anti-realist schools include positivism, pragmatism, instrumentalism, immaterialism, and phenomenalism.

[6] Etymology: Greek *dikhotomi*, from *dikhotomos*, divided in two: Division into two usually contradictory parts or opinions (The American Heritage, 2000).

[7] As this discussion delves more deeply into the philosophical aspects of science than what is the purpose here, the reader is referred to Chalmers (1999, chapters 1–2) for a good start on this interesting topic.

[8] A hypothesis covering phenomena that are unique is seen as having a short range. Note: The Swedish word used in the original text is *räckvidd*.

[9] Usage note: "This word is employed by English writers in a very loose and improper sense. It is with them usually convertible into hypothesis, and hypothesis is commonly used as another term for conjecture. The terms theory and theoretical are properly used in opposition to the terms practice and practical. In this sense, they were exclusively employed by the ancients; and in this sense, they are almost exclusively employed by the Continental philosophers." – Sir W. Hamilton (MICRA, Inc., 1998).

[10] Usage note: Paradigm first appeared in English in the 15th century, meaning "an example or pattern", and it still bears this meaning today: *Their company is a paradigm of the small high-tech firms that have recently sprung up in this area*. For nearly 400 years paradigm has also been applied to the patterns of inflections that are used to sort the verbs, nouns, and other parts of speech of a language into groups that are more easily studied. Since the 1960s, paradigm has been used in science to refer to a theoretical framework, as when Nobel Laureate David Baltimore cited the work of two colleagues that *"really established a new paradigm for our understanding of the causation of cancer."* Thereafter, researchers in many different fields, including sociology and literary criticism, often saw themselves as working in or trying to break out of paradigms. Applications of the term in other contexts show that it can sometimes be used more loosely to mean "the prevailing view of things." The Usage Panel splits down the middle on these non-scientific uses of paradigm. Fifty-two percent disapprove of the sentence *The paradigm governing international competition and competitiveness has shifted dramatically in the last three decades* (Princeton University, 1997).

[11] The Swedish terms used in the source are *inomvetenskaplig* and *utomvetenskaplig* styrning.

[12] Attribution: *Life* 9 Jan, 1950. Via Bartleby.com (www).

[13] A more recent philosophical movement has attempted to develop an account of universal method by adapting a version of probability theory. Known as the *Bayesians*, these philosophers base their views on a theorem about conditional probabilities proved by the eighteenth-century mathematician Thomas Bayes. The reader is referred to Chalmers (1999, chapter 12) for a more detailed investigation.

[14] The reader is referred to Yin (1994) for a more detailed discussion on the reasons for choosing a particular research approach based on the types of research question(s) posed.

[15] A related term is *systems thinking*.

[16] How the state of dynamic systems changes over time will be treated in more detail in Section 7.2.

[17] Systems perspective is also referred to as *systems approach* and *systems view*.

[18] www.emerald-library.com

[19] iel.ihs.com

[20] www.google.com

[21] www.altavista.com

[22] Little's Law states that work-in-process (WIP) equals *production rate* times *throughput time*. It is described in more detail in Askin and Standridge (1993, Section 1.3).

[23] Attribution: Lord Henry, in *The Picture of Dorian Gray*, 1891, Ch. 1. Via Bartleby.com (www).

5

Thesis Structure

This thesis is broadly divided into six *parts*, structured into *chapters* as follows:

PART I – INTRODUCTION presents and motivates the chosen field of research in *Chapter 1*, details the research questions and objectives in *Chapter 2*, moves on to state the scope and limitations of this thesis in *Chapter 3*, describes the research methodology in *Chapter 4*, and closes with the thesis structure here in *Chapter 5*.

PART II – FRAME OF REFERENCE explores the three primary areas of interest: manufacturing system development in *Chapter 6*, discrete-event simulation in *Chapter 7*, and integration in *Chapter 8*.

PART III – CASE STUDIES reports on case studies from Swedish industry in *Chapter 9*, and from Japanese industry in *Chapter 10*. These studies are then analyzed and concluded in *Chapter 11*,

PART IV – RESULTS presents the main contributions of this thesis: the need to learn from other disciplines and the specification of these disciplines in *Chapter 12*, the concept of simulation integration in *Chapter 13*, and the methodological framework in *Chapter 14*.

PART V – EPILOGUE closes this thesis with a discussion in *Chapter 15*, a conclusion in *Chapter 16*, and suggestions for future research in *Chapter 17*.

PART VI – APPENDED PAPERS includes the papers and articles on which this thesis is based.

SUPPLEMENTAL – Part V is followed by a bibliography on *p. 215*, a glossary on *p. 233*, a list of acronyms on *p. 241*, a list of figures on *p. 247*, a list of tables on *p. 251*, and a list of definitions on *p. 253*. Part VI is followed by an Appendix, starting on *p. 335*.

Part II

FRAME OF REFERENCE

That’s no moon, it’s a space station!

– Obi Wan Kenobi

6

Manufacturing System Development

To make an apple pie from scratch, you must first invent the universe.

– CARL SAGAN

This chapter will answer the following questions:

Q *What do we mean by manufacturing system development?*

Q *What are the problems associated with manufacturing system development?*

Q *What will characterize the development of future manufacturing systems?*

To this end, Section 6.1 provides the context and motivation of manufacturing as the basis of this research; Section 6.2 moves on to explore the very core of manufacturing, namely the *manufacturing system*; Section 6.3 looks at the set of activities needed to execute the function of the manufacturing system, i.e. the product realization process;Section 6.4 then looks at how manufacturing systems are *developed* to support his process; and Section 6.5 summarizes and elaborates on the *problems* associated with this activity. Finally, Section 6.6 tries to look into the *future* of manufacturing system development.[24]

6.1 Context and Motivation

From time to time, people seem to forget or disregard the importance of manufacturing as the basis for economic growth in industrialized nations. Indeed, with today's tendencies to look on services and information technology as stand alone sectors, it is particularly important to remember that the heart of an industrialized nation's economy still lies at the manufacturing industry.

However, with the burst of the "IT bubble" and the "New Economy" reduced to more worldly proportions, the beginning of the 21st century has seen manufacturing receive renewed attention. Again, manufacturing orders and manufacturer's stock levels are closely watched by economists and analysts as indicators of the economic state of a nation.

A look at manufacturing's share of GDP around the world clearly shows why manufacturing matters. From this, we see that in the U.S. manufacturing accounts for almost *one fifth* of the economy, and in Japan nearly *one fourth* of real GDP and more than 70% of exports. In Europe, we see that British, German, Italian, and Swedish manufacturers all account for over *one fifth* of their countries' economies, see Figure 6.1.[25] Here, it is important to note that these are *direct* figures. Manufacturing's *total* contribution to GDP, employment, and welfare after adding *indirect* effects is harder to measure, but is generally agreed to be significant (Wu, 1994).

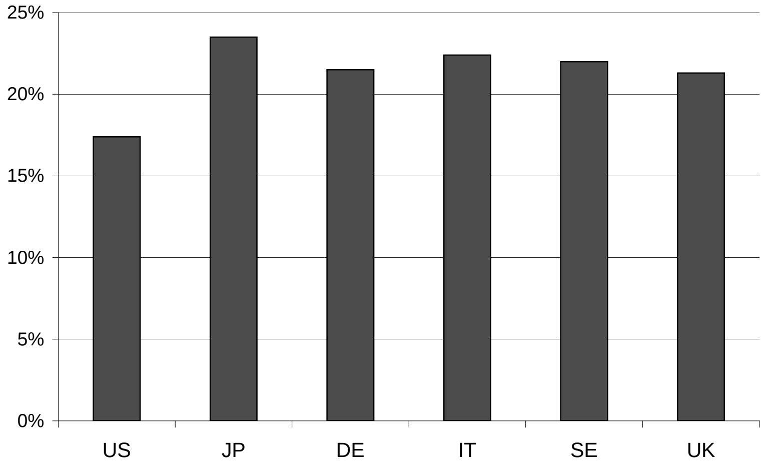


Figure 6.1 *Manufacturing's share of GDP in selected countries.*

Apart from accounting for a large share of GDP, expanding *production possibilities* – the quantity of goods and services that can be produced, limited by the available resources and by technology (Parkin et al., 1997, p. 46) – contribute to *economic growth*, as suggested in the introductory chapter of this thesis. The two key factors that influence economic growth are *technological* *progress* – the development of new and better ways of producing goods and services and the development of new goods – and *capital accumulation* – the growth of capital resources (Parkin et al., 1997, p. 52).

In this context, the term *productivity* is of fundamental importance as a manufacturing performance measure, evidenced by its frequent occurrence in economical analyzes, news reports, and textbooks. And as the above shows, manufacturing's contribution to total productivity remains significant. In fact, productivity (including its first and second derivatives), in particular when measured as output per worker – labor productivity – remains a key concern for all industrialized countries, especially those with growing gaps with leading economies, see e.g. The Economist (2001*a*).[26] In support of this view, Porter (1999) notes that:

> …we must realize that productivity […] is the central determinant of prosperity in the world economy. If we look at any nation, productivity determines wealth, productivity determines the wages you can earn, productivity determines the return on capital, productivity determines the standard of living of nations, productivity determines whether a particular geographic area […] is prosperous or not.

By these means, manufacturing has the potential of improving the quality of life for people everywhere, or as Womack et al. (1990) note, "…how we make things dictates not only how we work but also what we buy, how we think, and the way we live." With this in mind, the research presented here aims at contributing to technological progress and productivity growth, that will ultimately increase the amount of capital resources and thereby improve our standard of living and quality of life.

Looking at the more primary objectives of manufacturers, Chapter 1 mentioned that the manufacturing industry's need to meet *quality*, *time*, and *cost* objectives for both products and processes (or from both external and internal perspectives) is becoming harder to meet. Although the weight attributed to each of these objectives differs depending on product type, market conditions, etc, the traditional view on companies as focusing on just one or two of these objectives is changing. The current shift is to a situation where the market demands on the one hand that equal weights be attributed to all three, and for both product and process, and on the other hand requires an increase in absolute values of all three. These relative and absolute trends of the quality, cost, and time objectives are shown in Figure 6.2.

These trends put immense pressure on manufacturers to respond with a vast number of strategic and operational measures related to quality, cost, and time objectives, and, most importantly, they require new *means* of meeting these objectives. As this chapter will aim to show, one of these means is virtual manufacturing, and especially discrete-event simulation.

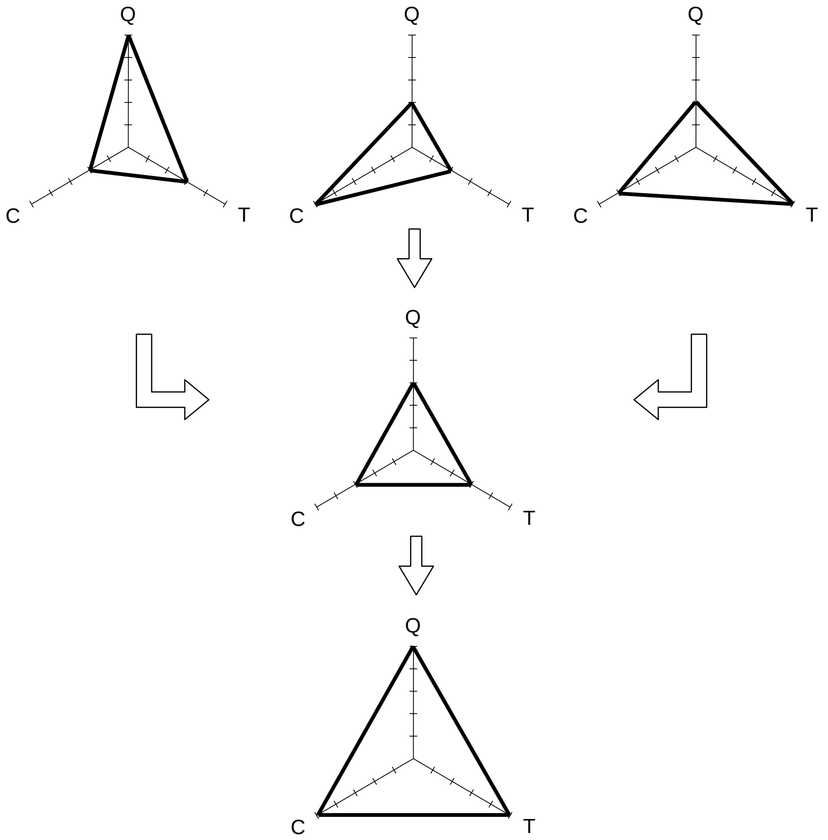


Figure 6.2 *A polar representation of the relative and absolute trends of the quality (Q), cost (C), and time (T) objectives. These are seen as the current shift from quality, cost, or time focus (top row from left to right), to equal focus on all three (middle row), and an increase in the market's absolute requirements on these objectives (bottom).*

In Chapter 1, we further saw that today's manufacturing environment can be characterized as:

- globalized
- integrated
- customer-driven, and
- dynamic.

Perhaps the simplest way of describing globalization is as *competition on a global level.* Here, we see frequent examples of how information, knowledge (of best business practices, technologies, trends, etc.), and capital move across the world, breaking geographical and cultural barriers, thereby putting immense pressure on companies to respond to customer requirements everywhere in the world faster and better than anywhere in the world. As evidence of the other characteristics, we have become accustomed to concepts and terms such as computer integrated manufacturing (CIM), extended (or virtual) enterprises, strategic alliances, and mergers & acquisitions (M&A) showing various forms of integration; customer relationship management (CRM), first to mind, make to order (MTO), market-in vs. product-out, etc., indicating customer-driven manufacturing; and time to market (TTM), time to customer (TTC), product life cycle, first to market (FTM), market window, lead time, throughput time, and so on, indicating an increased awareness of business dynamics.

Of course, most of these concepts cannot be clearly separated; for instance, an increased focus on time to customer is in itself an evidence of more customer-driven manufacturing, as are in fact most of the time-based means of competition (Stalk and Hout, 1990). Although customer demands are integrated into all these concepts, there is motivation behind the idea of making the customer conceptually more explicit.

Manufacturing is indeed exposed to all these trends, and if history has taught us anything, it is that manufacturing is in constant change. More than that: we have seen that all but a lucky few manufacturers *have to* change in order to survive. The next section will give a few examples of how some companies have managed change.

6.1.1 A Few Examples from the Real World

A good example of successfully managed *change* is the American bicycle manufacturer Cannondale.[27] In the late 1980s, Cannondale had built a strong reputation as an exclusive manufacturer of hand made aluminum frame bicycles. However, as demand was growing it became increasingly difficult to maintain an even quality of the frames at the necessary rate of production. In addition, time to market (TTM) was a concern with the extremely high rate of innovation that characterized mountainbikes then. There was also some growing concern among consumers that aluminum frames were more prone to breaking than those made by steel or carbon fiber, the two rival frame materials. If this continued, Cannondale realized that aluminum's reputation would suffer to the extent that market share might decrease in favor of these alternative materials.

Around this time, the late 1980s, frame makers mainly relied on manual production methods. However, it was soon discovered that even in bicycle frame manufacturing, computers offered considerable aid in design and analysis, and that lasers and robots could do a much better job of cutting and aligning the tubes. As a result, Cannondale changed its strategy from doing virtually everything by hand to becoming (in the opinion of this author) the most outspokenly high-tech bicycle manufacturer.

Now, every Cannondale frame is designed using computer aided design (CAD) and finite element analysis (FEM) systems. The finished designs are sent to the factory where the aluminum frame tubes are heat treated and cut by computer-guided lasers. The lasers provide a cleaner cut than traditional cutting methods, and ensure tight tolerances for greater weld integrity and a stronger frame. The tubes on Cannondale frames also feature a patented design that aligns the tubes for welding; by eliminating the need to build numerous production fixtures, or jigs, for each size and every new frame style, the system significantly reduces pre-production engineering tasks and allows for reduced TTM. As part of these changes a new production concept was developed – Cannondale Low Inventory Products System (CLIPS) – which significantly reduced inventory and WIP. Today, Cannondale frames still come with the label "handmade in the USA", but the only thing still done by hand is the actual TIG welding, since this, Cannondale claims, is an area where humans still outperform machines.

What this shows is but one of thousands of examples of how manufacturing is changing in order to survive. During the past twenty years, several computer-based technological changes have spread through industry to the extent that they are now taken for granted. Business without word processing, slideshows, CAD systems, computer numerical control (CNC) machines, or the Internet would be just as unthinkable as it would be impossible. Other technologies, however, have yet to show any significant impact on manufacturing operations and performance. As later chapters of this thesis will argue, discrete-event simulation is somewhere inbetween.

Not all changes come easy though. As other examples have shown, scientists and engineers may come up with the most marvelous and fantastic inventions that in various ways make our lives better. They may then sit down and transform these inventions and ideas into real products which on paper have all the quality characteristics that customers desire. But if these products cannot be efficiently and effectively *manufactured*, they will be made available only to an elite group of consumers that are willing and able to pay the premium that comes with inferior manufacturability. This strongly speaks against the view of manufacturing as having the potential of improving the quality of life for people and increasing the wealth of nations. Certainly, there are several examples of products that are by definition “exclusive”, such as hand made Italian sports cars and downtown Tokyo apartments. In the author’s opinion, however, there are numerous cases where people mistake inabilities of the manufacturer to operate efficiently and effectively for “exclusiveness”, as suggested by customers putting up with unmotivatedly hefty price tags, longer than necessary delivery times, and so on. This is certainly more due to hard-to-break-with traditions and reluctance to change than lack of potential for improvements.

A 1990 television documentary on the British car manufacturer Morgan provided a striking example of how not even hand made sports cars need be that exclusive (BBC TV, 1990). Morgan Motor, a family-owned car company with a long tradition of craftsmanship, had been making virtually everything themselves since the company was founded, and they made it with a minimum of machines and automated equipment. As an example, the process of making the walnut panels started by purchasing whole logs, since the workers claimed that this was the only way to ensure the highest quality. Moreover, the factory had grown slowly for decades and appeared to be, to any observer, in complete disarray. As an example, the cars had to be repeatedly pushed back and forth between buildings as they went through the various production stages. However, the new chief executive officer (CEO) did feel there was potential for improvements, a feeling driven by customers having to wait longer and longer for their orders without any significant improvement in production rate, and by the increasing difficulties in finding craftsmen. He called in a management consultant from London to have a look. What followed can provide several lessons in culture clashes, but in summary this is what happened: the consultant, of course, found a huge number of points for improvements. The bottomline was that the customers would get the same product but in shorter time, and at less cost. The employees, in the end, agreed on only a fraction of the suggestions, none of them particularly significant (although they did agree to slight modifications of the flow). The reason: a corporate culture with extremely conservative opinions. Employees felt that how they did things was the best way of doings things because that was how they had always been doing things. As the official Morgan Website states in their record of events in the early 1990s (Morgan Motor Co., www):[28]

> A BBC television programme, entitled "Trouble shooter" caused quite a stir. Industrialist Sir John Harvey Jones visited the factory, and analysed the business. His conclusions were significantly at odds with the views held by the Morgan family, who said so. Even today, many conversations start with reference to the programme,

> which has entered British folk lore. His programme had the effect of including hundreds of orders into the factory, and ironically is one of the principal reasons behind the extensive waiting list.

To conclude these introductory sections, we see that a number of trends in the manufacturing industry and its environment shift down as requirements and constraints on the very core of these companies, namely their *manufacturing systems*, which as a result are becoming increasingly complex. Not only are competition, technology, and customer demands making these requirements and constraints harder to meet; they are also bringing about more frequent *changes* of the manufacturing systems, which to a larger extent have to exist in an *integrated* environment, relying on highly sophisticated *knowledge*. It has also been suggested that technology and knowledge of technology alone is not enough to successfully manage change We have thus touched on several of the problems characterizing manufacturing in the early 21st century, and summarized them in three key words: *complexity*, *dynamics*, and *change*. But before we explore these further and look at means of dealing with them, it is time for a more detailed look at the *manufacturing system*, coming up in Section 6.2. The reader is also referred to Appendix A for the basic definitions of manufacturing and production used in this thesis.

6.2 The Manufacturing System

The previous sections spoke of inputs and outputs, and how these were transformed into goods, supported by a number of flows, or processes. In fact, it is common to characterize manufacturing as an *input-output system* which produces outputs (economic goods) through activities of transformation of inputs (factors of production) (Wu, 1994). This corresponds to the functional aspect,as will be further explained in Section 6.2.1.

As an example, in its simplest and most abstract depiction, manufacturing, even with the broader definition used here, can be viewed as the process of transforming a signal to a response[29], as in Figure 6.3.[30] For example, if *customer requirements* are the signals, then *customer satisfaction* is the response of a manufacturing system. The processes of the manufacturing system are controlled by a set of strategic and operational measures ordered by the management function, corresponding to control factors. In this process, management must eliminate or reduce the effects on the response of a variety of disturbances, i.e. noise factors. Of course, the resources transformed by the manufacturing operations also include *raw materials* and *information*.

As Wu points out, however, such simplified formalisms should not obscure the huge diversity of manufacturing that exists today. In fact, more than 450 different manufacturing industries have been identified, producing about 20 major groups of products, broadly divided into capital and consumer goods,

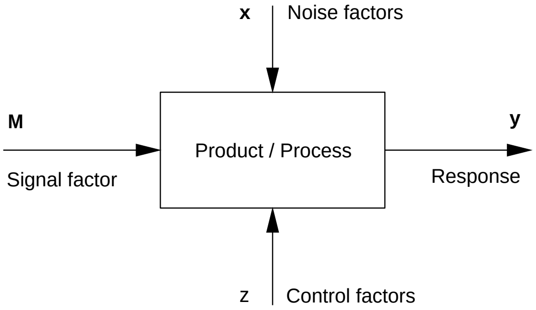


Figure 6.3 *Block diagram of a product/process as an abstract representation of the functional aspect of a manufacturing system. Source: Phadke (1989, p. 30).*

although several product types comprise both categories (Wu, 1994). It is also important to remember that a manufacturing system is an open system, as mentioned previously, and that it has to interact with a large number of other systems, as illustrated in Figure 6.4 on the next page. As a result of this openness, disturbances will stem from a large number of different sources outside the control of the manufacturing system.

Given the definition of *manufacturing* chosen in Appendix A and considering the definition of a *system* in Section 4.4.1, a *manufacturing system* is here defined as follows:

> **Definition 6.1** MANUFACTURING SYSTEM
>
> A complex whole formed by a group of interacting, interrelated, and interdependent elements with the purpose of executing all the activities and operations needed to put a product on the market.

The production system, comprising the fabrication and assembly systems is defined in a similar manner based on the definitions of production, fabrication, and assembly in Appendix A. The hierarchical relationship between these systems is shown in Figure 6.5 on the following page.

What, then, is the purpose of all this? As Askin and Standridge (1993, p. 3) state:

> The purpose of manufacturing, at least idealistically, is to enrich society through the production of functionally desirable, aesthetically pleasing, environmentally safe, economically affordable, highly reliable, top-quality products.

To realize this, a manufacturing system needs to execute a large number of functions through a series of business processes. These functional subsystems of a manufacturing system are shown in Figure 6.6 on page 63.

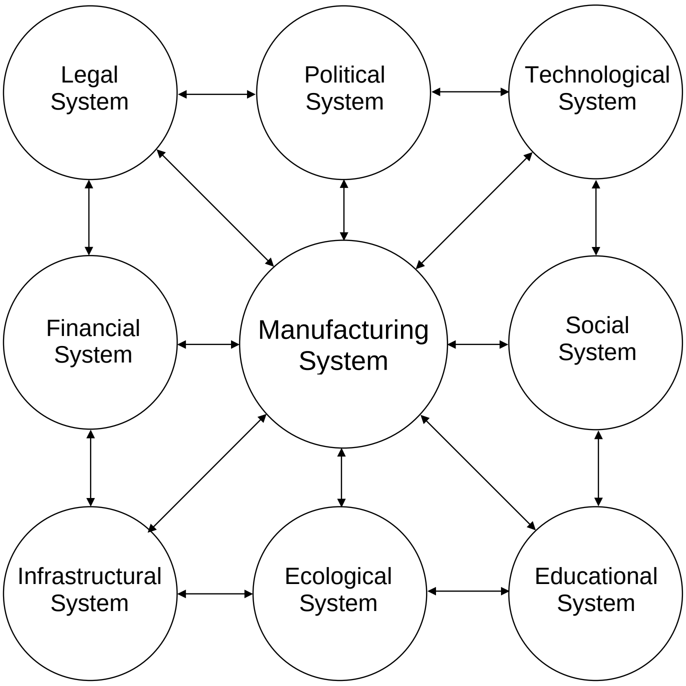


Figure 6.4 *A manufacturing system in relation to other systems.*

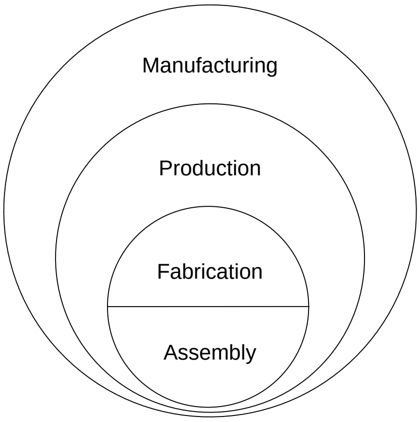


Figure 6.5 *The hierarchical relationship between manufacturing, production, fabrication, and assembly. Based on Bellgran (1998, p. 38).*

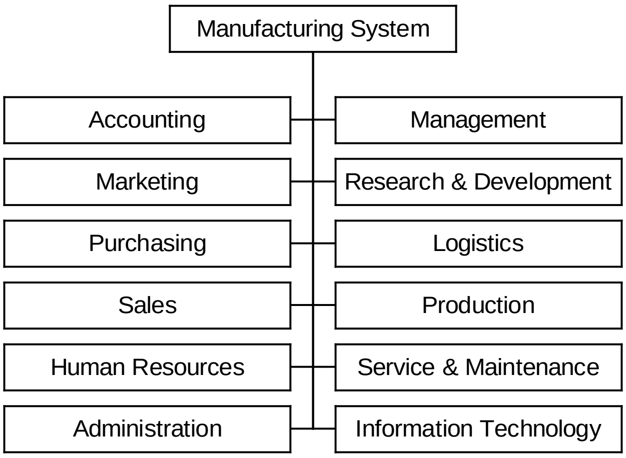


Figure 6.6 *Business function diagram (BFD) of a manufacturing system.*

6.2.1 Manufacturing System Properties

So much for the basics. If we attempt to study a manufacturing system in more detail, it becomes necessary to adopt more formal and structured approaches. Recalling what was said on systems in Section 4.4.1, we can describe a manufacturing system with the following properties:

1. Structure
2. Function
3. Hierarchy
4. Procedure

The essence of manufacturing system in terms of its *structural* components is simple: it can be said to consist of people, hardware and software, as shown in Figure 6.7 on the next page. The structural aspect of a manufacturing system can also be viewed from the perspective of the *production system*, which forms a static spatial structure (or layout) of a plant. This structure influences the effectiveness of the functional aspect, i.e. the transformation process in production. In this sense, the optimum design of the plant layout is a problem of the structural aspect of the system (Hitomi, 1996).

The *functional* aspect refers to the process of converting materials into products, where the main concern from the point of view of this thesis is the material flow, as mentioned previously. The functional aspect mainly depends upon decisions related to manufacturing technology, including production processes, machine tools, and industrial engineering techniques (Hitomi, 1996).

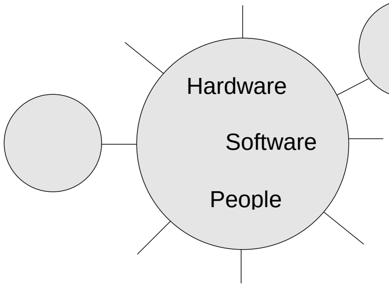


Figure 6.7 *The basic structure of a manufacturing system.*

The *hierarchical* aspect depends on the type of organization and processes under investigation, and means that different components of the manufacturing system can be seen as belonging to different subsystems, that have different relations to their respective supersystems and the whole system. Most of these subsystems are *real*, but there also exists *abstract* subsystems, such as value systems and normative systems (Bruzelius and Skärvad, 1995). The hierarchical aspect thus has implications for the level of detail at which we choose to study the manufacturing system.

Here, a four level hierarchy of shop floor production activities, known as the shop floor production model (SFPM), has been developed by the International Organization for Standardization (ISO), which is based on the five level National Bureau of Standards (NBS) model. The combined levels of these models are shown in Figure 6.8 (Bauer et al., 1991; ISO/TC 184/SC 5/WG 1 N160, 1990). The SFPM covers the four lower levels of this, and thus provides an abstract model of decision levels in production.

Figure 6.9 further exemplifies the hierarchical aspects of a manufacturing system. Here, A is a subsystem of the entire manufacturing system. At the same time, B is a subsystem of A, meaning that A is the system to which B belongs.

The *procedural* aspect means the *management cycle*, and includes the planning, logistics, implementation and control of productive activities, whose goal is to convert raw materials into finished products to meet production objectives. The procedural aspect is often referred to as *production management* and is primarily concerned with the information flow across business processes (Hitomi, 1996; Yien and Tseng, 1997). An example of the procedural aspect is shown in Figure 6.10.

With all these perspectives on manufacturing, a thorough analysis of its processes of course becomes extremely difficult. In other words, a manufacturing system is so complex that it can be described in an almost infinite number of ways. This becomes particularly true when we try to describe not only, say,

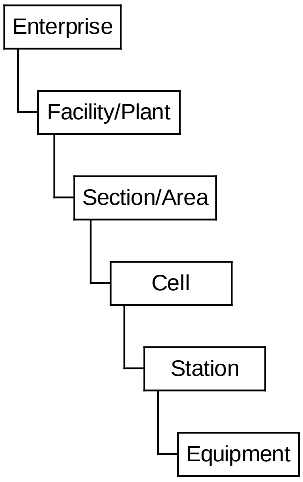


Figure 6.8 *Decision level model of the manufacturing enterprise.*

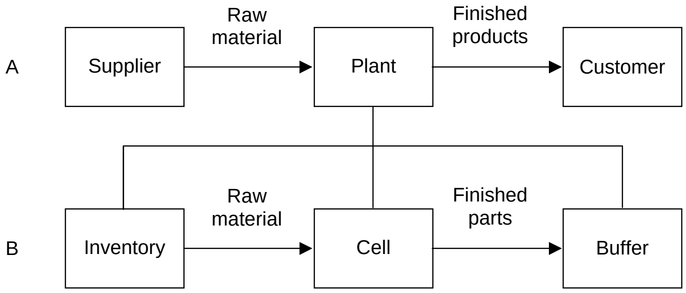


Figure 6.9 *System (A) and subsystem (B) as examples of hierarchical aspects of a manufacturing system.*

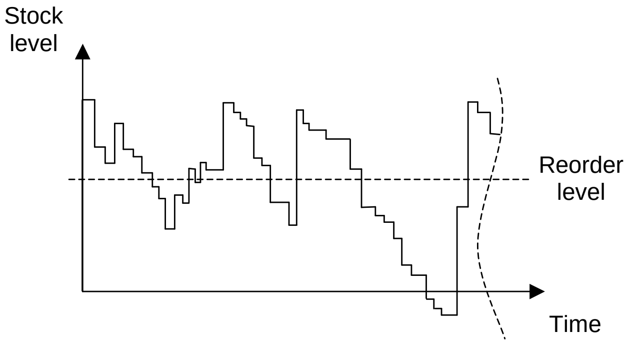


Figure 6.10 *Inventory levels as an example of the procedural aspect of a manufacturing system; in this case inventory management. Adapted from Hitomi (1996, p. 35).*

structural aspects, but also functional, hierarchical, and procedural aspects at the same time. Thus, some formalism that can serve to describe this complexity is necessary. Here, the Generalized Enterprise Reference Architecture and Methodology (GERAM), which mainly builds on the CIMOSA, GIM, and PERA frameworks, has been developed as a means to describe and model a manufacturing system from different perspectives and at different levels, and across its life cycle (Vernadat, 1996).[31] We will return to GERAM in Chapter 14.

Despite this complexity, however, some industry trends are so evident that they can hardly be missed. These trends all in some way relate to the use and application of *computer technology*, and they have done nothing less than *revolutionized* manufacturing. This, the latest industrial revolution, characterized by an increasing application of computers in all aspects of manufacturing, has therefore seen the major advances been brought about not so much by hardware development – although the close attention to equipment still plays a crucial role in all manufacturing – as by the *software* that controls this hardware and processes the information generated by machines and humans (Wu, 1994). This development has pushed for information and communications technologies that can handle the enormous amounts of data and information that have followed. All these developments, conceptually known as advanced manufacturing technology (AMT), are affecting not only software, however, but also hardware and people. In addition to managing information, technology must facilitate *communication* between people, between machines, and between people and machines. All these developments are taking place in areas such as programmable equipment, e.g. computer-controlled work centers (CNC, etc.), robotics and other automation, and computer-aided and -integrated systems, such as CAD, computer aided manufacturing (CAM), computer aided engineering (CAE), flexible manufacturing system (FMS), computer integrated manufacturing (CIM), and virtual manufacturing (VM). As Bellgran (1998) notes, an important issue here is to also consider the *social* subsystems, consisting of people, with respect to the technical subsystems, that is, the hardware and the software, all of which constitute the manufacturing system.

6.2.2 Common Types of Manufacturing Systems

As one might expect, there are several different ways of executing the function of a manufacturing system. Conversely, there are many different types of manufacturing systems, and even different names for similar types of systems. Some of the more common systems are the flexible manufacturing system (FMS), flexible assembly system (FAS), cellular manufacturing system (CMS), and computer integrated manufacturing system (CIMS), which all have different scopes (Yien and Tseng, 1997). For example, an FMS covers both fabrication and assembly, whereas an FAS only covers assembly. In other cases, different names refer to similar types of systems, such as the CMS and CIMS, although they emphasize different aspects.

Some of these systems cannot in themselves be considered as manufacturing systems if the term is understood in the broader sense defined previously. Such systems, including the FMS, FAS, and CMS, only focus on the material flow, i.e. production and logistics aspects. On the other hand, a computer integrated manufacturing system integrates all the activities and system components necessary to comply with our definition (Yien and Tseng, 1997).

A further exploration of different manufacturing system would be beyond the scope of this thesis since discrete-event simulation as a technology is not necessarily limited to a certain type of manufacturing system. What is relevant here, though, is that the large number of different manufacturing and production systems, as well as the extremely fragmented terminology used to describe these systems are significant causes of problems related to discrete-event simulation of these various systems. The reader is referred to Metaxiotis, Ergazakis and Psarras (2001) for a good review of different production systems.

6.2.3 Manufacturing's Performance Objectives

Section 6.1 briefly stated that the overriding objectives of any manufacturing system, whether referring to its products or processes could be expressed in terms of quality, cost, and time. Looking in more detail at these objectives, it is obvious that they can be broken down further. For example, *time* can refer to both *doing things fast* and *doing things on time.* As mentioned previously, one of the means of meeting these objectives is flexibility. However, upon closer examination, flexibility appears to be such a fundamental condition for meeting the quality, time, and cost objectives that it can be regarded as an overriding objective in itself. As a result, there is a total of *five performance objectives*, that each give the company a specific advantage (Slack, Chambers, Harland, Harrison and Johnston, 1995). Figure 6.11 on the next page shows these five performance objectives and the advantages they contribute to.

Of course, neither of these objectives can be clearly or succinctly described since different products and customers will require different performance objectives, which will be differently valued either becuase the customers are different or because market conditions differ. In short, the meaning of these performance objectives will depend on the type of operations. Of these five objectives, only flexibility will be treated in more detail here. The reader is refered to Slack et al. (1995, Chapter 2) for a detailed exposition of the remaining objectives.

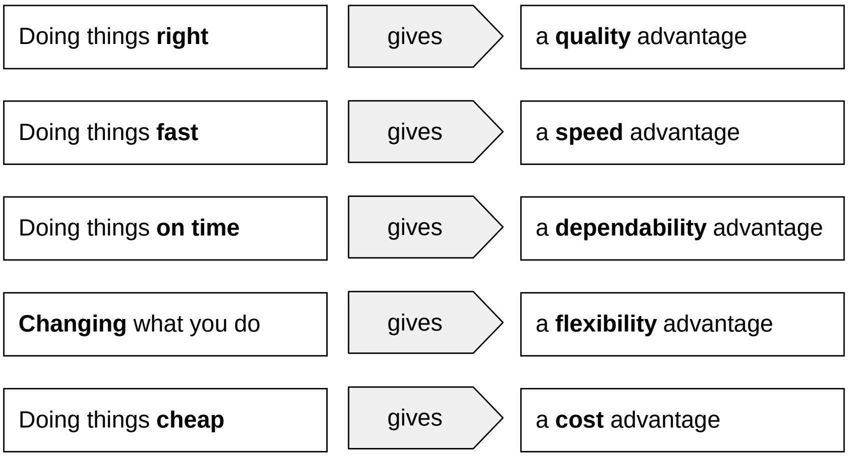


Figure 6.11 *The five operations performance objectives that contribute to a manufacturing firm's business strategy. Adapted from Slack et al. (1995, p. 54).*

6.2.4 Flexibility

There has been much talk in recent years of the need for manufacturers to be flexible. Some authors have taken the concept one step further and are talking of *agility* instead, and of *agile manufacturing* as a new paradigm (Kidd, 1994). There also exist a number of related terms, such as *adaptability* (see e.g. Katayama and Bennett, 1999), and *hyper-flexibility* (see e.g. Bolmsjö, 1999). As well as being brought about by global business dynamics and tougher customer requirements, an increased flexibility has also been enabled by developments in the CIM and information and communications technologies (ICT) areas. Several types of flexibility are possible (Vernadat, 1996, p. 6–7):

- **organizational flexibility**: the capability of an enterprise to reorganize its business processes and organizational structure to face permanent management of change,
- **operational flexibility**: the capability of using or interchanging pieces of equipment for different operations,
- **product flexibility**: the capability of modifying rapidly a product design to face changing market trends, or particular customer requirements,
- **production flexibility**: the capability of dealing with production volume (capacity) variability.

A more formal approach that applies to manufacturing whether referring to products, production volumes, or manufacturing processes is to define flexibility in terms of (Upton, 1995):

- **range**: which applies to products and can mean different things; a plant can have the ability to make a small number of products that are very different from each other, or the ability to produce concurrently a large number of products that are only slightly different from one another,
- **mobility**: which means a plant's ability to change nimbly from making one product to making another, a concept associated with quick response times since it minimizes the need for lung runs and allows production to follow demand without excess inventory,
- **uniformity**: which refers to the uniformity of performance, meaning that within a certain range of products a plant always has one or a few products that maximize productivity, quality, or some other performance measure, and when the plant or production system moves away from this favored set of parameters, performance declines. Conversely, this type of flexibility measures how well a plant can manufacture *any* product within a range and still achieve the same performance.

In summary, to be more flexible a company must increase both range and mobility, while achieving uniform performance across a specified range.

The theoretical analyses of flexibility do not stop here though. The reader is referred to Slack et al. (1995) who provides a good introduction to the topic in the context of operations management, while Fourie and van der Merwe (1999) discuss some additional types of flexibility. A more comprehensive framework is suggested by Koste and Malhotra (1999), who divide range into *range-number (R-N)* and *range-heterogeneity (R-H)*, thereby in effect adding R-H to the set of elements described by Upton (1995) and others. The result is a set of four elements that can be used for mapping different types of flexibility. Using these elements, the authors provide 10 flexibility definitions that apply to manufacturing.

Flexibility will not be further explored here. However, this description, although brief, should be seen as important in describing characteristics of today's manufacturing environment that require technologies that can handle flexibility and all the design parameters thereby imposed. Flexibility is both a result of and implies *dynamics* and the need to *change*, which, as can be recalled from Chapter 1, are fundamental reasons for motivating the adoption of discrete-event simulation.

The next section will describe two phenomena that severely limit a manufacturing system's ability to be flexible – *constraints* and *disturbances*.

6.2.5 Constraints and Disturbances

As mentioned in Section 4.4.1, a manufacturing system is an open system, and as such it is exposed to constraints and disturbances. Constraints can be divided into *internal* and *external* constraints. Internal constraints can be further classified as *strategic* and *operational*. Conforming to a particular manufacturing paradigm or concept, such as agile manufacturing or build to order (BTO), gaining or keeping a particular market share, etc. are examples of strategic constraints imposed on the manufacturing system. These higher-level strategic constraints transfer down in the manufacturing system as a number of operational constraints, such as allowed lead time and throughput times, required capacity, maintenance intervals, working schedules, delivery times, and various sorts of cost.

External constraints are imposed by customers, suppliers, or any other of the manufacturing system's related systems (refer back to Figure 6.4 on p. 62). Moreover, constraints exist at all the different decision levels (see Figure 6.8 on p. 65), and can be functionally grouped into material, information, and cost constraints.

In addition, all these constraints have a time variation (Mårtensson, 2000*b*), that is, existing constraints change over time and/or disappear altogether, and new constraints are introduced.

The amount of research done on flexibility seems to overshadow what has been done on disturbances. This is somewhat surprising, given the significantly adverse effects of disturbances on manufacturing performance objectives (see e.g. Ericsson, 1997). However, recent years have seen incrased attention to this area, and a few trends can be discerned regarding the research directions. Based on the fact that disturbances arise from a large number of complex interactions between different functions of the enterprise, the handling of disturbances can no longer be seen as the responsibility of the shop-floor personnel alone. To overcome this situation, Harlin (2000) proposes a framework for strategic management of disturbances. where the idea is to lift these issues up to the management level. Ingemansson (2001) identifies the need to explicitly *model* disturbances in production systems, and proposes an approach based on the use of discrete-event simulation.

6.2.6 Measuring Manufacturing Performance

Now that considerable effort has been spent in describing what a manufacturing system is and what it is supposed to do, as well as different ways of doing it, the next questions are obvious: How well does the manufacturing system do what it is supposed to do? And does every part of the system do it? The continuous answering of such questions is a fundamental task for every manufacturing enterprise. And a difficult one. In fact, it is widely agreed upon that the design of performance measurement systems is one of *the* most difficult tasks for manufacturers today (see e.g. Bititci, Suwignjo and Carrie, 2001; Duda, 2000; Kaplan and Cooper, 1998; Koste and Malhotra, 1999).

Of course, every manufacturing system has (or should have) strictly defined goals. This chapter so far has implied several of these. But goals alone are not enough; there also has to be a set of measurable characteristics if system performance is to be evaluated. Most of these manufacturing performance measures can be expressed in terms of quality, time, cost, and flexibility (Yien and Tseng, 1997). The introductory chapter of this thesis and previous sections of this chapter has already shown that these characteristics can be further broken down into a large number of different measures.

Obviously, with such a huge diversity of measures and ways of measuring, and different perspectives from which to measure, and with the large amount of factors that affect these measures, it is readily understood that analysis and evaluation of manufacturing systems is an enormously difficult task.

This section does not aim to explore this further, but will return to this subject when discussing applications and advantages of simulation in Chapter 7.

6.2.7 A Unified Approach to Manufacturing

So far the manufacturing system has been treated from a rather fragmented point of view. As implied by what has been said, however, it is obvious that manufacturing depends on the combined knowledge from a great number of areas. In the 1970s, as a response to this, several researchers began to take a more unified approach to studying and analyzing manufacturing systems.

In an influential book on manufacturing that first appeared in 1975 in Japanese, Hitomi (1996) was the first to promote a unified approach to the discipline of manufacturing, stressing the importance of *integrating* the following three aspects:

1. **manufacturing technology**, which is concerned with the *flow of materials* from raw material acquisition to shipment of finished products to customers,
2. **production management**, which deals mainly with the *flow of information* with the purpose of managing the flow of materials efficiently by planning and control, and
3. **industrial economics**, which treats the *flow of costs*.

The discipline that integrates these three aspects is referred to as *manufacturing systems engineering (MSE)*, which Hitomi (1996, p. 29) defines as "a methodology associated with the optimum design, installation, and execution of large-scale manufacturing systems which are made economically feasible by utilizing scientific laws and empirical rules which exist in manufacturing".

According to Hitomi, this unified approach to manufacturing leads to acknowledging the following six aspects of manufacturing:

1. process systems,
2. management systems,
3. value systems,
4. automation systems,
5. information systems, and
6. social implications.

Here, the focus will be on process, management, and information systems. The next section will look at the *activities* needed to execute the functions of a manufacturing system from this perspective.

6.3 The Product Realization Process

Based primarily on the three aspects of manufacturing chosen in the previous section – the process, management, and information systems – a certain set of activities can be identified as necessary to put a product on the market. This is referred to as the *product realization process (PRP)*. The simplest account of the PRP found by this author is *design – engineering – production* (Jones and McLean, 2000). The PRP can of course be further broken down, organized differently, or be given a similar but slightly different terminology. Some alternative PRPs make certain activities such as assembly more explicit. While for instance Hitomi offers a detailed account of this process, others are more simple.[32]As an example, Askin and Standridge (1993) divide the manufacturing system into five interrelated functions, or core activities, and they include assembly in "manufacturing operations". They do not, however, refer to this as the PRP, but rather as the set of functions needed for product realization. As yet another example, Prasad (1996) defines the product realization process as consisting of seven groups of activities. In other words, it would seem that the PRP needs to be more clearly specified before it is treated in more detail.

First, it is important to note that there is no universal PRP that may be useful for every company. Instead, a PRP should be tailored to the specific type of organization, and the particular types of products manufactured. A PRP that works for one company is not guaranteed to work for another, depending on structural, functional, or cultural differences of organizations. In addition, the PRP has to be seen as a dynamic process since its environment, the manufacturing system, is in constant change, and as such the PRP should be continuously improved to adapt for these changes. Moreover, the PRP in its most generic form should involve all aspects of the enterprise – in addition to engineering and manufacturing it must include marketing, sales, finance, etc.

For consistency with the herein used definitions and terminology, we start by adopting the following PRP based on Askin and Standridge (1993) and Hitomi (1996): [33]

1. requirement specification
2. definition of objectives,
3. product planning and design,
4. strategic production planning,
    (a) establishing production objectives,
    (b) planning production resources,
5. operational production management
    (a) aggregate production planning,
    (b) process planning and design,
    (c) scheduling,
    (d) control,
6. production operations:
    (a) fabrication,
    (b) assembly,
7. delivery and service.

Here, we note that the level of decomposition of production into fabrication and assembly operations is sufficient for our purposes, since, as Askin and Standridge (p. 5) observe, “our interest is in taking a step back from the level of the individual processing step and looking at how material will flow through the system and how processes are linked to obtain the desired volume of production at the intended quality level”. Obviously, issues such as tool wear, machining speeds, material defects, path planning, etc. are important in manufacturing, but outside the scope of this thesis. Similarly, product planning and design need not be broken down further here.

As noted from the example of Askin and Standridge (1993) above, however, some authors prefer to group product realization activities into functions rather than to use the term *process* since the latter implies a certain degree of precedence relationships. On the other hand, there is reason to use the term process since all companies at some point *must* actively decide in what order to execute these activities and deal with precedence constraints.

Also, what we are dealing with here is simply a specification of the activities or functions of the process. This, however, does not determine the order of the activities, which generally go through a series of iterations and loops. This subject is treated in Section 6.3.7.

In addition to the activities that are part of the PRP, there can be said to exist a number of supportive activities necessary for the continuous execution and development of a manufacturing system’s function. Based on Hitomi (1996) and the perspectives chosen from the previous section we can identify the following development activities:

1. material flow analysis,
2. layout planning and design,
3. logistic planning and design,
4. inventory management.

To what extent and with what frequency these development activities are carried out, as well as how they relate to the PRP will of course vary between different types of manufacturing systems, and over the life cycle of a given system and product.

Next, the PRP and supportive activities will be described in more detail, based on Askin and Standridge (1993, pp. 4-7) and Hitomi (1996). This description will not include *requirement specification* or *definition of objectives*. This is not because they are unimportant (as in any process these activities are more than important: they are crucial) but because they are much harder to describe beyond their self-explanatory meanings reflected in their names. Suffice it to say here that the requirement specification should be based on and correctly interpret market requirements and conditions, and that the definition of objectives should result in unambiguous, well-documented and well-communicated guidelines that are defined with respect to the capabilities of the enterprise. In addition, these objectives should be *measurable* as discussed in Section 6.2.6, that is, there should be specific *performance objectives* against which the business can assess the contribution of these activities to its strategic objectives (Slack et al., 1995). It should also be noted here that, as outlined above, these initial activities are based on very high level strategic decisions. They do not stop here though, but return in subsequent stages of the PRP, in which they are refined and further broken down into more specific objectives, a process referred to as *instantiation*.

6.3.1 Product Planning and Design

Product planning is responsible for taking the inputs from marketing regarding customer desires and constructing the description of products that can be profitably manufactured to satisfy these desires. The organizational unit responsible for the planning stage is product research & development (R&D), which provides the technical specifications for the final design. In this process, a trade-off is sought between market requirements and technical possibilities, and design tools such as quality function deployment (QFD), robust design (RD), and axiomatic design (AD) may be used here. The results are usually in the form of conceptual models, physical prototypes, computer models, or a combination thereof. After this stage, *product design* carries on, a stage which some authors include in product planning, e.g. Hitomi (1996). This activity determines the detailed characteristics of the product so that it can perform its specified function(s) (Hitomi, 1996). From the traditional representation with blueprints, products are now described with CAD systems and analyzed for e.g. mass and strength properties using computer-based mathematical tools such as FEM software.

6.3.2 Strategic Production Planning

Strategic production planning is the question of "what to manufacture?", and deals with long term issues related to the manufacturing system and its environment. It can be divided into the following two activities (Hitomi, 1996):

1. **establishing production objectives** – the most basic decision-making activity, mainly concerned with what to produce, which includes make or buy decisions,
2. **planning production resources** – deals with determining requirements on money, facilities, equipment, materials, and personnel, and the planning for their acquisition from within the system or from the external environment, and the optimum allocation of these resources to the various organizational units of the enterprise.

The main problems here are closely related to product planning (see above), long term profit planning, capital investment for new plant construction or expansion, geographical distribution of production, and so on. Strategic production planning may also be seen in conjunction with operational production management, in which case it is referred to as *production and operations management*, or just *operations management*, which has the following roles (Slack et al., 1995):

1. as a *support* to business strategy,
2. as the *implementer* of business strategy, and
3. as the *driver* of business strategy.

Other ways of seeing operations from these three roles are, in the above order, as (i) a *follower* of strategy, i.e. by developing appropriate objectives and policies for the resources managed operations provide the capabilities which are needed for the organization to achieve its strategic goals; (ii) as an *effector* of strategy, i.e. by putting strategy into practice operations translate strategic decisions into operational reality since as Slack et al. (1995) note, strategy in itself can be neither seen nor touched, it is just an intent; and (iii) as a *leader* by providing real means of achieveing competitive advantage.

In this later role, several functions can be acknowledged as important strategy drivers, including financing and marketing. Of all the various functions of a manufacturing system, however, operations management is the most fundamental. Slack et al. (1995, p. 48) explain this driving role of operations as follows:

> No amount of excellent financial management or clever market positioning, however, can compensate for poor operations performance. Badly made products, sloppy service, slow delivery, broken promises, too little choice of products or services or an operations cost base which is too high will sink any company in the long term. Converseley, any business which makes its produts and/or services better, faster, on-time, in greater variety and less expensively than its competition has the best long-term advantage any company could desire. The important point here is that all the things which promote long-term success come directly or indirectly from the operations function.

The reader is referred to Slack, Chambers and Johnston (2000), which is the latest edition of Slack et al. (1995), for a good and comprehensive treatment of operations management, including an account of the influential *four-stage model* originally developed by Hayes and Wheelwright (1984) as a means of determining the ability of any operation to fulfill its three roles.

6.3.3 Operational Production Management

Operational production management, also referred to as production planning and control (PPC), consists of the following activities:

1. aggregate production planning,
2. process planning and design,
3. scheduling, and
4. control,

Aggregate Production Planning – Aggregate production planning means combining information on market demands, production capacity, and current inventory levels to determine planned production levels for every product variant over the medium and long term, the optimal product mix, and the lot-sizes, which may be done with the help of a manufacturing resource planning (MRPII) system, material requirements planning (MRP) and capacity requirements planning (CRP). This is usually established in the form of a master production schedule (MPS) and a bill of materials (BOM).

Process Planning and Design – Process planning can be defined as the function of transforming design information into work instructions (Wu, 1994). It involves the specification of the sequence of production operations required for converting the raw materials into parts and then assembling parts into products. The finished process plan is a set of instructions specifying how the product should be manufactured, including the sequence of machine tools, the tools, jigs, and fixtures required, the machine settings and other process parameters, inspection requirements, and storage and transportation instructions. It thus depends on the kinds and quantities of products to be finished, kinds of raw materials and parts, production resources, available technology, and so on.

Process planning includes the two stages *process design* and *operations design*. These work at different levels and within different feedback loops. Process design is the macroscopic decision-making of an overall process route based on the activities *flow analysis* and *workstation selection*, whereas operations design is the microscopic decision-making of the types of individual operations in this route, based on *operations research and analysis* activities, which include man-machine systems analysis. Depending on the type of production system, other activities such as *line balancing* may be included here. Process design decisions are often fed back to product planning, calling for a modification of product design and further development. Operation design decisions lead to production implementation, i.e. operations done in the factory (Hitomi, 1996).

As Wu (p. 128) notes, process planning is “an extremely important part of the total manufacturing process – any mistakes here will have a significant and undesirable impact on subsequent production operations”. In addition, process planning will also provide data for other functions of the organization, such as cost-control. Traditionally, process planning has been carried out with manual-based systems, which rely heavily on the knowledge, skill, and experience of trained production engineers. To reduce this dependency and improve the efficiency of the process planning function, computer-aided process planning (CAPP) systems have been developed.

Scheduling – The production plan is then disaggregated through several steps to obtain short-term schedules, showing for every production cell, its goals for the next shift. The jobs are then sequenced by the order in which they will be loaded onto the machines. This process is referred to as *scheduling*, which thus involves the specification of the sequence of operations required for converting the raw material into parts parts and then assembling parts into products, the sequence of machine tools, the tools required, and the machine settings. Depending on the type of manufacturing system, scheduling may also involve the determination of run lengths, a task referred to as lot-sizing, with the objective to minimize setup costs and setup times (Metaxiotis et al., 2001). Scheduling also includes *dispatching*.

Control – As mentioned previously, control is the measurement and correction of the scheduled activities to ensure that they are consistent with the plan. This can be done manually or with the aid of computers, so-called shop floor control systems, or a combination thereof. Control is also referred to as monitoring. In this context, it should also be noted that *real-time* management will affect the way in which planning and control is carried out. As Davis (1998) explains, in the real-time management setting, planning and control cannot be addressed independently, since a controller cannot rely upon another, separate planning entity to perform its planning. Each controller much plan its own strategy, and then implement this strategy.

6.3.4 Production Operations

Production operations, which may also be seen as the *implementation* of the production plan and as such are part of production management (Hitomi, 1996), are generally of either a *fabrication* or *assembly* nature, where fabrication (or parts manufacturing) refers to the removal of material from the raw stock or a change in its form for the purpose of obtaining a more useful form, and assembly refers to the combination of separate parts or raw stock to produce a more valuable combined unit.

6.3.5 Material Flow & Layout Planning

Material flow, also known as *internal logistics*, is concerned with the techniques used to transport parts, tooling, and scrap throughout the facility, and *layout planning* is concerned with the physical placing of production processes within the facility, the spatial relationships of the related processes, the delivery of required services such as compressed air, lighting, and electricity to the work areas, and the removal of waste products such as paint and welding fumes, chips, and coolant from those areas. Its overall aims are to achieve an efficient production, a stable utilization of production facilities, low WIP levels, a flexible and adaptable production, and an economical production as determined in previous stages (Hitomi, 1996). Its primarily results are the material handling system (MHS) and the physical layout.

6.3.6 Logistic Planning and Design

Logistics, the second aspect of the material flow as mentioned previously, deals with *transportation* and *distribution* problems. Transportation (or materials-supply) means allocation of the raw materials purchased from suppliers to the organizational units of the manufacturing enterprise, and delivery of the finished goods to its delivery points, such as distribution centers, markets, and end customers. Distribution looks at how the total transportation distances or times can be minimized, a problem known as the traveling salesman problem. Logistic planning and design activities are commonly referred to as *supply chain management (SCM)*.

The next section will look into more detail at the order in which these PRP activities are carried out.

6.3.7 From Serial to Concurrent Engineering

Traditionally, PRP activities have been carried out in a serial sequence – known as serial (or sequential) engineering. As Starbek et al. (1999) state, “at the beginning of the information age it seemed that sequential execution of activities was the only possible way of ensuring information flow control”. As evidence of this, the so-called *waterfall methodology*, which is basically a model of a sequential series of activities that originated in software development (Royce, 1970), was commonly used to illustrate the product realization process (Lund and Tschirgi, 1991). However, these activities are today not seen as strictly sequential stages, but rather as taking place with a certain degree of concurrency, a concept familiarly known as *concurrent engineering (CE)*.[34]

Concurrent engineering is a systematic approach to integrated, concurrent development of products and their corresponding production processes, including supporting activities such as maintenance, and distribution.

Today, there seems to be a general agreement in both academia and industry that the concurrent development of products and processes in a direct dialog with customers in the market places is required in order to obtain a good customer satisfaction (Sohlenius, 1992).

Concurrent engineering trends are also suggested by the introduction of the *spiral methodology* as proposed by Boehm (1988), and modifications of the waterfall methodology that incorporate various forms of feedback loops, see e.g. Oura (2000).

In theory, the benefits of CE are evident – by overlapping activities so that they occur in parallel the total lead time in development projects can be significantly reduced. In addition, it is widely agreed upon today that as much as 70% to 80% of the total product development cost is incurred in the early development stages (see e.g. Kulvatunyou and Wysk, 2000). This is another major reason for concurrent engineeering: to support the exchange of information between cost-deciding activites and cost-consuming activities.

However, the fact that CE requires a much higher degree of cooperation and communication among functional areas than serial engineering makes it difficult to implement in practice. The reason is that this requires both well-functioning information systems and organizational changes. The latter is necessary to deal with what Starbek et al. (1999) call *information deadlocks*, i.e. organizational barriers (or walls) between departments that hinder efficient and effective communication by allowing for little more than feedback on the errors and defects that have been passed on from previous departments or functions. On top of this, a full scale CE implementation requires the involvement of suppliers, customers, and partners in the product realization process.

Indeed, the extent to which the manufacturing industry really has managed to organize these activities to occur in parallel is subject to much debate. While a considerable amount of theoretical material exists, this author would argue that there seems to be a limited degree of success in implementing CE principles in real life.

In any case, research in this area continues. Among the issues addressed is the need to map interactions between activities, usually described with *loops*, in order to decide the appropriate degree of concurrency. Obviously, all PRP activities cannot be performed concurrently as different informational requirements will limit the parallel execution of individual activities. Here, Starbek et al. (1999) support the use of 3-T loops, meaning that each loop has interactions among three activities, and highlight the need to build a supporting information system.

As evident from the above, *information* plays a crucial role in both PRP and CE activities. As Askin and Standridge (1993) state, information flow is what drives all PRP functions, oversees their coordination, and measures compliance with corporate objectives. In this context, it is also important to note that the requirement on a manufacturing system's information system (IS) to interact with accounting, purchasing, marketing, finance, human resources, and other administrative functions. Although these other functions have not been treated in detail here, it is of fundamental importance to acknowledge their impact on the MSD process: all these interactions increase the communication channels and add tremendously to the amount and diversity of information that the manufacturing system has to handle, particularly in the transition fromm sequential to concurrent engineering.

6.3.8 From Physical to Virtual Manufacturing

The previous section described a transition in *time*, from serial to concurrent execution of activities in the product realization process, a paradigmatic shift in the view on PRP activities. Perhaps an even more profound shift of the PRP is the transition of these activities from the *physical* to the *virtual* world. This is known as *virtual manufacturing (VM)*, and can be defined as (Lin et al., 1995):

> **Definition 6.2** VIRTUAL MANUFACTURING
>
> The use of computer models and simulations of manufacturing processes to aid in the design and manufacturing of products.

A more comprehensive description is the following (Lockheed Martin SAVE Team, 1998, p. 3):

> Virtual Manufacturing (VM) is the integrated use of design and production models and simulations to support accurate cost, schedule and risk analysis. These modeling and simulation capabilities allow decision-makers to rapidly and accurately determine production impact of product/process alternatives through integrating actual design and production functions with next generation simulation.

Few studies exist, however, that describe the actual implementation of VM in industry. One problem is to assess when a company moves from just using simulation to virtual manufacturing. Does it require a formal VM strategy? Are a particular tools or set of tools needed? Does there have to be a VM methodology? It seems that many of these questions are left unanswered.

Nevertheless, some indications of problems exist. According to the Lockheed Martin SAVE Team (1998), growth in the use of virtual manufacturing tools has been limited by the costly, manual transfer of data among the set of simulation tools. Design teams typically use 2-D or 3-D CAD data during product development. On the basis of this data, the cost, schedule or risk impacts of these decisions on production operations are assessed through the use of another set of VM tools. These tools use much of the same data as input, but each requires different internal data formats. Manual reformatting and reentry of these data have prohibitively high costs associated with them, but few methodologies seem to exist that address the question of how these manual tasks should be avoided.

6.4 The Manufacturing System Development Process

If the product realization process is the set of activities needed to execute the function of the manufacturing system, the *manufacturing system development process* can be thought of as the set of activities needed to execute the PRP.

Based on this view and given the system properties described earlier, manufacturing system development is here defined as:

> **Definition 6.3** MANUFACTURING SYSTEM DEVELOPMENT
>
> The act or process of planning, implementing, or controlling the set of activities that creat, change, or remove the properties of a manufacturing system with the purpose of executing the operations of the product realization process.

The term “development” in manufacturing system development thus comprises activities that are referred to as design, implementation, operations, redesign, reconfiguration, reengineering, etc. of manufacturing systems and operations. From this definition, it should also be evident that “manufacturing system development" and the "manufacturing system development process" carry synonymous meanings.

Moreover, they take place over the manufacturing system *life cycle*. In industry several classifications and terms are used to describe this life cycle. For example, several companies in the automotive industry uses the gate system (see e.g. Klingstam and Olsson, 2000). As with the PRP, the ultimate representation of the life cycle will depend on a number of factors, such as the type of operations, etc. Here, the generalized system life cycle terminology defined by GERAM will be used as an illustration. According to this model, the life cycle consists of the following steps:

1. identification,
2. concept,
3. requirements,
4. preliminary design,
5. detailed design,
6. implementation,
7. operation,
8. decommission.

How the MSD process is ultimately specified and what terminology is used will depend on the particular firm. Several differences in terminology exist, and will not be further explored here. As an example of these steps in a virtual manufacturing context, they can be broken up into the following set of methodologies (Brown, 2000):[35]

1. define all constraints and objectives of the production system,
2. define the best process to build the product and its variants according to targeted constraints and objectives,
3. define and refine the production system process resources and and architecture, and measure its anticipated performance,
4. define, simulate and optimize the production flow,
5. define and refine the plant layout,
6. develop and validate the control and monitor functions of the production system, execute the schedule,
7. balance the line, calculate costs and efficiencies of the complete production system and select the appropriate solution,
8. download valid simulation results to generate executable shop-floor instructions,

9. upload, accumulate and analyze performance data from actual production system operations to continuously optimize the production process, and
10. support field operations with maintenance instructions and monitor maintenance history.

This example illustrates the particular activities that need to be carried out in virtual manufacturing. However, there is no consensus as to the exact nature of VM, neither regarding the steps to be taken nor the impact on the physical process of actions done in the virtual world.

6.5 Problem

As this chapter has showed, the development of manufacturing systems is complex, dynamic, and subject to uncertainty to such an extent that problems related to these activities are inevitable. It is therefore not surprising that there is ample evidence of such problems. Askin and Standridge (1993, p. 12) illustrate some of the problems in the following way:

> The natural environment changes slowly. Physical phenomena such as gravity continue as constants through time and across space, facilitating recognition and description. [...] Manufacturing systems, on the other hand, are relatively new, complex, and dynamic. Their performance varies with changes in human knowledge and needs instead of any inherent properties. [...] two manufacturing systems with the same number of machines could have widely disparate production rates, throughput times, and quality. [...] When designing systems [...], humans create artificial constructs for interpreting and integrating components. These include how machines are located and maintained, how parts are batched and dispatched, and how performance is measured. Even the terminology and framework with which we view the system is artificial and subject to change through time.

Here, Wu (1994, p. 12) observes that, “there has been no shortage of statements about how things can go wrong with manufacturing in today’s business environment”, and exemplifies these problems as:

- failure to invest in new plant and equipment,
- inefficient management practice,
- lack of coherent management strategy,
- inadequate educational and professional training system,

- lack of the awareness of the importance of manufacturing,
- high cost of materials and labor,
- unfair overseas competition, and
- cultural background and social attitudes.

To solve these problems (or at least attempt to solve them), it is usually said that the means of doing so relate to *management*, *organization*, and *technology*. These in turn break down into several subgroups, in which there are basically two kinds of measures to be taken – *strategic* and *operational*.

To start with the strategic measures available for manufacturing enterprises, it should be obvious that the development of the manufacturing system is a key strategic activity mainly for two reasons:

1. **added value** – the production system adds most of a product's value, and is critical to the quality of products and services;
2. **cost and complexity** – a production system is capital intensive and its development and operations connected to other activities to such an extent that its design is the key to efficient and effective coordination of resources.

Thus, the manufacturing system releases or ties up money, time, and people from other business processes depending on the degree of success of its development. Improvements in manufacturing performance thereby 'enhance overall business performance by supporting innovative, strategical and competitive competencies and capabilities' (Small, 1999, p. 267).

However, due to the inherent complexity and dynamics, the development of manufacturing systems requires a great deal of information to be dealt with, efficiently, accurately and fast, by a great number of people. Hence, it becomes crucial to *manage* all this information, efficiently and effectively.

Manufacturing system development is made difficult because of the ever-persistent business dynamics, forcing organizations to be flexible in many different ways, as outlined in Section 6.2.4.

Moreover, activities related to the development of manufacturing systems compete with each other, mainly for three reasons: (i) they cross organizational boundaries by involving customers, partners, suppliers and sometimes competitors; (ii) they encompass organizational structures by involving different kinds of business processes, activities and information; and (iii) they have to share limited resources of time, money, equipment and people.

In this situation, it becomes increasingly difficult to *organize* a large number of people, processes, activities, systems, technologies, etc. acting in different organizational structures and corporate cultures, so that the right people and the right processes have the right information and the right resources at the right time. This, however, is necessary for successful development of manufacturing systems.

In other words, there is a need for a *management* function, which can *organize* all these activities and deploy the necessary *technology* so that they are carried out with a maximum of efficiency and effectiveness, something that calls for both strategic and operational measures that are based on well-informed and correct decisions.

The manufacturing industry is of course trying to deal with this in many different ways; through the use of more advanced manufacturing technologies, information and communication technologies, enterprise resource planning, and new management and manufacturing philosophies, strategies, and concepts, including lean and agile manufacturing, concurrent engineering, enterprise integration, modularization of products, hyper-flexible assembly, mass-customization, outsourcing of activities, virtual and extended enterprises, virtual manufacturing, or other strategic and tactical measures, some of which have been mentioned earlier in this chapter.

So, how successful has the manufacturing industry been then? The answer seems to be “it depends”. Although there is a large number of successful cases of managerial, organizational, and technological change, the results have been inconsistent across the industry. In a sense, it thus appears as if success depends more on an individual company’s ability to use its resources of production in the best way, and less on the availability of generic methodologies to guide system development. Of course, it is easily argued that this fact will always hold true; that companies, though appearing structurally similar on the surface, will always perform differently due to differences in inherent characteristics, and that, conversely, there simply is not much one can do, least of all try to develop “manufacturing panaceas” – a cure for all and everyone. Indeed, it is difficult to argue against that. On the other hand, it can be argued that the availability of holistic, generic and structured approaches will enable more manufacturing firms to successfully deal with today’s business environment by improving the efficiency and effectiveness with which they develop their manufacturing systems.

At the same time, however, we find that several researchers acknowledge the absence of such approaches, at least in industry. As Yien and Tseng (p. 392) note, “manufacturing system design still remains mostly in the trial-and-error stage [...] Historically, manufacturing systems are built with heavy dependence on empirical experience”. In other words, it appears that most of today’s manufacturing systems have evolved more or less ad hoc (Yien and Tseng, 1997), or as Mårtensson (2000*b*) suggests, through evolution rather than deliberate design. Early on, Shingo (1989) noted that the division of the production system into functional areas, including the division into fabrication and assembly with separate sets of engineers working with each area leads to thinking from a limited perspective and to the optimization of individual production operations instead of entire processes. This phenomenon, known as *sub-optimization*, means that performance measures for each functional area, such as efficiency and cost-effectiveness, may be increasing while the performance of the manufacturing system as a whole, and thus its profits, are both declining. This was labeled the *Productivity Paradox* more than a decade ago in a famous article by Skinner (1986).

Several years later, however, Yien and Tseng (p. 395) note that, “there is still no consensus as to the approaches and techniques best suited for the design of manufacturing systems”. Wu (1994, p. 19) agrees, stating that, “the functions and underlying mechanism of the relevant manufacturing systems in question have not been sufficiently analyzed and understood by the people concerned in manufacturing industry”.

What about empirical evidence of these problems? A 1998 survey of the development, operation and maintenance of manufacturing systems in Swedish manufacturing firms showed that methodologies were rarely used by the surveyed companies (Gullander and Klingstam, 1998).

As another example, a 1997 investigation of overall equipment effectiveness (OEE) of 28 companies in the Swedish manufacturing industry showed that output was less than half of what it could be (Nord and Johansson, 1997).[36]

As mentioned above, one way of dealing with this is to develop holistic, generic, and structured approaches. Part IV will look at this in more detail.

In conclusion, this section has detailed a comprehensive amount of problems related to the development of manufacturing systems. Obviously, the research presented here does not aim to solve them all. If we summarize the main problems that do seem to be within the scope of this thesis, they are the following:

1. dealing with complexity and dynamics,
2. managing information,
3. measuring manufacturing performance,
4. specialized and fragmented views on the manufacturing system, and
5. unstructured *ad hoc* approaches to system development,

These problems can be addressed by the following:

1. modeling & simulation,
2. information management,
3. performance measurement systems,
4. holistic and systemic views,
5. structured and generic approaches to system development,

Based on this summary of problems, the following will detail how this thesis addresses them. As should be evident by now, virtual manufacturing and modeling & simulation are central to this research. They will be described in more detail in the remaining sections of this chapter. Information management *per se* is not the topic of this thesis, but should be seen as both an important prerequisite and a spin-off of successfully performed development projects, including simulation studies. In addition, it is important to recognize the strong dependence of all manufacturing operations, including of course simulation, on information systems. Chapter 7 will attempt to explain why this is so in more detail. The same can be said about performance measurement systems, since discrete-event simulation in itself does not have this functionality. If used wisely, however, Chapter 8 will argue that discrete-event simulation can indeed be seen as a provider of important performance measures, and that, as such, it can support and control the manufacturing strategy. The choice of holistic and systemic views is the foundation of this research approach, and was motivated in Chapter 4. Structured and generic approaches to system development is what this entire thesis aims at. As stated in Chapter 2, it is the overriding objective of this research, ”to suggest a methodological framework for integrating simulation into manufacturing system development”. This will be done in Chapter 14, which will also discuss the genericity of the proposed methodological framework.

The next section will summarize the three areas that are seen as the most important for future manufacturing system development.

6.6 The Future of Manufacturing System Development

Given the diversity and complexity of manufacturing operations, several research areas are needed in future directions of manufacturing system development. From the perspective of this thesis, however, it seems safe to pinpoint the following three areas as the most important:

1. structured approaches to manufacturing system development,
2. the view on modeling & simulation in manufacturing.

We could add, of course, several information-related issues, such as infrastructures, modeling, etc. These are important areas too, but outside the scope of this thesis.

Structured Approaches to Manufacturing System Development – As argued by several researchers, (recent work in this area include Almström, 2001; Bellgran, 1998; Klingstam, 2001; Mårtensson, 2000*a*) manufacturing system development needs to follow structured approaches based on design theories, such as AD.

A concept or discipline that attempts to deal with these issues is enterprise engineering and integration (EEI), which is also the most relevant in the context of this thesis. It will be described in more detail in Section 8.4.

Modeling & Simulation in Manufacturing – The 1990s saw an increase of the use of simulation as a tool to cope with these conditions. In addition to what can be termed as traditional use of simulation, one of the overall objectives was to integrate market, design and production activities by supporting and increasing the efficiency of the exchange and sharing of information through the use of advanced simulation tools (Bolmsjö and Gustafsson, 1998).

This author believes it was for a good reason: as will be further argued in the next chapter, simulation is a technique well suited to deal with high degrees of complexity and dynamics, and support a large variety of decisions that require change.

A fundamental component in both virtual manufacturing and simulation is *modeling*. As Askin and Standridge (1993, p. vii) state, “models address a wide range of manufacturing system design and operational issues and are therefore essential tools in many facets of the manufacturing system design process”.

As Section 6.5 described, not only are there many different manufacturing system types, with their own system description and design and operations problems, but no two manufacturing systems are identical. Conversely, thorough knowledge of appropriate modeling techniques becomes very important.

6.7 Summary

As we move into the 21st century, we see that globalization has put manufacturers in a position where they not only have to compete on a tremendously huge market – the largest enterprises now operate in more than 100 countries – but where any market presence means tougher competition and more demanding customers than in the past.

Certainly, the impacts are profound in virtually all areas of society. For example, as frequently seen in media reports, global operations have political implications in that they put focus on world trade and employment issues, or on environmental considerations.

While these issues may be outside the scope of this thesis, we can easily identify several important relationships to events taking place outside the boundaries of the manufacturing system. These events occur with regulatory bodies, financial markets, unions, and as a result of technological development, and they affect the manufacturing system as uncertainties and pressure to change.

Focusing on the context of this thesis, these developments are no less profound: they bring with them increased complexity, stronger dynamics, and more frequent change of manufacturing operations all over the world. Moreover, it is becoming increasingly difficult for manufacturing enterprise executives not only to formulate a corporate strategy, but more importantly to translate that strategy into guidelines for managing everyday business processes including manufacturing operations.

With these trends being continuously reinforced, top executives and managers of large manufacturing enterprises will increasingly have to base their decisions less on direct experience and more on corporate information systems. In addition, they must make sure that these decisions can be implemented through formalized and structured approaches, rather than ad hoc courses of action, and they will have to make their decisions more frequently than ever.

Here, it should also be noted that this situation in no way confines to large multinational corporations only. As always, a majority of the challenges that these large manufacturers face will transfer down to their suppliers, the small and medium-sized enterprises (SMEs), representing a large number of companies and individuals. As an evidence of SMEs trying to cope with these conditions, we see frequent changes in buyer-supplier relationships, perhaps most notably in but certainly not limited to Japanese industry.

Thus, as we try to improve the development of manufacturing systems, we have to consider interactions within an entire industry, as well as between that industry and its environment; all characterized by *globalization*, *dynamics*, and *change*. Next, we turn to one very powerful way of dealing with this situation: discrete-event simulation.

Notes for Chapter 6

[24] Appendix A provides the basic definitions of manufacturing and production.

[25] The exact figures for these countries are as follows: Germany 21.5%, Italy 22.4%, Japan 23.5% (all figures taken from the United Nations Industrial Development Organization (UNIDO), www), Sweden 22% (Teknisk Framsyn, 2000), United Kingdom 21.3% (The Economist, 2001*e*), and the United States 17.4% (The Economist, 2001*e*). Note: These figures stem from different years. Please refer to the original sources for further information.

[26] Since productivity has such a wide scope and is treated by a large number of authors, the reader is referred to Hitomi (1996, pp. 15-22) for a good start on a more detailed discussion on this and related topics.

[27] The Cannondale story is mainly based on the author's own experience and knowledge of bicycle manufacturing in general, and Cannondale bicycles in particular. Some of the technical information was taken from Cannondale's Web site (www.cannondale.com), which also features the article "Tour de Cannondale" by Lennard Zinn, reprinted from VeloNews. This article gives a more detailed account of how Cannondale and bicycle manufacturers in general went about making frames around 1988, the time when Cannondale started implementing its new production philosophy, and how things changed dramatically after that.

[28] Morgan Motor Company remains the world's oldest privately owned car manufacturer, and is still run by the founder's descendants. To be fair, things have improved at the company, and the same consultant, according to the official Morgan Website (Morgan Motor Co., www), proclaimed one of the models (the Aero 8) to be "an outstanding success" when he revisited the factory in March 2000. However, judging from the following text found on an enthusiast Website (Morgan Mania, www), tradition still holds strong: "The factory at Malvern Link hand build around 10 cars per week and there is a 5 to 7 year waiting list to purchase a new car. They also have the record for the longest production run of a single model in the world, the 4/4, first made in 1936 and still being hand built."

[29] Phadke (1989) defines the response as any quality characteristic of a product or a process.

[30] The principal difference in Figure 6.3 to the IDEF$_0$ model should be noted here.

[31] The reader is referred to Vernadat (1996) for a more detailed description of the GERAM, CIMOSA, GIM, and PERA frameworks.

[32] Although Hitomi offers a detailed account of the product realization process activities, it is somewhat inconsistently presented. For clarity, Hitomi's contribution is best seen through the perspectives of the six manufacturing aspects.

[33] Provided that all precedence relationships are respected, the exact order of

these activities should not be seen as occurring strictly as here outlined. This subject is further treated in Section 6.3.7.

[34] Concurrent engineering is also referred to in literature as *simultaneous engineering*, *parallel engineering*, and *integrated product and process design (IPPD)*.

[35] Brown (2000) uses the term *digital manufacturing*.

[36] The study is based on data from 130,000 hours of production covering 100 manufacturing subsystems (MFSS) within the 28 companies.

7

Discrete-Event Simulation

On screen!

– Captain James T. Kirk

This chapter will answer the following questions:

- Q *What is simulation and discrete-event simulation in particular?*
- Q *What can it do for manufacturing system development?*
- Q *What are the problems with discrete-event simulation?*
- Q *Where will the future take this technology?*

To this end, the chapter is organized as follows:

In order to provide for the basic understanding of simulation needed for the rest of this text, Section 7.1 puts simulation into proper context and motivates its status in this thesis, Section 7.2 describes simulation *theory and practice*, Section 7.3 goes into more detail of this subject by exploring simulation *methodology*, and Section 7.4 summarizes the advantages and disadvantages of simulation. Section 7.5 then takes a closer look at what this technology can do for *manufacturing systems*, and Section 7.6 summarizes and elaborates on the *problems* associated with discrete-event simulation of manufacturing systems. Finally, Section 7.7 tries to look into the *future* of discrete-event simulation in a manufacturing system development context.[37]

7.1 Context and Motivation

From the inner workings of atoms to the expansion of the universe; nearly everything known to our world can be simulated. Manufacturing, being one of the most basic, yet wonderfully complex systems devised by man, is of course no exception. Simulation, and discrete-event simulation (DES) in particular has been applied to various aspects of manufacturing since the 1960s. The introduction of computers in simulation made possible the analysis of more complex problems, and the 1990s in particular saw the possibilities of simulation greatly expand as a combined result of software development and reduced cost of computing power.

Turning to the scope and context of this thesis, it is often argued that simulation in general, and discrete-event simulation in particular has attained the status of an important problem-solving methodology for the solution of many problems in the manufacturing industry. Indeed, among the various simulation techniques available, discrete-event simulation can be said to be the most generally usable, and in a manufacturing system context, supply chains and production systems are being simulated with increasing frequency (Banks, 1999).

Shortly, we will look into more detail at why this is so, and whether things could be even better. For now, suffice it to say that the potential of this technology is indeed great: understanding systems behavior and the parameters that affect performance is vital in development and operations of manufacturing systems. In this context, discrete-event simulation is fundamental to the assessment of a new manufacturing system design or operations management policy since many of the measures used are dynamic in nature. Discrete-event simulation thus provides analysis, description and evaluation capabilities of systems, and if successfully applied can support collaborative work across organizational boundaries and thereby improve information and communication. In addition, it can be used for training and educational purposes. By these means, simulation can provide several benefits, such as significantly improve system knowledge, speed up production ramp-up time, shorten development lead time, increase utilization and productivity and support decision making throughout an organization. The author has also found that simulation increases the awareness of performance measurements and emphasizes the importance of those measures to the people involved in simulation projects. Simulation can also be seen in the context of organizational learning, a focus of recent years' management theory.[38] As Senge and Fulmer (1993, p. 21, 25) state:

> Although mental models are rich in detail, they are deficient in critical ways. They focus deeply on particular parts of a business and are superficial regarding other [...] parts. They are predominantly static and do not clearly distinguish assumptions about structure,

> behavior, and expected outcomes of policy changes. Mental models are largely tacit, expressing themselves as intuitions […] that are difficult to communicate and share […] through computer-simulation models […] micro worlds[39] could transform how organizations learn.

As will be argued here, however, a number of problems remain to be solved if the full potential of discrete-event simulation is to be realized. Before these problems are described, we will briefly go through the history, theory and practice of DES, outline the steps taken in a typical simulation study, summarize the advantages and disadvantages of simulation, and take a closer look at the application areas in manufacturing.[40]

7.2 Theory and Practice

One of the simplest definitions of simulation that this author has found is given by Page (1994, p. 15):

> **Definition 7.1** SIMULATION (I)
>
> The use of a mathematical/logical model as an experimental vehicle to answer questions about a referent system.

As the author observes, “this definition seems to be efficient in the use of words and careful not to presume certain conditions or implicit purposes. For example, computer simulation is not mandated; the model could follow either discrete or continuous forms; the answer might not be correct; and the system could exist or be envisioned.” Simulation can be defined in several other ways however. Banks, Carson, Nelson and Nicol (2000, p. 3) offer the following:

> **Definition 7.2** SIMULATION (II)
>
> The imitation of the operation of a real-world process or system over time. Whether done by hand or on a computer, simulation involves the generation of an artificial history of a system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system.

In this context Fishwick (1995) gives an appealing *description* of simulation:

> The use of simulation is an activity that is as natural as a child who role plays. Children understand the world around them by simulating (with toys and figurines) most of their interactions with other people, animals and objects. As adults, we lose some of this childlike behavior but recapture it later on through computer simulation.

These definitions and the description were chosen because they each emphasize one of three important characteristics of simulation, namely:

1. the answering of questions, *through*
2. the imitation of systems, *resulting in*
3. an increased understanding of the world.

The purpose of the questions answered by simulation is to form the basis of some *decision*, hence the common label on simulation as *decision support*. As Page notes, the overriding objective of simulation is not only to support decisions, but to support *correct decisions*. Whatever the purpose of the simulation, whatever the technique used or time available, this objective should never be compromised.

While most simulations could be performed manually, this process would usually require an unrealistic amount of time. The computing required in many simulation cases will often correspond to years, decades or even centuries of comparable man hours. When speaking of simulation in general terms, it is therefore usually understood that the simulation is done with the aid of a computer, taking advantage of its speed in imitating a system over time, i.e. *computer simulation*. Computer simulation methods have developed since the 1950s, and as Pidd (1998, p. 3) notes, “the basic principles are simple enough. The analyst builds a model of the system of interest, writes computer programs which embody the model and uses a computer to imitate the system’s behavior when subject to a variety of operating policies”. More formally, the computer simulation domain can be seen as consisting of three primary subfields, or core processes, as shown in Figure 7.1.

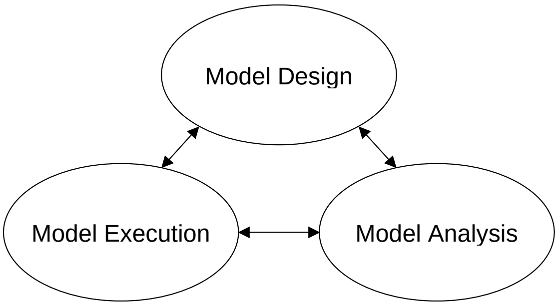


Figure 7.1 *Three sub-fields of computer simulation. Source: Fishwick (1995).*

The implications of these three sub-fields will be further explained in later sections; the concept of *model* in Section 7.2.2, and the set of activities needed to execute the activities in these fields, i.e. *simulation methodology*, in Section 7.3.

From what has been said about simulation so far, we can now identify the following set of key simulation principles: (i) system, (ii) model, (iii) technique, and (iv) software.

The remainder of this section will describe these simulation principles in the order that they have to be decided on in a real case, starting with *system*.[41]

7.2.1 System

Simulation starts by deciding on something that is to be simulated. This something is usually seen as a *system*, and does not have to exist in the real world; it can be an idea or a concept.

As suggested previously, there are several ways of describing systems. Some of the predominant were mentioned in Sections 4.4.1 and 6.2. Basically, there should be no need to introduce new system aspects or terminology specifically for simulation purposes other than what is already used to describe systems in general. However, in many cases simulation makes the need to formalize systems more explicit.

Before we move on, the time has come to expand our systems frame of reference by adding two fundamental definitions (Banks et al., 2000, p. 10):

> **Definition 7.3** State
>
> The collection of variables necessary to describe the system at any time, relative to the objectives of the study.

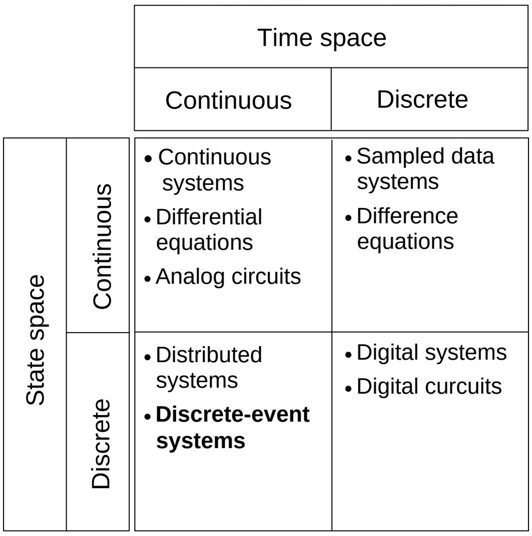
> **Definition 7.4** Event
>
> An instantaneous occurrence that may change the state of the system.

Depending on how the state variables change over time, there are basically two types of systems – *discrete* and *continuous* – leading us to the next two definitions (Banks et al., 2000, p. 12):

> **Definition 7.5** Discrete System
>
> A discrete system is one in which the state variable(s) change only at a discrete set of points in time.

> **Definition 7.6** Continuous System
>
> A continuous system is one in which the state variable(s) change continuously.

The scope of this thesis is focused on discrete systems. Relating to this division between discrete and continuous state change, a distinction can also be made between the *time* and *state* space. The time space of manufacturing systems is always continuous. In discrete-event simulation it is therefore the state space that denotes the “discreteness” as shown in Figure 7.2.



		Time space	
		Continuous	Discrete
State space	Continuous	• Continuous systems • Differential equations • Analog circuits	• Sampled data systems • Difference equations
	Discrete	• Distributed systems • **Discrete-event systems**	• Digital systems • Digital curcuits

Figure 7.2 *System taxonomy. Adapted from Kim (www).*

Once a system has been chosen, it is necessary to represent this in a way that will increase understanding of the system and make possible the studying of the system, possibly with a computer. For this purpose, a *model* is used.

7.2.2 Model

A model can be defined as follows (Banks et al., 2000, p. 13):

> **Definition 7.7** MODEL
>
> A representation of a system for the purpose of studying the system.

As Banks et al. (p. 12) state, “model components are represented similarly to system components. However, the model contains only those components that are relevant to the study”. Here, Banks (2000, p. 1.6) points out the following:

> A model should contain enough detail to answer the questions you are interested in, without containing more details than necessary.

A large variety of model types exist in both theory and practice. Which type of model that is used will depend on the type of system and the purpose of study. Figure 7.3 provides for a basic classification of model types.

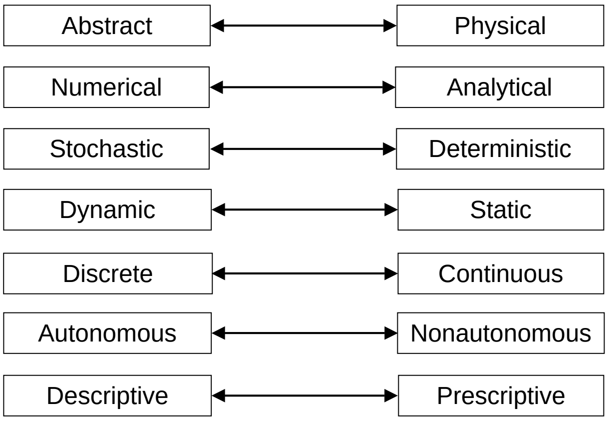


Figure 7.3 *Various types of models and their distinctions.*

The models considered here, i.e. discrete-event models designed for computer simulation, are abstract, numerical, stochastic, dynamic, discrete, autonomous, and descriptive, although several exceptions exist; for instance, some stochastic and discrete simulation models may be both partly deterministic and partly continuous.[42]

A few comments can be made here however. First, apart from always being abstract, numerical, and dynamic, the models considered here are always *descriptive*, in other words they describe the behavior of the system without any value judgment on the quality of such behavior. A prescriptive (or normative) model, on the other hand, describes the behavior of a system in terms of the quality of such behavior. When solved, such models provide a description of the solution as optimal, suboptimal, feasible, infeasible, and so on (Page, 1994).[43] Secondly, discrete and continuous simulation *models* are defined in analogy with discrete and continuous *systems*. However, a discrete simulation model is not always used to model a discrete system, nor is a continuous simulation model always used to model a continuous system.

In addition to what has been said above, it is important to note that for each model type, there exist several levels of abstraction and many different ways of building the model, something that has led several authors to refer to modeling as a form of *art* rather than a science (Banks et al., 2000; Fishwick, 1995; Page, 1994).

With the above definitions given, we have enough theoretical material to look at simulation *techniques*, the choice of which is made on the basis of system and model type.

7.2.3 Technique

Computer simulation techniques can be divided into three categories:

1. static,
2. continuous,
3. discrete-event.

Static simulation, often referred to as *Monte Carlo* simulation (so named after one of its application areas), is a method by which an inherently non-probabilistic problem is solved by a stochastic process, and where explicit representation of time is not required (Page, 1994). The technique has no common use in manufacturing.[44]

In a continuous simulation, the variables within the simulation are continuous functions of time, usually in the form of a system of differential equations. In manufacturing, a common application area is simulation of mechanisms, also known as robot simulation or geometric simulation, which is used e.g. for off-line programming (OLP) of industrial robots.

In a discrete-event simulation the variables change only at distinct points in simulated time, known as *events* (Pritsker, 1998). More formally, discrete-event simulation is defined by Banks et al. (2000, p. 67) as:

> **Definition 7.8** DISCRETE-EVENT SIMULATION
>
> The modeling over time of a system all of whose state changes occur at discrete points in time – those points when an event occurs.

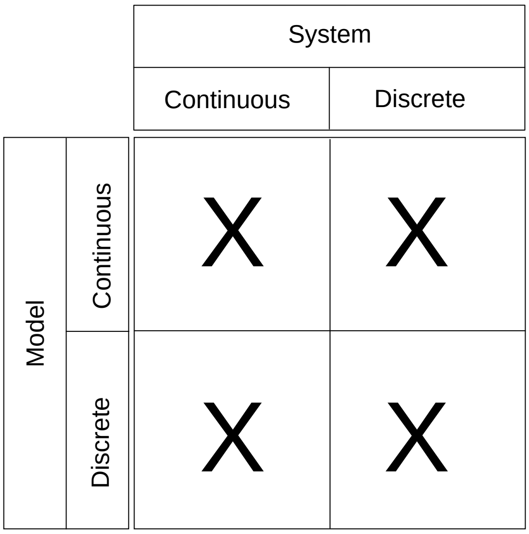
Basically, the question of which technique to choose centers on two questions. First, does time influence the behavior of the system? If not, static simulation will do, such as that performed with a spreadsheet application.

If, on the other hand, time does influence system behavior, the modeler is left with two choices: continuous and discrete-event simulation.

The second question to consider can then be stated as: what is the nature of the behavior that we want to capture in the simulation *model*?

As suggested previously, to answer this question we must look at the state space to determine whether it is discrete or continuous. However, it is important to note that we consider the state space of the *model* rather than the actual system.

As Pidd (1998, p. 22) explains, “in a discrete simulation the variables are only of interest as and when they point to a change in the state of the system”. Here, it can once again be noted that this is not analogue with the behavior of the *system*, but rather the behavior of the *model* of the system. In other words, and as mentioned in the previous section, discrete simulation is not always used to model a discrete system, nor is continuous simulation always used to model a continuous system. In fact, all combinations are possible, as shown in Figure 7.4.



		System	
		Continuous	Discrete
Model	Continuous	X	X
	Discrete	X	X

Figure 7.4 *Discrete and continuous models vs. discrete and continuous systems: all combinations are possible.*

A few examples are in place here. To program an industrial robot, we need to tell it exactly how to move from point A to point B, and thus the whole path needs to be explicitly represented in the simulation model. In other words, the behavior that we want to capture is continuous. The same applies to simulation of sheet metal forming or chemical processes. Here, continuous simulation techniques are required.

If, instead, we consider machines on a production line, we will be interested in whether or not they are working properly; if they are, we want to know if they are in running, setup, waiting, or blocked state; and if they are broken, we will wonder if they are being repaired, waiting for service or waiting for failure detection. All these states change (or can be assumed to change) at discrete points in time. In other words, we see that for a production line, a majority of the states we are interested in change discretely. Here, discrete-event simulation is the right choice of technique.

In other cases, the same system can be modeled both discretely and continuously, depending on what we are interested in, i.e. what the purpose of the study is. As an example, consider a school. If we want to make a schedule for the use of classrooms, our only concern is whether or not a classroom is available. Hence, the system state has only one type of variable – occupancy –

with two possible states: *occupied* and *free*. Since these states will change at discrete points in time only, we can satisfactorily model the system of classrooms (i.e. the school) as discrete. On the other hand, if we are interested in, say, the reasons some pupils feel tired or get headaches (other than lack of interest in the subjects!), we would need to consider a set of variables – such as humidity, amount of oxygen, and temperature – which are all continuous functions of some parameters. Conversely, the system in this case would need to be modeled as continuous.

In recent years, software packages have emerged that can model both discrete and continuous change, since, "the vendors of simulation software have realized that the separation of discrete and continuous simulation is somewhat artificial" (Pidd, 1998, p. 23). A dairy is a good example of the need to model both types of state changes: here our objects of interest appear both as continuously changing amounts of liquid and as discretely changing parts, such as milk packages. Hence, queues also take both forms: tank levels change continuously while the number of pallets in a buffer changes at discrete points.[45] Examples of packages that handle mixed change include AweSim, Extend, and Quest.

Once the technique has been chosen, several important aspects remain for the simulation specialist to consider or at least be aware of. The most significant of these are (Page, 1994):

- simulation programming languages,
- world views,
- time flow mechanisms,
- statistical analysis capabilities, and
- model life cycle support.

Simulation software[46], including simulation programming languages, and world views are described in Section 7.2.4 and Appendix B respectively. Time flow (or time-handling) mechanisms and statistical analysis capabilities are to a lesser degree considered to be within the scope of this thesis, and will not be further described here. The reader is referred to Pidd (1998) for an exposition of time flow[47], and to Banks et al. (2000) for a detailed account of various statistics issues in discrete-event simulation.

7.2.4 Simulation Software

For quite some time, simulation meant running simulation programs written in hard code: from the FORTRAN, ALGOL, and GPSS languages available in the 1950s and early 1960s, to SIMSCRIPT, GASP, and SIMULA appearing over the next few years (Banks et al., 2000).

In those early days, there were basically three kinds of programming languages available to represent simulation models: (i) general-purpose languages, (ii) simulation specific languages, also known as simulation programming language (SPL), and (iii) general languages designed for simulation (Page, 1994).

It was not until the late 1970s that a shift in the focus of the DES community occurred. Existing languages were expanded – GPSS to GPSS/H, GASP to GASP IV, and so on – and new SPLs emerged, such as SLAM II and SIMAN. This was motivated by an evolving recognition of two factors: (i) representing models with programming languages meant having to deal with implementation-related information that obscured actual model behavior, and (ii) using a particular language had direct and often hidden influences on the structure of the model formulation. Thus, a shift from a *program*-centric view of the simulation process to a *model*-centric view started taking place (Page, 1994). Software developments during this period were further driven by the emergence of desktop computers and microcomputers (Banks et al., 2000).

Also, with the emergence of microcomputers in the 1970s and the reduced cost of graphical displays that followed, simulation software packages featuring simple 2-D graphical user interfaces were developed. Some were built on existing SPLs or general purpose languages, while others came with their own unique SPL. The 1980s and 1990s saw the number of such packages increase dramatically, some of the more predominant being Extend and Witness. The 1990s then saw these 2-D based softwares evolve further into packages offering advanced 3-D animation capabilities, such as AutoMod and Quest. With these packages it was no longer necessary to write a computer program in order to build a simulation model; instead the model could be built using graphical user interfaces (GUIs) that provided icons and menues for creating elements, connections, etc. Pidd (1998) refers to this as a *visual interactive modeling system (VIMS)*, whereas Banks et al. (2000) use the term *simulation environments*. Here, the latter term is adopted. A classification of simulation languages and environments, including examples for every class is given in Table 7.1 (Banks et al., 2000; Trick, 1996).

Today, there are hundreds of commercially available DES software packages; some based on the above SPLs, some on general programming languages, and yet others on proprietary SPLs; some are 2-D, others come in 3-D, and a few offer both; and they range in price from a few hundred dollars (e.g. Extend and Simul8) to tens of thousands of dollars (e.g. Arena, AutoMod, and Quest).[48]

These simulation packages can be further classified into *general-purpose simulation packages* and *application-oriented simulation packages* (Law and McComas, 1999), meaning that they differ in their area of application, from very general (such as Extend and Simul8) to highly specialized packages for various manufacturing applications (such as AutoMod and Quest), or call centers (such as Arena's "Contact Center Edition"), just to mention a few. In fact, the level of specialization in manufacturing goes even further, as evidenced by e.g.

Table 7.1 *A classification of simulation languages and environments.*

SIMULATION LANGUAGES	
General-purpose programming languages	ALGOL, C, C++ FORTRAN, Pascal
Simulation programming languages	GASP, GPSS, GPSS/H SIMAN, SLAM
General languages designed for simulation	SIMULA, SIMSCRIPT

SIMULATION ENVIRONMENTS	
2-D animation	Arena, Extend, Witness
3-D animation	AutoMod, Quest, Taylor ED

automated storage and retrieval system (AS/RS) modules (such as for Quest).

Several sources of information exist that provide good descriptions of simulation software from various aspects, including plain descriptions of popular packages and languages used in simulation[49]; similarities and differences between packages (Banks et al., 2000; Klingstam and Gullander, 1999); what to consider when selecting a package; user requirements surveys (Hlupic, 2000); and updated lists of current version and price of the most popular packages.

But which alternative is the best? This seems to be one of the questions where simulation specialists disagree the most, and a "languages vs. environments" debate could fill several pages, (see e.g. Pidd, 1998, pp. 150-151), just as could a discussion on which simulation language or what software package to use. As in many other cases, there is no right answer here other than "it depends." These topics will therefore not be further explored here. A brief note is in place however: the distinction of simulation language vs. environment is not a sharp one since most software environments are based on simulation languages, thereby allowing, and sometimes requiring the user to build the model through programming. For example, Arena is based on the current version of SIMAN (SIMAN V), which can be accessed by the modeler at any time, either to alter or build the model. Similarly, AutoMod and Quest are based on their own proprietary SPLs. Their use differ however. In AutoMod, the language is used to build the model, while Quest's SPL, known as Simulation Control Language (SCL), is an object-oriented language used to build custom logic.

In any case, we have not seen the last of development in this area, or as Banks et al. (2000, p. 95) state, the history of simulation software, "is just reaching middle age". As for where we are now, Banks et al. refer to the current period, which they claim started in 1987, as "the period of integrated environments." The interested reader is referred to Banks et al. (2000) or Pidd (1998) for more material and arguments on this topic, and to Appendix B, which explores the concept of *world views*. The latter is aimed at providing for a better understanding of simulation software used today.

The next section will turn to more practical matters, and look at how simulation studies are performed through the use of *simulation methodology*.

7.3 Simulation Methodology

Page (1994, p. 2) observes that at least until the late 1970s, there actually was such a thing as a *typical* simulation study, and it could be easily described as involving "systems analysis using a single model generated by a relatively small group of modelers, analysts, users, and decision makers."

This, of course, no longer holds true. Discrete-event simulation studies may well comprise several models, distributed across geographical locations, on different computer platforms, involving, directly or indirectly, a large number of people, who may even extend beyond the traditional boundaries of an organization. The nature of the models themselves have also changed, adopting today almost every imaginable purpose, size, life-cycle, or other model characteristic available.

Despite this diversity, the simulation research community seems to agree that simulation studies need to go through a certain number of phases in a specific order if they are to be successfully carried out.

The first observation to be made here is that simulation is not to be seen as one single activity, but rather is to be broken down into a set of phases and procedures.

A frequently used term in this context is *modeling & simulation (M&S)*, indicating that one *first* builds a model of a system, *then* simulates the system.

Another way of describing a simulation study focuses entirely on the *model* as illustrated in Figure 7.1 (refer back to p. 96). According to this view, the steps to be taken are (Fishwick, 1995):

1. model design,
2. model execution,
3. model analysis.

This model-centric view is highly motivated. As Page (1994, p. 4) notes:

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

Conversely, a large number of researchers have concentrated on various modeling issues. Pritsker (1998) set up these basic modeling principles:

1. Conceptualizing a model requires system knowledge, engineering judgment, and model building tools.
2. The secret to being a good modeler is the ability to remodel.
3. The modeling process is evolutionary because the act of modeling reveals important information piecemeal.
4. The problem or problem statement is the primary controlling element in model-based problem solving.

With this basic knowledge of the simulation process in mind, the remainder of this section will briefly detail the actual steps to be taken in a simulation study. The flow chart in Figure 7.5 illustrates one popular view on how these steps should be performed.[50] The order in which the steps are presented below basically follows this figure.

Problem Formulation and Setting of Objectives – These first steps, which collectively can be referred to as *initialization*, assume two things: (i) that a general problem has been identified, and (ii) that an investigation of solution technique has been made resulting in the choice of simulation as the preferred technique (in this case DES). The latter is not necessarily an easy task, since it will depend on a large number of factors. A few guidelines can be mentioned here however, namely that simulation should not be used if (Banks et al., 2000):

1. the problem can be solved using common sense,
2. the problem can be solved analytically,
3. it is easier to perform direct experiments,
4. the costs exceeds the savings,
5. resources are not available,
6. time is not available,
7. data is not available,
8. verification and validation cannot be performed,
9. managers have unreasonable expectations,
10. system behavior is too complex, or cannot be defined.

Based on this, the initialization phase basically involves a refinement of the problem formulation, the setting of objectives including an establishment of performance measures, and the determination of an overall project plan including important milestones (Musselman, 1998).

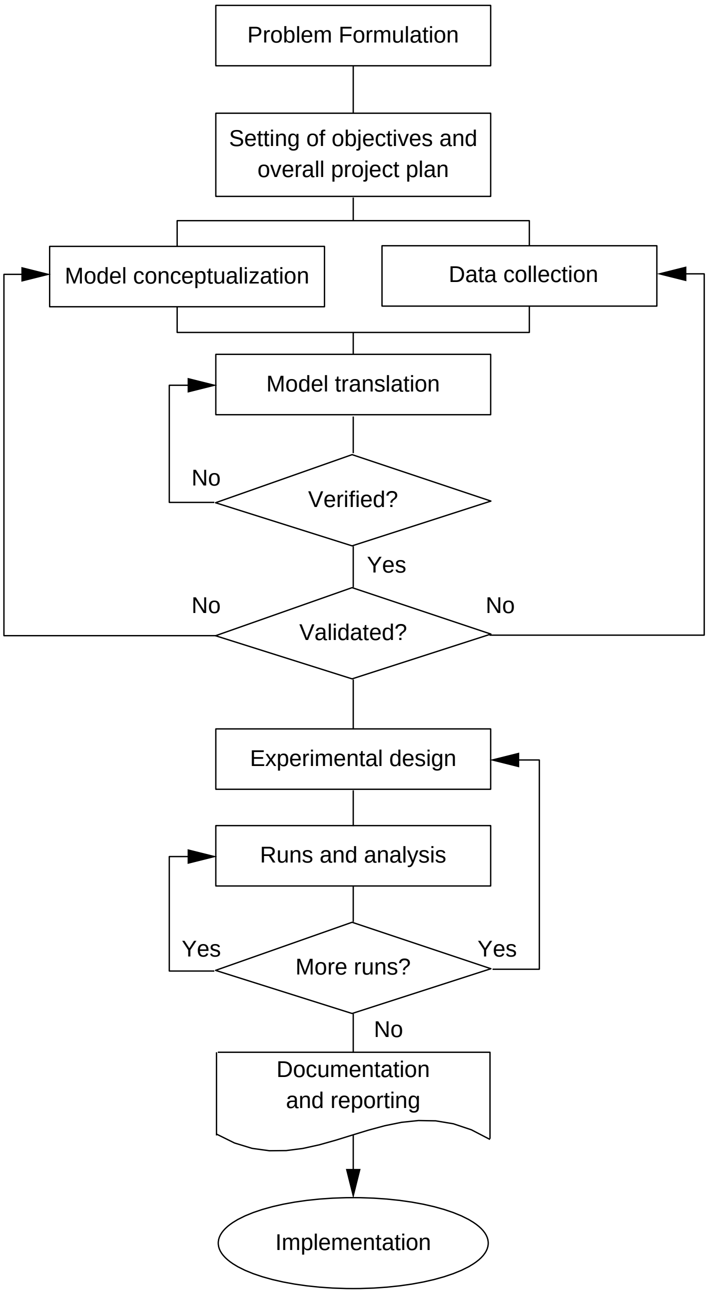


Figure 7.5 *Steps in a simulation study. Source: Banks et al. (2000).*

Model Conceptualization – Some authors distinguish between a conceptual model and a communicative model (Page, 1994). Here, we use the term *conceptual* to denote both, thus implying that model conceptualization is a stepwise process in which the model is made more communicative in steps. These steps make frequent use of flow charts, or state transition charts, and other simple tools, but may also involve more sophisticated modeling techniques such as activity cycle diagrams (described e.g. by Pidd, 1998).

Input Data Collection – This phase can be broken down into several steps, although not every simulation study needs to go through all (*optional step):

1. identify input data needs, such as failures, cycle times, etc.,
2. generate*, if data does not exist in any form,
3. collect*, either automatically or manually,
4. transform*, from one data format to another,
5. identify probability distributions,
6. choose parameters, and
7. evaluate for goodness-of-fit, using e.g. chi-square tests.

As Banks et al. (2000) note, this is not a sequential step in a simulation. Instead, there is a constant interplay between modeling (conceptualization and translation) and the input data collection process. For instance, as the model is better understood in the previous step, the required data elements may change. Also, this step is usually the most time-consuming in a simulation project (Perera and Liyanage, 2000), and should therefore be started as soon as possible. Hence its depiction as a parallel step to model conceptualization in Figure 7.5). A model might also be driven by actual historical data, in which case it is called a *trace driven* model. This will be the case when input data collection according to the above procedure has not been possible.

Model Translation – This phase means translating the model from its conceptual form to one that can be understood by a computer. This step thus involves some form of adaptation of the conceptual model to a model that is described by the programming language used by the simulation software application either directly or through a graphical user interface (GUI).

Design of Experiments – This step involves the determination of what alternatives to simulate, and is usually based on previous runs. More formally, Kleijnen (1998, p. 174) defines design of experiments (DOE) as selecting the combination of factor levels that will actually be simulated in an experiment with the simulation model. Basic issues to resolve here are warm-up time, run-length, and thenumber of replications. This step may be based on a variety of methods, such as the Taguchi method used in R&D. This method is based on reduced trials using orthogonal arrays, an aims at maximizing the signal-to-noise (S/N) ratio (for a good introduction to robust design see Phadke, 1989).

Verification, Validation and Accreditation – Validation answers the question: *"are we building the right model?"* whereas verification answers the question *"are we building the model right?"* In other words, validation determines that the model built is a correct model of reality, while verification compares the computer translated model to the conceptual model. Accreditation is the official determination by the user that the capabilities of the models and simulations fit the intended use and that their limitations will not interfere in drawing correct conclusions (Chew and Sullivan, 2000). This part of verification and validation seems to be gaining increased attention judging from the number of times the term verification, validation & accreditation (VV&A) is appearing in various simulation papers. Chew and Sullivan (p. 817) state that, "as perfect as the equations, algorithms, and software design of an M&S may be after conceptual model validation and design verification, it will probably fail results validation if the data that drive the simulation are inaccurate or inappropriate for the task at hand." This is particularly true in simulation projects that extend over longer periods of time, during which the input data collected or the conceptual model itself may become outdated. According to Kleijnen (2000), different statistical techniques should be used in this step depending on which *real-life data* is available, namely (i) no data, (ii) only output data, and (iii) both input and output data. As the available data improves from (i) to (ii), so does the power of these statistical techniques. McGregor (2000) points to a number of issues that simulation practitioners must be aware of, such as that (i) VV&A is not a discrete step in the simulation process but rather a set of activities that should be applied continuously throughout the simulation process, (ii) the cost of VV&A increases exponentially with the level of verification, (iii) more planning for VV&A needs to be done before the simulation study starts, including a decision on how much of the total resources that should be devoted to VV&A (McGregor recommends 20% to 30%), (iv) the model developer may not be the best person to ascertain VV&A due to their biased opinions of the models (McGregor also points out, however, that adding members to the project team increases costs and is not always popular with the client), (v) there is no one best way to perform VV&A and conversely VV&A procedures will differ according to system and model type and study objectives, (vi) the Type III error (solving the wrong model) should be avoided, (vii) statistical techniques are not always easily used when it comes to VV&A since they usually need multiple sets of data, and (viii) animation and built-in debuggers can provide greater help in verifying a model than what many seem to think.

Experimentation – This step (included in *runs and analysis* in Figure 7.5) means running the simulation program or model according to the parameters set in the DOE phase. The way the model behaves during experimentation may lead to a redefinition of the model (Page, 1994).

Output Data Analysis – This step (also included in *runs and analysis* in Figure 7.5) relies heavily on the use of statistical techniques, and the results obtained will determine whether more experimentation is required. The methods used in this step can also be described as being based on the one hand on general statistical theory and methodology, and on the other hand as requiring simulation specific considerations and/or modification of these methods. The reader is referred to Eriksson (1997) for a good investigation into practically useful output data analysis techniques, such as Analysis of Variance (ANOVA).

Documentation – Although this phase is self-explanatory, it is difficult to do in practice. Its placement as a last step in Figure 7.5 is also debatable. In this author's opinion, every simulation project must be continuously documented throughout all steps, as suggested e.g. by Musselman (1998).

Implementation and Feedback – The last step in a simulation study is the implementation of the model or the results obtained. The success of implementation depends on how well the previous phases have been performed as well as the degree to which the analyst, i.e. the *model builder* has been able to involve the *model user* in the process. Obviously, this and other issues related to implementation will depend largely on *organizational* factors in the company. Feedback highlights the need for the people involved in the simulation study to update the model according to experiences made during the implementation phase. This strongly relates to the need for the model to live on after the project closes and become reusable and remembered rather than unusable and forgotten.

Provided that simulation is used properly and according to a structured approach as the one just outlined, the next section will outline its advantages and disadvantages.

7.4 Advantages and Disadvantages

When evaluating simulation, we can start by comparing it to two other means of system analysis:

- simulation vs real-world experimentation,
- simulation vs other modeling approaches.

The first thing to note when comparing simulation to real-world experimentation is that, by definition, a model implies an abstraction and thus a simplification of the system it represents. If this was not the case, the model would cease to be a model and become the system itself. In other words, modeling means that information of the system is lost. The conclusion is therefore simple: If experimentation with the real system is possible, this is the best alternative since it will give the most accurate measures of how the system behaves. In theory. In practice, a number of reasons speak against experimenting with the real system, most of which are obvious. In brief, these reasons may be *practical*, such as not wanting to disturb or change some existing system, like a running factory, because this would be associated with significant costs or losses; they may be *physical*, as in the case of simulating something that does not yet exist and conversely renders real-world experimentation impossible unless the system, e.g. a planned production line, is actually built; they may be *ethical*, as when real world experiments are possible but for some moral reason considered wrong or cruel; they may also be *legal*, such as trying out the effect of yet to be implemented changes in legislation, e.g. working hours for truck drivers; and they may be *risk-eliminating*, when real world experiments would be dangerous or hazardous, such as testing the failure of a production line.

A comparison to *mental* models was made in Section 7.1. As further shown in Section 7.2.2, a large variety of model types exist. Conversely, there is a wide selection of modeling approaches available, each with its own set of advantages and disadvantages. A majority of these do not apply to what are generally considered to be simulation problems, and hence will not be treated here. There are a few, however, that may be seen as alternatives to discrete-event simulation modeling, particularly *Petri nets*, *queueing models*, and *system dynamics* models. A description of these would be outside the scope of this thesis however.

7.4.1 Advantages of Simulation

Based on Banks et al. (2000), Banks (2000), Law and Kelton (1991), and this author the advantages of simulation are here summarized as:

1. **Cost**: enables cost reductions and/or avoids costs,
2. **Time**: reduces ramp-up time of production and possibly development lead-time,
3. **Complexity**: enhances understanding of relationships, interactions, dependencies, etc.,
4. **Dynamics**: captures time-dependent behavior,
5. **Replicability**: experiments can be repeated at any time,
6. **Visualization**:provides visual analysis capabilities.

7.4.2 Disadvantages of Simulation

According to Banks, Carson and Nelson (1996) and this author the disadvantages of simulation are:

1. **Need for special training**: Building a simulation model is an art that is learned over time and through experience. Although simulation software

may look simple, simulation requires a lot of work both *before* and *after* the analyst clicks on “run”. Simulation thus extends lightyears beyond the relatively simple task of learning the software.

2. **Difficulties of interpreting the results**: Since most simulation outputs are random variables, it can be difficult to distinguish between system interrelationships and randomness in the results. In most cases, a significant amount of knowledge of statistical theory and methods is required.
3. **Time and cost**: Modeling and analysis can take a lot of time and may be expensive. There is usually a clear trade-off between the resources allocated for modeling and analysis and the quality of the resulting simulation model in terms of how well it mimics reality.
4. **Inappropriate use**: Simulation is sometimes used when an analytical solution would have been possible or even preferable, or in any of the other cases described previously (see Section 7.3).
5. **Non-optimized results**: Simulation is *not* optimization, and even when near optimal results are achieved there is a risk for sub-optimization.

However, these disadvantages can be defended with the following arguments (based on Banks et al., 1996):

1. Simulation software has become user-friendlier, requiring less input from the user and featuring easy-to-understand graphical user interfaces (GUI) with 3D visualization and animation. Other user-friendly features include Windows-like interfaces with icons, menu bars, and dialog-boxes (Klingstam and Gullander, 1999), and trends toward modules for specific applications can also be discerned. While this is no help in itself, it does leave more time for the simulation analyst to learn *simulation*.
2. Output analysis capabilities have been integrated into many software packages, reducing the specific knowledge required for analyzing statistical data. Also, while no real defense *per se* it can be argued here that most real cases will provide input data in so insufficient amounts that statistical analysis of it becomes meaningless.
3. There are mainly two activities that take time in simulation: model building and running. Model building, despite the shortcomings of most simulation software, is being made easier with every new release. Today most major software packages contain a large number of (almost) ready-to-use constructs such as storage systems, automated guided vehicles (AGVs), conveyors etc. Run time and hence cost is also being constantly reduced due to the advances in computer hardware. Thus the entire simulation process can be performed faster. The cost relates to the acquisition of the software as well. While this cost can be significant, most simulation specialists (including this one) would argue that the initial investment is paid back after the first implementation of the simulation results. What

remains is to convince the simulation-skeptics (this subject is treated in more detail in later parts of this thesis).

4. While it is true that some systems can be modeled analytically, e.g. with closed-form models, most real problems are too complex for these kinds of solutions.
5. Although it seems a common misconception that simulation is a form of optimization there are two things to say in the defense of this. First, under certain conditions and if the simulation study is correctly performed, the simulation results may well be near optimal. Even if they are not, they will be closer to the optimum than what would have been the case by just guessing or modeling the system statically. Second, research and development of optimization algorithms and application is likely to result in more integrated simulation and optimization application, in which case the border between these two domains will become blurred (this subject is treated in more detail at the end of this chapter).

Next section will look further at the principal application area in this context: *manufacturing system development*.

7.5 Discrete-Event Simulation in Manufacturing System Development

As mentioned in Section 7.2.4, computer simulation methods have developed since the early 1960s, and for nearly as long, discrete-event simulation has been applied to manufacturing systems.[51]

The *principal* applications of DES in manufacturing system development can be identified as:

1. explorative studies of existing systems to improve them,
2. studies of existing systems with some changes made to them, similar to the first purpose but used to validate a specific alternative, e.g. a proposed investment, and
3. design and validation of new systems.

In practice, simulation projects often combine these three applications.

As further suggested in the introduction to this chapter, the application areas of simulation are vast. Within the scope of this thesis – manufacturing systems – the general application areas include but are not necessarily limited to (Manufacturing Systems Integration Division, www):

- Business process modeling

- Discrete and continuous manufacturing process modeling
- Process and system visualization
- Supply chain modeling

Focusing more specifically on *production systems*, we find again a large number of application areas (Banks et al., 2000; Miller and Pegden, 2000):

- Assembly operations including order and accessibility
- Buffer sizing
- Control strategies for:
    - automated guided vehicle systems,
    - automated storage and retrieval systems,
    - material handling systems,
    - production lines,
    - shifts and labor movement.
- Costs and work in process levels
- Disturbances
- Ergonomic studies of work areas and manual tasks
- Lot sizing
- Material flow including bottleneck detection
- Motion and collision control of industrial robots
- Off-line programming of equipment including industrial robots
- Plant layout effects
- Scheduling evaluations
- PLC program verification and validation

With these vast application areas, DES has become one of the most powerful decision support tools available in the manufacturing industry. As such, it can help managers and planners analyze the effects of a large variety of policies with a high number of alternative combinations of different parameters. A manufacturer of some medium complex product wishing to increase its throughput might ask itself a number of questions: what happens if we introduce a new product into the existing production line? Can we meet our production targets? Are the real bottlenecks in our current system where we assume them to be? Should we increase the number of machines, and if so at what stage in production? Would we be better off changing the layout or routing instead? Or should we look at the batch and buffer sizes? What about the shifts? Would it be economically viable to invest in a new material handling system? Or do we just need more fork trucks? Or some combination of these policies?

Not only can simulation answer such questions, but it can answer them without disrupting or in any way affecting the real world business processes in the company. In addition to saving cost and time and increasing customer satisfaction by helping to assure the right quality, price and delivery time through better informed decisions, a large part of all simulations are justified because other means of experimentation would not be possible, as was mentioned in Section 7.4.

Discrete-event simulation, however, is not and will never be the manufacturing *panacea* some advocates would claim. Instead its purpose is simple: to support correct decisions efficiently and effectively. By efficiently and effectively is understood simulations that meet the time, cost, and quality criteria. This view is shared by several researchers. For example, Page (1994, p. 14) notes that “the primary function of discrete-event simulation involves decision support”.

7.6 Problem

One might wonder, after having read the previous sections: if simulation can do all this, then what is the problem? In fact, this question seems even more relevant after having attended presentations of successful simulation cases frequently given at various simulation software user conferences and simulation symposiums, and even at scientific conferences. Surely, there are few reasons why simulation should not already have become a widespread and successfully used technology, as commonly present and as effortlessly used as, say, the PC or spreadsheets?

Actually, a closer look at the facts reveals that the practical use of discrete-event simulation (DES) within the context of manufacturing system design and development is still modest, particularly outside the U.S. For example, Busenius (2000) states that “it seems as if the optimistic forecasts by renowned companies and research institutes at the beginning of the 90s did not come true.”

In fact, many companies do not use DES at all, while some of those who do seem to have mixed emotions about the potential of this technology. It thus seems that the full potential of discrete-event simulation has not been realized in the industry as a whole, even if some companies have come a long way. For example, the quote from page 80 goes on to state that (Lockheed Martin SAVE Team, 1998):

> The use of simulation software to achieve the objectives of virtual manufacturing has been rapidly increasing throughout industry.

> The potential for these tools to significantly improve affordability and reduce cycle times is widely accepted, but the potential has not been fully achieved.
>
> Many commercial simulation tools with excellent capabilities exist on the market today.Although many of these tools rely on similar types of data, differences in internal storage structures and nomenclature have prevented easy tool to tool data integration. Often, large amounts of data must be reentered, at considerable time and expense, to accommodate these differing formats. Some point-to-point solutions do exist between specific tools, but as the number of tools grows, this integration solution becomes unmanageable, and the benefits from using an integrated tool suite go unrealized.

Speaking in general terms, the problems with simulation can be related to three temporal aspects – *adoption*, *use*, and *integration*. Adoption issues are treated to some extent in Section 12.3. Integration aspects will be explored in the next chapter. The remainder of this problem description will therefore focus on simulation use. First, to validate the claim that discrete-event simulation use in the manufacturing industry is not as widespread as one would think, the next section will take a look at the data that exists on actual simulation use in various parts of the world. After this, some general thoughts based on own experience will be given.

7.6.1 Simulation Use Around the World

As mentioned previously, the few empirical studies that exist seem to indicate that discrete-event simulation use is still modest in the manufacturing industry, particularly outside the U.S. (Eriksson, 2001*b*; Holst and Bolmsjö, 2001*b*; Hirschberg and Heitmann, 1997; Umeda and Jones, 1997).

According to a roughly estimated comparison of licenses for 13 discrete-event simulation software packages in the U.S. and Germany, the U.S. outnumbers Germany in all but one, often by a magnitude or more (Busenius, 2000). Busenius (2000) also estimates turnover and world market share according to geography, and arrives at figures that clearly show the dominance of the United States. It should be noted, however, that the number of licenses alone is not a reliable measure, since this figure fails to show how many of these licenses are actively used, and for those that are, in what manner. Nevertheless, this author believes that even if this parameter was considered, the U.S. would still take the lead, perhaps by even more.

Moving on to more reliable empirical evidence, a 1999 simulation survey of 150 Swedish manufacturers of various size showed that less than *one tenth* of the companies used simulation, and that only *one third* would consider to use it in the future (Eriksson, 2001*a*)[52]. The same study also indicated a low level of simulation competence in general; less than half of the respondents found their simulation competence to be good..

Another survey conducted in Germany in 1997 showed that 38% of 395 respondents used DES, while 11% were considering to use it in the future (Heitmann, Hirschberg, Rauh and Wunderlich, 1997).[53] While these figures may seem high, the authors of the study assert that "based on [our] and other experts' experience, the dissemination of simulation is considerably lower."[54] The reasons are believed to be due to simulation users being more inclined to answer a simulation survey than simulation non-users. In other words, the real figures of simulation use in German industry use are *lower*.

The only comprehensive survey of simulation use in Japan is Umeda and Jones (1997), but does not present comparable figures. The study concludes that simulation use is "modest compared to the U.S., but [...] on the rise."

These are the only comprehensive surveys of simulation use that have been found. For instance, no empirical data regarding the U.S. seems to exist.

According to Banks, "many managers are realizing the benefits of utilizing simulation for more than just the one-time remodeling of a facility. Rather, due to advances in software, managers are incorporating simulation in their daily operations on an increasingly regular basis" (Banks, 1999, p. 10). While this may be true for the U.S., as mentioned above no empirical studies have been made to support that view. More importantly, few researchers have addressed the issue of *how* such a scenario should be realized. Also, the authors would suggest that DES use, particularly from an integrated point of view, lags considerably in Europe and Japan as a whole.

A testimony to this situation is the following:

> Although studies have recognized the potential of manufacturing simulation and visualization, there are a number of technical and economic barriers which hinder the use of this technology. Industry expenses for implementing simulation technology is much greater than the cost of computing hardware, peripheral devices, software licenses and maintenance. Typically companies must factor in the cost of salaries and training for simulation and support staff, translation of existing company data, systems integration of applications, and development and maintenance of models. These costs are likely to be much greater than the initial acquisition costs for the simulation software and hardware.

However, there is no doubt that DES of manufacturing systems is a highly complex activity, touching upon several operational and strategic issues. While the last decade saw simulation software and methodologies develop considerably, several problems remain. These problems regard such diverse matters as information sharing between different functions involved in manufacturing system development, interoperability and collection of data, standardized application interfaces, organization of simulation activities and several aspects on the strategic view on simulation.

In summary, the current situation seems to indicate a need for research on methodologies that can aid companies in their adoption and implementation of simulation, or in other words, raise their levels of integration. Chapter 8 will take a closer look at these various integration aspects.

However, another problem arises when we talk about simulation out of its context, which is or should be *flow analysis*. In this context, simulation is but one tool among others, but one phase in an overall process, and but one component in a different way of thinking. This is another important aspect, which also calls for holistic views on integration.

7.6.2 Own Experience

On more than one occasion and regardless of company size, this author has come across the belief that to make simulation widespread, production engineers should be trained to be simulation specialists on top of their current job specifications. In an ideal world, this would surely be the preferable solution. However, if this chapter has showed anything, it is how the modeling of complex dynamic systems puts extremely high requirements on the *modeling & simulation* competence level of simulation specialists. This author has yet to see a production engineer at a major corporation that would be able to cope with this added burden on top of things that already need to be dealt with.

Another example of this lack of understanding of the need for proper simulation training shows in statements like: “with the development of more user-friendly software, it is increasingly the user who builds the model, not an expert.” The source of this quotation is less interesting than how often similar statements are encountered on, even in scientific articles and papers.

In contrast to this view, Pritsker (1998, p. 31) states that “model building is a complex process and in most fields involves both inductive and deductive reasoning,” and lists the following reasons why modeling a complex, large-scale system (such as a manufacturing system) is difficult:

- few fundamental physical laws are available,
- many procedural elements are involved which are difficult to describe and represent,
- policy inputs are required which are hard to quantify,
- random components are significant elements, and
- human decision making is an integral part of the system.

Fishwick (1995) describes how a simulation specialist adds value to system analysis by virtue of representing a unique discipline rather than the multitasking advocated by others:

> Working closely with people of other disciplines is one of the things that makes simulation fascinating [...] As a simulationist, your responsibility is to understand the common vocabulary of systems, modeling terminology and algorithmic procedures which form the simulation foundation. You will often find yourself seeing relationships between people's problems [...] It is this synergy which creates a great deal of satisfaction for the simulation discipline.

Balci (1998, p. 335) among others supports this view and states that "a typical simulation study requires multifaceted knowledge in diverse disciplines such as operations research, computer science, statistics, and engineering." Because of this, however, Balci (p. 335) argues that to increase the likelihood of a successful simulation study, an organization must have a *simulation quality assurance (SQA)* unit, responsible for total quality management. In other words, Balci (1998) argues for *methodological* support.

7.7 The Future of Simulation

Some of the future directions of simulation were mentioned in Chapter 1. Jain (1999) summarizes them as follows:

> Simulation models will be widely used across all stages of development and operation of an organization. In the area of manufacturing, use of simulation has grown widely from design applications to operation support application. The use of simulation models from design to operation stages wil also lead to to a life cycle for simulation model parallel to the real system life cycle. The value of such use has already been realized though it is not practiced widely. In many cases, simulation models used at the design stage turn into shelfware as the real life system goes into operation. In the future, simulation models will be developed as the concept of a system develops, grow as the design grows in detail, support system integration validation activity as the real life system is built and installed, and support decision making during the real system operation stage. As the real system is modified, the corresponding simulation models will be updated.

As should be evident from the above, as well as the quotes cited in Chapter 1, the simulation community show no lack of grandiose visions. The question, of course arises of what needs to be done in order to deal with the problems outlined in Section 7.6, and ultimately make these visions come true.

As should be clear from the title of this thesis, the author believes that one of the keywords in this context is *integration*. Chapter 8 will look more closely at what this means.

Furthermore, and as stated earlier, the ultimate objective is to realize the full potential inherent in simulation. To this end, the following three actions are proposed in this thesis:

1. focused research in selected simulation areas,
2. learning from other disciplines, and
3. developing a holistic, generic, and structured approach to integration.

The remainder of this chapter will take a brief look at the most important research areas, Chapter 12 will present in more detail what other disciplines we as simulation advocates could learn more from, and Chapters 13 and 14 will present the framework for a structured approach to integration.

7.7.1 Important Research Areas

The topics at any of the leading simulation conferences, including of course the Winter Simulation Conference (WSC), range across a bewildering array of topics. However, there seems to be some agreement among researchers as to where the focus should be over the next years, namely in the following areas:

- Model size and complexity
- Verification and validation techniques
- Optimization
- Parallel and distributed simulation
- Internet-based simulation
- Human behavior and uncertainty modeling
- Integration

Although arguments can be made for and against the significance of each and every one of the above topics, from this author's perspective a few stand out as particularly important for the future of simulation. Therefore, all but the last of these will only be briefly described in the following sections; integration, as mentioned previously, will be further detailed in Chapter 8.

Model Size and Complexity

In a panel discussion on the future of simulation, Nicol (1999) predicts that the DES world will see the same development as in continuous simulation, where the size and complexity of the models that simulation analysts would like to build have outgrown the available computing power, which has forced a focus on new and more efficient solution techniques. Although DES has emphasized different types of problems than those usually solved with continuous simulation techniques, hardware development nevertheless "opens the way for simulation to be used in new domains, e.g. control of very large systems where real-time decisions are made as a result of forecasting (through simulation) the results of various decision options" (Nicol, 1999, p. 1510). This calls for dealing with a number of issues related to "huge" models, such as (i) representing the models in a way comprehensible to humans, not only computers, (ii) model validation, and (iii) visualization of simulation results. A general problem in this context is also that the amount of computation needed to solve or run a model increases by more than a linear factor of model size, which calls for novel *multi-resolution* techniques rather than parallel simulation through the use of multiple processors.

Furthermore, although complex systems usually have to be considered at various degrees of resolution, there is a lack of methodological support that allows going from higher to lower resolution models. As Bargiela (2000) notes, "it is usually the case that the next level mathematical model is determined independently from the more detailed one", and further argues that, "the absence of rigorous bridges connecting [these lower-resolution large-scale] models to the more detailed models means that their construction requires extensive fitting, tedious and expensive compilation of databases and it results in a limited ability to support ampliative reasoning". A challenge in this context is therefore to develop methodologies for modeling multiple levels of abstraction.

In addition, as models grow increasingly large and complex the same model will need to be developed by a team of simulation specialists rather than a single modeler, and these modelers will increasingly be geographically dispersed. For instance, based on the simulation projects carried out at BT Products and described in Section 9.2, Randell (2000) has proposed a methodology for lead-time reduction in discrete-event simulation projects based on incremental, concurrent andwell-documented development of DES models supported by configuration management (CM). This represents important facets of handling large and complex models.

Verification, Validation and Accreditation

In the same panel discussion as quoted in the previous section, Balci (1999) focuses on issues related to VV&A of M&S applications. These issues include

(i) automation of VV&A tasks, (ii) component-based model development that would support the reuse of verified and validated model components, (iii) more emphasis on education and training in M&S and especially in VV&A rather than mere spending on technology, (iv) a unified terminology, (v) knowledge of the "mother discipline" of M&S VV&A namely software engineering, (vi) more peer-reviewed VV&A publications, and (vii) government funding.

In another strategic outlook, Kleijnen Kleijnen (2000) points to two problems related to VV&A: *philosophical* problems – such as those discussed in Chapter 4 – and *statistical* problems. Focusing on statistical problems, Kleijnen argues that many times even simple simulations are not validated through correct statistical techniques, while complex simulations are usually not validated at all, or are only subjectively validated. In other words, Kleijnen claims that there is "an *abyss* between validation practice and statistical theory". To bridge this gap, most simulationists will need more statistical knowledge in addition to what they are usually good at, namely modeling and programming. In Kleijnen's opinion, however, this is somewhat obstructed by the fact that mastering modern simulation software leaves too little time for statistical training. Not only knowledge is needed, however: part of the solution would also be more user-friendly statistical software. As for verification, there is need for developing simulation programs to improve i.e. their pseudorandom number generator (PNG) modules.

Law (2000) who also focuses on validation, notes that in the past twenty years there has been little development of new validation techniques. However, due to the inherent problems of the validation of modified or new systems, Law does not see model validation as a particularly fertile area for future simulation research. In practice, the only way to do a statistically correct validation of a model, i.e. one that maintains the independent and identically distributed (IID) requirement on data, is to collect several independent sets of data from the actual system and to compute a performance measure from each set. As Law notes, this poses practical problems of data availability and as a result it is almost never possible in real simulation projects. Instead, efforts should be focused on developing a general-purpose, confidence-interval procedure rather than a hypothesis test, that is based on one set of real world data.

On the other end of the scale of measures to be taken, McGregor (2000) argues that there is no need whatsoever for additional future research in VV&A. What *is* needed is to put VV&A into practice. Here, McGregor argues that the missing parts in most simulation projects are client awareness of the importance of a close involvement in the VV&A process, and simulation practitioner awareness of the VV&A issues referred to in Section 7.3.

Sargent (2000) stresses that VV&A approaches including their management and software support need to be tailored according to the size and type of simulation study. Regarding very large-scale simulation models, however, Sargent argues that it is impossible to verify and validate them to a reasonable confidence level, and that research should aim at investigating how a set of smaller simulation models could be used instead of one large model. Finally, Sargent identifies a need for developing cost models that can predict the cost of conducting VV&A studies.

Bargiela (2000) also focuses on visualization-based validation of complex models, and states that, "given the diversity of human agents that are presented with simulation results, an important research challenge will be the development of objective techniques for the assessment of visualization".

Optimization

Most simulation specialists would argue that simulation is an excellent descriptive tool for experiments and analysis of a system. In many cases, a good description will come a long way in increasing understanding of system behavior. In others, the number of choices is small enough to allow for the simulation of every possible alternative.

However, the selection, evaluation and testing of a given solution is largely based on such things as experience, estimates, statistical analysis and "feeling" by the people involved, sometimes requiring time-consuming and costly "fine-tuning". While simulation alone can make substantial improvements to a system, it is sometimes necessary to conduct a targeted and extensive search for the best solution using dedicated computer aid tools. This is particularly true for complex integrated systems with a large number of combinations and contradictory criterion functions, and when designing new systems, i.e. when true validations are not possible.

The importance of optimization is increasing as manufacturing and production systems are becoming more dynamic and complex, and as business processes are re-engineered.

Optimization can be regarded as a numerical method where one or several criterion functions are to be optimized, and as such the task is to find an appropriate stepsize and search direction, and from these initial values and with minimal effort receive a new search step in the direction of the optimum. Moreover, the optimum is to be found, i.e. the method is to converge, with the least amount of computational effort and with a specified accuracy.

Optimization problems in manufacturing applications of discrete-event models generally involve a large number of parameters. These parameters can be either continuous, discrete or both, and often include constraints in their allowable values. There may also be multiple and contradictory criterion functions. The goal of the optimization is to find a solution that represents a global maximum or minimum. In contrast to simulation models, optimization models are solved rather than "run". These optimization methods can be divided into two large groups: continuous and discrete optimization (also known as local and global methods), which in turn can be divided further into a very large number of methods and algorithms. General problems include speed of convergence and sensitiveness to the estimation of initial values, particularly when the criterion function has more than one optimum, a case in which the algorithm might find the local optimum instead of the desired global optimum. Another large problem is to choose the right method and algorithm.

Lately, optimization modules that can be used in conjunction with a number of simulation applications have emerged, including the commercially available optimizer OptQuest. The optimization software ISSOP (Integriertes System zur Simulation und Optimierung) developed by Dual-Zentrum GmbH, Germany (Krug, 1997), is another example with interfaces to a number of commercially available software packages, including ARENA.

Parallel and Distributed Simulation

Parallel and distributed simulations are those applications that span multiple computers, executables, or geographic areas, and includes what is often referred to as distributed interactive simulation (DIS) and distributed manufacturing simulation (DMS) (McLean and Riddick, 2000; Smith, 1999). First, however, it should be noted that there seems to be much debate as to the practical significance of parallel and distributed simulation (PADS). According to Fujimoto (1999), the world's leading expert in the field, this situation changed considerably in the favor of PADS during the late 1990's as evidenced by a number of factors. Among the most important, argues Fujimoto, is the inclusion of PADS in the High Level Architecture (HLA) developed by the U.S. Department of Defense (DoD). Also, parallel simulation systems are already being used in commercial air traffic modeling, in the design and management of air transportation systems, and in several large-scale defense simulation projects in the United States. Fujimoto further argues that PADS technology growth and adoption is increasing because it supports two important requirements on simulation technology: model/software reuse and transparency. Important research directions relate to synchronization algorithms, new application domains such as distributed virtual environments (DVEs), and heterogeneity of languages and software. In summary, this author is of the opinion that several major obstacles remain to be overcome before PADS becomes common in manufacturing simulations.

Internet-Based Simulation

Internet-based or Web-based simulation[55] which formally falls under the category of parallel and distributed simulation, is the utilization of Internet technology and infrastructure to perform large-scale distributed simulations, online and possibly on a global basis. In fact, Bargiela (2000) argues that web-based simulation represents a paradigm shift from distributed to global simulations.

Human Behavior and Uncertainty Modeling

Human behavior modeling As Smith (1999, p. 1517) argues, "we are in dire need of techniques for inserting intelligent, reactive, unique human behavior in the virtual world". Youngblood (2000) states that human behavior representation is one of the major focus areas in M&S research at the U.S. Department of Defense (DoD). This view is supported by Bargiela (2000), who from a general simulation perspective notes that unlike other objects, human agents cannot be adequately described by reference to the laws of physics. Therefore, this implies a need for research that will put emphasis on the development of M&S methodologies that deal explicitly with human-induced uncertainty in systems. Apart from being useful in a wide spectrum of industrial M&S applications, such research could broaden the formal systems modeling framework to include social, economical, and political systems. In addition a number of other rarely modeled aspects need to be addressed, specifically disturbance modeling for the purpose of analyzing the cause and effects of disturbances on manufacturing performance, as proposed by e.g. Ingemansson (2001).

Integration

As mentioned previously, integration is the subject of the next chapter. However, it should be noted that most of the research areas mentioned here in some or another touch on integration issues, including several aspects of parallel and distributed simulation and its concepts, such as the HLA.

7.8 Summary

After more than four decades of presence in the manufacturing industry, we can conclude that simulation as a technology has become extremely powerful, that simulation software, while not always entirely adequate, still appears as very capable, and that the methodologies for performing simulation projects are well-developed and documented. As an evidence of what this technology can do, successful cases from various industrial sectors abound.

Despite this seemingly rosy picture, it is argued here that several problems associated with the use of DES still exist. These problems show up in two ways. First, far from a majority of companies use simulation, and many of these do not even have enough beliefs in what simulation can do for their organization to consider using it in the future. Second, companies that use simulation do not seem to have realized the full potential of this technology. In the terminology of this thesis, they have not fully *integrated* simulation into their MSD process.

To address this situation, the following three actions are suggested:

1. focused research in selected simulation areas,
2. learning from other disciplines, and
3. developing holistic, generic, and structured approaches to integration.

This chapter took a brief look at the most important simulation research areas. Chapter 12 will present in more detail what other disciplines we as simulation advocates could learn more from, and Chapters 13 and 14 will present the framework for a structured approach to integration. Before that, however, the concept of integration will need to be further explored. This is the subject of the next chapter.

Notes for Chapter 7

[37] The reader already well familiar with simulation may skip Sections 7.1–7.3

[38] It should be noted here that, normally, other simulation techniques than DES are used for this purpose.

[39] The term *micro world* is used in the article to describe an interactive computerized environment that simulates a real-world situation.

[40] Section 7.2 is mainly based on Banks et al. (2000), Law and Kelton (1991), Page (1994) and Pidd (1998). The descriptions in this section are held brief, and a number of theoretically important concepts are not explained as they are considered outside the scope of this thesis. For example, neither modeling terminology and its differences – such as part vs. load and buffer vs. queue in the software packages Quest and AutoMod respectively – nor practical examples of how simulation works are treated in detail here. The reader is referred to the previously mentioned titles, and recent WSC contributions for more comprehensive literature on simulation, particularly DES applied to manufacturing systems.

[41] The description is based on the assumption that a decision has been taken to simulate, i.e. that simulation is considered the proper technique in the case at hand. If not, the same approach may still be used, but with a different perspective. In this case, deciding on what *technique* to use will of course correspond to deciding on whether or not to *simulate* the system under investigation. It should be noted here, however, that deciding on this is in itself a key issue, which will be treated in Section 7.3. See also Section 7.3 for a set of rules indicating when simulation should not be used.

[42] A detailed exploration of different types of models and their corresponding modeling theory would be beyond the scope of this thesis.

[43] The purpose of optimization in a simulation context is to gain prescriptive results. Optimization is further described in Section 7.7.1.

[44] Monte Carlo simulation models are more frequently used as portfolio selection models in finance. As Trick (1996) explains, "given a portfolio with different probabilistic (and correlated) payouts, it is possible to generate a possible yield. Such a model might become a dynamic model if it incorporates changes in the portfolio over time, or if the model of payoff must be simulated over time.

[45] The tank levels could be modeled as changing in small discrete portions, in which case a fully discrete model could be used. In this case, however, the results would be less accurate, and the system more complicated to model.

[46] This chapter, and indeed this thesis, reflects the author's familiarity with a limited number of software packages – particularly Arena, AutoMod, and Quest – and should not be seen as an endorsement of any particular package here men-

tioned, nor as a dismissal of packages that have not been mentioned. Rather, the size and scope of the simulation software market and the large number of vendors offering software packages is acknowledged as a fact that makes the task of keeping up and familiarizing oneself with a comprehensive amount of simulation software both difficult and outside the scope of thesis.

[47] Pidd (1998) refers to time flow as "time-handling".

[48] It should be noted here that some of the mentioned packages (e.g. Arena and AutoMod) offer different editions of their software, and that these may range in price from free (such as AutoMod's "Student Version") or a few hundred dollars (such as Arena's "Business Edition") to the upper price range mentioned (in excess of USD 10,000 for both Arena and AutoMod in full versions.).

[49] Papers offering short descriptions of some simulation languages and environments include the following: Arena (Bapat and Swets, 2000), AutoMod (Banks, 2000; Rohrer, 2000), C++ (Bolier and Eliën, www), eM-Plant (Heinicke and Hickman, 2000), Extend (Krahl, 2000), GPSS/H (Henriksen and Crain, 2000), Promodel (Harrell and Price, 2000), and Micro Saint (Bloechle and Laughery, 1999).

[50] The reader is also referred to Balci (1998, p. Figure 10.1) for a complementary illustration of the simulation study life cycle.

[51] See e.g. Savén (1995) for a more detailed account of DES in the Swedish manufacturing industry during this period.

[52] The actual figures were 7% and 33% respectively, as estimated by this author from the original data as the sum of percentage shares for answers marked with a 3 or higher by the respondents on a five point Likert-like scale.

[53] The figure of 38% is not explicitly stated in the report. It was calculated by this author by taking the total percentage share of respondents classified as simulation users regardless of type of simulation (65%) and multiplying it by the percentage share of respondents within this group that were classified as flow simulation *(Ablaufsimulation)* users (58%), i.e. 0.58 x 0.65 = 0.377.

[54] The text was translated from German by this author. The original text is provided here for reference: Gestützt auf Erfahrungen des iwb, des FAPS und weiterer Experten ist der Verbreitungsgrad der Simulation deutlich geringer.

[55] Web-based simulation seems to have become the accepted term here. However, it would be more correct to refer to this as *Internet-based simulation* since the concept is based on utilizing the Internet protocol rather than just the World Wide Web. Neither of these terms are to be confused with *on-line simulation* (see e.g. Davis, 1998).

8

Integration

This chapter will attempt to answer the following questions:

Q *What do we mean by integration in the context of this thesis?*

Q *What are the benefits of this particular type of integration?*

Q *What are the problems associated with such integration?*

Q *What have been the attempts to solve these problems?*

Q *What future directions can be discerned in this area?*

Q *What does this imply for the research presented here?*

Conversely, this chapter is organized in the following way:

Section 8.1 puts integration into context and motivates its high profile in this thesis; Section 8.2 explores *various forms of integration* and emphasizes those appropriate here, thereby laying a foundation for some of the main points of this thesis; Section 8.3 moves on to describe and elaborate on the *problems* associated with simulation integration; Section 8.4 then describes *enterprise engineering and integration*, one of the key concepts that attempts to deal with some of the integration problems, linking this to Chapter 13 which defines and presents the concept of *simulation integration*, believed to be the holistic and systems oriented view largely missing in research and practice so far, and thus part of the solution to the problems described here. Finally, Section 8.6 tries once again to predict the *future* of this area, and also acts as a bridge to Part IV, which presents the main contributions of this thesis.

8.1 Context and Motivation

The world is becoming more integrated in every imaginable way. On the macro level and on the micro level, across technical, economical and social systems, and from nations to integrated circuits, world events are characterized by integration. Or disintegration some would say, because these are just as powerful forces that attempt to obstruct this integration. These forces can be seen as the increasing complexity, dynamics, and rates of change that characterize many real life systems, including of course manufacturing systems. Ironically, these are the same forces bringing about integration.

For example, there is an evident trend in industry evolving into where product and process engineers are able to concurrently interact with each other regardless of time, location, or organizational barriers (Kulvatunyou and Wysk, 2000). At the same time, the products, processes, technologies and competencies that are the subject of this integration have become so information-loaded and interrelated that integration is made extremely difficult.

Clearly, integration spans several functional areas and business processes both within and outside enterprises. This diversity of integration as a concept is fully in line with the overall manufacturing industry trends as outlined in previous parts of this thesis. In brief, we find that tougher customer requirements, globalization and the increased competition and uncertainty which are following are making it ever harder for manufacturers to meet quality, cost, and time objectives. As means to deal with this, companies are resorting to a number of measures – primarily various forms of *flexibility*, *total quality measures*, *a*nd *integration*. The various forms of flexibility and quality measures were treated in previous parts of this thesis. Regarding integration forms, they can be seen as ocurring from a number of different perspectives, all of which have been brought forward by the increased complexity and dynamics (Vernadat, 1996, p. 9):[56]

- integration of markets
- integration between several development and production sites
- integration between suppliers and manufacturers
- integration of design and production
- integration of multi-vendor hardware and software components.

As a result of these trends, we see an increasing number of research articles and papers mentioning the word *integration*. This applies just as well to the context of this thesis, where there is a considerable amount of research aiming to increase the level of integration, from various aspects, of DES into manufacturing system development.

On the general level, Kosturiak and Gregor (1999) and Ball (1995) have suggested approaches for applying and integrating DES in the MSD process. Feldmann and Schlögl (1999) show an actual implementation of such concepts in electronics production. McLean and Riddick (2000) present an overview of the HLA which aims to integrate various manufacturing simulations from the supply chain down to the shop floor level and across geographical locations, as well as simulation systems with other manufacturing software applications.

More specific examples are also represented. For instance, Ilar and Kinnander (1999) show how supporting processes such as those concerning human factors can be modelled and thus integrated into the technical processes.

Several other researchers focus on various costing applications. Rasmussen, Savory and Williams (1999) present an approach for integrating activity-based costing (ABC) information and DES of sequencing in manufacturing systems.

von Beck and Nowak (2000) connect DES and ABC models with the purpose of having the ABC model using driver values generated as output from the DES model. The result is improved accuracy of the cost estimates.

Harmonosky, Miller, Rosen, Traband, Tillotson and Robbie (1999) present a similar approach based on interfacing DES and costing software applications. The approach is specifically intended to support decisions in the ramp-up phase when companies decide to step up from small volume job-shop like production to higher volume production run manufacturing, and differ from that of von Beck and Nowak in that output from the costing application is used to feed initial simulation models. The results show improved volume-flexibility.

Nembhard, Kao and Lim (1999) focus on using DES to produce real-time generated statistical process control (SPC) charts with the purpose of improved quality management.

Integrating optimization and simulation is another area where much research is done. Fu et al. (2000) discuss various issues and seem to conclude that several benefits have been realized,especially with the emergence of commercially avaiable optimizers. but also identify a number of research and practice issues to be dealt with, ranging from algorithms to software application.

As another example, Giaglis (1999) propose the integrated use of business process simulation (BPS) in organizational design studies. This is motivated on the basis that change management approaches such as business process re-engineering (BPR), continuous process improvement (CPI), and Total Quality Management, which Giaglis refer to as being part of a process-oriented paradigm, are subject to high failure rates. Since being process-oriented, simulation is well suited to model these changes.

The next section will further explore the concept of integration.

8.2 Basic Forms of Integration

Turning first to a popular information technology dictionary, we find that there are several common usages of integration as a concept in the manufacturing industry (whatis.com, www):

1. Integration during product development is a process in which separately produced components or subsystems are combined and problems in their interactions are addressed.
2. Integration is an activity by companies that specialize in bringing different manufacturers' products together into a smoothly working system.
3. In marketing usage, products or components said to be integrated appear to meet one or more of the following conditions:
    (a) They share a common purpose or set of objectives (this is the loosest form of integration).
    (b) They all observe the same standard or set of standard protocol or they share a mediating capability, such as the Object Request Broker (ORB) in the Common Object Request Broker Architecture (CORBA) standard.
    (c) They were all designed together at the same time with a unifying purpose and/or architecture.
    (d) They share some of the same programming code.
    (e) They share some special knowledge of code (such as a lower-level program interface) that may or may not be publicly available.

With the above as a basis, it is time to classify integration from these different perspectives. A common classification is (Vernadat, 1996):

- **horizontal integration**: physical and logical integration of business processes from demand to delivery regardless of the organizational boundaries,
- **vertical integration**: decision-making integration between the various management levels of the enterprise.

Other views on integration on the enterprise level focus on the organizational boundaries (Vernadat, 1996):

- **intra-enterprise integration**: integration of processes within a company,
- **inter-enterprise integration**: integration of processes from different companies.

In the context of this thesis, these views are based on how the MSD process interacts with other parts of the value chain and its related business processes, as shown in Figure 8.1. In practice, intra-enterprise integration is manifested in the form of CIM and CE, while inter-enterprise integration is emerging through the virtual or extended enterprise (EE) concept.

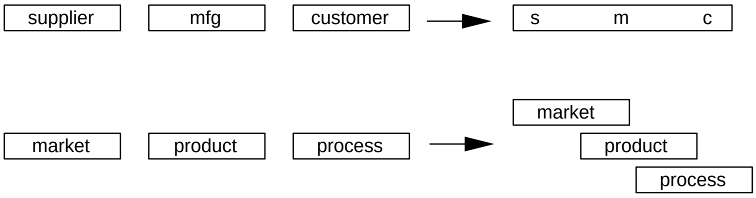


Figure 8.1 *Examples of inter-enterprise integration (top) and intra-enterprise integration (bottom).*

If one instead looks at the *extent* of integration within an enterprise, the following types defined by Vernadat (1996) apply here:

1. **system integration**, which essentially concerns systems communication, i.e. interconnection and data exchange by means of computer networks and communication protocols,
2. **application integration**, which concerns interoperability of applications on heterogenous platforms as well as access to common shared data by the various applications, and neccesitates e.g. application program(ming) interface (API), standard data exchange formats, etc., and
3. **business integration**, which concerns integration at the enterprise level, i.e. business process coordination, and often requires to go deeper in the enterprise knowledge base to precisely model business operating rules.

These three basic ways of classifying integration are in some ways overlapping. Some variation in terminology can also be seen among academia. For instance, Bernard (2000) labels “the sharing of common information between aplications” as *information integration*, which is esentially the same as *application integration* in the above.

As another example, Eversheim, Bochtler, Grassler and Kolscheid (1997) classify integration into three main categories:

- **information-oriented integration**: integration of tools for computerized support such as CAD, CAPP, CAM, and CIM.
- **organizational-oriented integration**: implementation of team-oriented concepts such as CE.

- **procedure-oriented integration**: use of methods and techniques for structuring the work in the development process such as QFD, DFMA, AD, etc.

All these can be further decomposed. Regarding for instance system integration, it range from no integration at all to loose and full integration according to the following (Vernadat, 1996):

- **loose integration**: is when systems merely can exchange information with one another with no guarantee that they will interpret this information the same way.
- **full integration**: if and only if (i) the specificities of any one of the systems are known only to the system itself, (ii) the systems contribute to a common task, and (iii) the systems share the same definition of each concept they exchange.

In this context Matsuda (1990) argues that system integration has the following three features:

1. **syncretism**, integrating different fields whilst maintaining their own autonomy;
2. **symbiosis**, obtaining symbiotic gain; and
3. **synergy**, synergistically obtaining amplification effects.

Regarding more specific ways of classifying application and higher levels of integration, there seems to be little consensus among academia. The reader is referred to Randell, Holst and Bolmsjö (2001) for a more detailed exploration of these integration types.

8.3 Problem

Although integration seems to have become something of a general buzzword in industry, ranging across everything from activity-based management on an enterprise level to simulation and execution environments for industrial robots, such as the integration of sensors on a cell-level, much remains to be done when it comes to integrating modeling and simulation of manufacturing systems into the development process.

In the previous chapter, the discussion related to problems with simulation centered on empirical evidence and experience showing that simulation use is modest and that when used, the full potential has not been realized. Discrete-event simulation is often used on a ‘one-shot’ basis, trubleshooting specific problems such as bottlenecks, and as a stand-alone tool, not integrated with other applications and systems.

When looking at reasons for this limited use of simulation, albeit with a less than satisfactory empirical base, a few common factors have been identified. First, there is still a low level of simulation knowledge and competence in industry, which results in poor commitment to simulation projects, or even worse, no simulation at all (Eriksson, 2001*a*). In particular, there seems to be a focus on *costs* rather than benefits.

There also seems to be a wide gap between simulation investment and company ability to achieve the required or expected benefits from this investment. However, evaluation or investment appraisal of DES is problematic because of the difficulties inherent in measuring the benefits (and to some extent the costs) associated with such investments. It is also argued here that the process of adopting and integrating simulation into the development process is today largely based on tacit knowledge, i.e. the experience and ideas of people, instead of explicit knowledge, formalized through a methodological approach.

Another reason becomes evident when simulation is seen in the context of Computer-Aided Manufacturing System Engineering (CAMSE), which is defined by McLean (1993), “the use of computerized tools in the application of scientific and engineering methods to the problem of the design and implementation of manufacturing systems.” The goal of this engineering process is to find a good solution to a problem given a set of requirements and constraints. However, the requirements on tools needed for CAMSE are extremely complex since they should make available information which is used in a number of disciplines, e.g. (based on McLean, 1993; Randell, 2000):

- manufacturing engineering,
- plant engineering,
- materials processing,
- environmental engineering,
- modeling and simulation,
- quality engineering and control,
- statistical process control,
- economic and cost analysis,
- computer science,
- management science.

Most of this information is currently spread in different sources and different mediums, ranging from books and binders to different kinds of databases. Most of these sources of information are badly organized, highly specialized, or store the information in inconsistent data formats. Consequently, they are not able to share information or work together. Thus, organizations have difficulties coping with these problems within their own limits. Yet, the requirements on integration will only be driven to higher levels by the emergence of extended and virtual enterprises and further implementations of computer integrated manufacturing system (CIMS).

According to Williams (1994), the three major reasons for disappointment with CIM projects are:

- **top-down approach**, which by attempting to tackle the problem as one massive project soon exceeds the resource capabilities of even the largest enterprise„
- **bottom-up approach**, which means integrating the enterprise piece by piece which has led to so-called *islands of automation*,
- **poor acceptance**:, which means that these systems are not accepted by their operational or administrative staff even when the projects are technologically successful.

The current situation thus seems to indicate a need for methodologies that can help companies manage adoption and implementation of simulation as an integrated set of activities in a manufacturing system development context. In other words, simulation engineers and manufacturing system developers need to share the same flow of information, the same view on process and content, and synchronize their working procedure of both the problem and project parts of their work to a much larger extent than is the case today.[57] This would provide for a more relevant view on the benefits of simulation as well as more efficient and effective adoption and usage of simulation.

This view is supported by several authors, e.g. Vernadat (1996, p. 10-11) who states that:

> So, on the one hand there is a clear need expressed by industry for more integration of operations and information systems, but on the other hand, experience has shown that enterprise integration is a high risk endeavor requiring major capital investment. New techniques, tools, and methods to cope with such system complexity are therefore necessary if CIM potentials are to be achieved and exploited by industry.

Regarding for instance models used in FMS design, Borenstein et al. (1999, p.8) report that “these models present a unique common characteristic, they were developed as "stand-alone" models, in which the emphasis is on the application of the model to solve isolated problems”. This isolated use shows in the form of poor documentation and a virtual "shut-down" of all simulation activities inbetween the solving of these isolated problems.

As for manufacturing system development in general, the need for simulation integration has been implicitly brought up by several researchers, e.g. Harrell and Tumay (1995) and Hibino et al. (1999), and more explicitly by Ball (1995) and Klingstam (1999).

However, with the large number of DES application areas and emerging integration capabilities mentioned above, the problem of simulation integration has become very complex, thus necessitating a holistic and well-structured approach to the problem.

Altogether, however, few researchers have focused on such methodologies for reaching integration, which, to paraphrase Kaplan and Cooper (1998, p.13) must be "based on concepts and theory, not just the ready availability of data and information."

At the same time, in the manufacturing industry several factors work together to make the adoption and use of DES more time-consuming, more inefficient, less accepted, less accurate and less likely to succeed than would be necessary. In other words, problems connected to discrete-event simulation projects are present in several areas that are both technical and organizational in their character, and at different strategic and operational levels.

The next section will look at one concept that attempts to deal with comprehensive set of integration problems – *enterprise engineering and integration.*

8.4 Enterprise Engineering and Integration

The general aims of enterprise integration are (Vernadat, 1996, p.20):

- to provide interoperability of IT applications,
- to enable communication among the various functional entities of the enterprise, and
- to facilitate coordination of functional entities for executing business processes so that they synergistically contribute to the fulfilment of enterprise goals.

This author would argue that in its present form, the real value of enterprise integration should be seen at the conceptual level. The message here is that integration issues must be lifted up to the highest level. Enterprise integration relies heavily on reference architectures and methodologies, which will be briefly described in the next section.

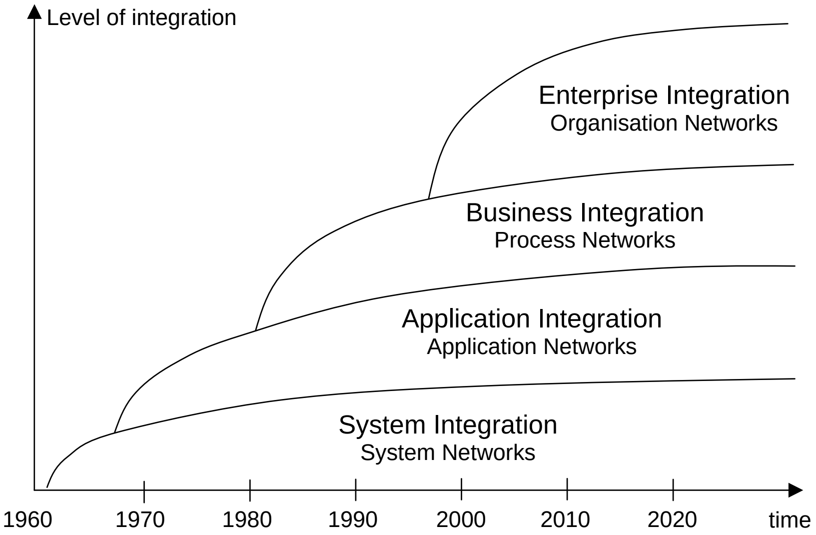


Figure 8.2 *Integration levels from an enterprise integration perspective. Adapted from Kosanke et al. (1998, Figure 1).*

8.5 Reference Architectures

An enterprise reference architecture (also known as a type 2 architecture) deals with the structural arrangement (or organization) of the development and implementation of a project or program (ISO 15074, 1998), such as the product realization process.

In contrast, a *system* architecture (or a type 1 architecture) deals with the structural arrangement (or design) of a system (ISO 15074, 1998).

An enterprise reference architecture thus serves both as a means of modeling an enterprise and as a way to position the required models, methods, and tools over the enterprise lifecycle. The main basis of the herein described methodology is the Generalized Enterprise Reference Architecture and Methodology (GERAM) (ISO/TC 184/SC 5/WG 1, 1990) including the developments of this presented by Klingstam (2001).

GERAM is shown Figure 8.3 and will not be further detailed here.

8.6 The Future of Integration

Integration, as a concept, has few shortcomings. In reality, however, several problems remain as described in this chapter. As a consequence, the future of integration will need to be focused on solving the problems rather than

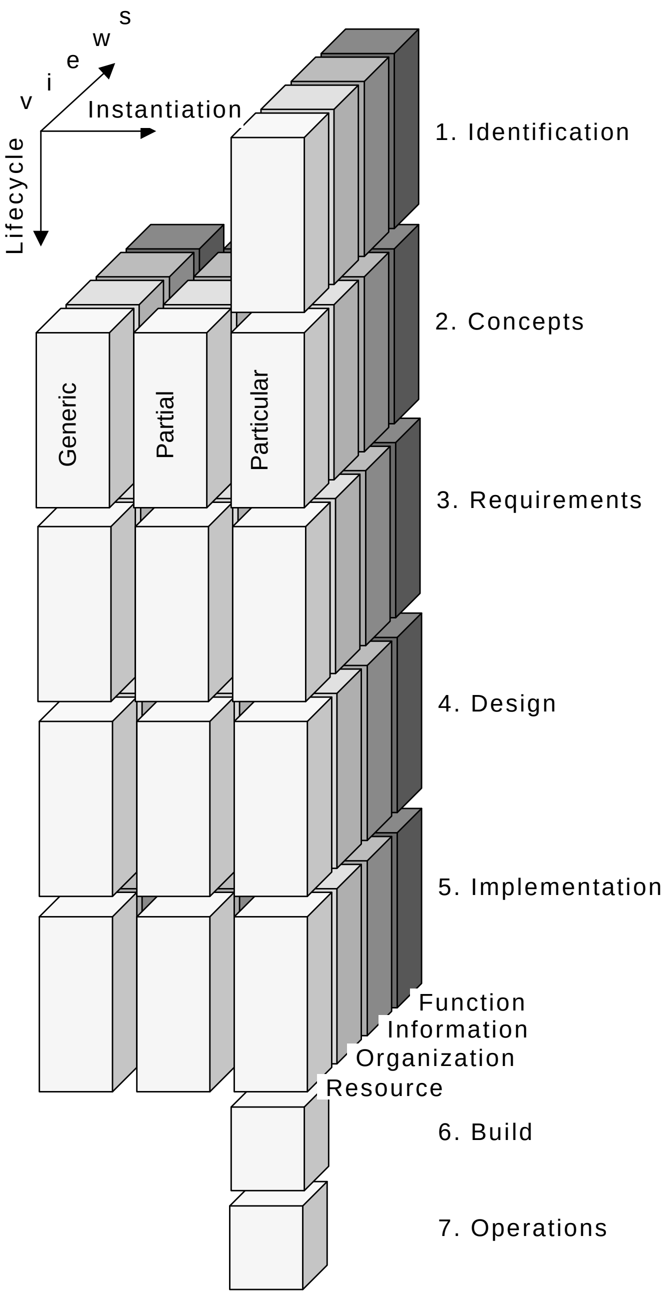


Figure 8.3 *GERAM. Source: Vernadat (1996).*

improving the concept as such. These problems are summarized by Kosanke et al. (1998, p. 236) as:

- lack of an accepted common base in the research community,
- limited awareness in the user community, and
- insufficient information technology support by the vendor community.

This author will attempt to address the first issue in Chapter 13. In addition, one important problem is not mentioned in the above. This is the need for structured approaches or formalized and easy to use guidelines for how to actually reach higher levels of integration. A concrete challenge hereis to make the reference architectures more practically useful. This need has been acknowledged by very few researchers. One exception is presented by Klingstam (2001), who decomposes the eight life-cycle phases defined in the GERA component of GERAM into eight Main Project Features (MPFs), which provide a more detailed description on how to carry out various tasks. More specifically, the MPFs provide guidelines for using the different methodology components; methods, models, tools and architectures. These issues will be further addressed in Chapter 14.

8.7 Summary

This chapter has presented an overview of different integration aspects and basic classification schemes. It is believed to have put light on the fragmented, reductionist and unstructured views on integration that seem to exist in industry and academia today.

In fact, several problems remain regarding adoption, usage, and integration of simulation into the manufacturing system development process. These problems regard such diverse matters as information sharing and exchange between different functions involved in manufacturing system development, interoperability and collection of data, organization of simulation activities, acceptance of new technologies, and several aspects on the strategic view on simulation.

With the large number of DES application areas and emerging integration needs and capabilities that characterize industry today, the problem of simulation integration has thus become very complex, thus necessitating an advanced, holistic, and well-structured approach to the problem. Today, such an approach is largely missing. One of the few exceptions is reported in Klingstam (2001), a work on which this thesis is partly based.

A first step in developing such an approach is to structure the concept of integration itself. As a start, this section has looked at the various forms of integration in existence today, in order to clearly account for the context in which the need for holism and structure is to be seen here.

Chapters 13 and 14 are direct responses to the need to change this view to provide a unified, holistic, and structured framework for integration.

Notes for Chapter 8

[56] In his book, Vernadat (1996) uses the term “manufacturing” in the narrower sense. For consistency with the herein adopted terminology, the terms “manufacturing” and “production” have been interchanged.

[57] The distinctions of process vs. content and problem vs. project are explained by Pidd (1998, p.25-28)

Part III

CASE STUDIES

Things known by report always prove quite different
when one has actually seen them.

– Kenkō

9

Swedish Industry

Many of the ideas contained in the herein proposed framework are based on experience from Swedish industry, mainly a case study at *Segerström & Svensson Eskilstuna AB* in Eskilstuna and two simulation projects that spanned two years and were carried out at *BT Products AB* in Mjölby. These studies are described Sections 9.1 and 9.2 respectively.

9.1 First Company

The first case study was performed in 1999 at *Segerström & Svensson Eskilstuna AB* in Eskilstuna, Sweden (S&S). The company is a major supplier of sheet-metal components to the automotive industry. Their environment is best described as turbulent and highly competitive. Organizationally, S&S belongs to the *Segerström* group's Automotive division and accounts for about one fifth of the groups total turnover while employing 240 of its 1,800 people (the group's total turnover was 1,800 MSEK in 1998). This case study has also been reported in Almström et al. (1999).

In their Eskilstuna plant, S&S develops and manufactures complex sheet metal components. Of total production, the Automotive division accounts for 70%, with the main customers being Volvo Car Corporation and SAAB Automobile. The production processes are mainly pressing and various types of robotized welding.

The study focused on an analysis of the company's product and process development, and had two objectives: (i) to provide the researchers with material for continued studies, and (ii) to provide the company with a basis for continued improvement work.

The data collection was performed through a combination of factory tours, interviews, process mapping, and a survey. Prior to this study, the company did not have a description or documentation of their entire development process. For this reason, a thorough mapping of that process was performed and documented. The results describe an ideal working methodology rather than a particular case or project.

The extensive survey designed as part of the case study was performed to quantify working methods and behavior during the development work. The questionnaire featured topics such as methods and information technology (IT) tools used, information flow, dependencies, cooperation and psycho-social factors. The analysis pointed to a number of recommendations to Segerström & Svensson for their future operations:

- continue the process mapping,
- spread the ideal working methodology through the organization,
- increase the efficiency of early project phases,
- look further at production flow analysis based on simulation.

Increasing the efficiency of early project phases was recommended through better use of engineering methods, searchable databases including experiences and data from earlier projects, and early evaluation of new manufacturing methods and processes

Production flow analysis was seen as having a particularly strong potential to reduce material handling costs and increase efficiency in production.

9.2 Second Company

The second case study was performed during 1999 and 2000 as part of two simulation projects carried out at *BT Products AB* in Mjölby, Sweden (BTP). The company is a world leading manufacturer of electrical warehouse trucks, and was acquired by Toyoda Loom Works in 2000. The herein proposed methodology is primarily based on experiences made during this work.

In late 1998, BTP embarked upon an ambitious and comprehensive simulation program, which included DES for flow analysis purposes. Prior to that, BTP had never used discrete-event simulation and there was no in-house competence or previous experience with this technology. With an increasingly complex production, and competitive and market pressure to reduce lead times, increase capacity, and introduce new products, BTP partnered with the Department of Mechanical Engineering at Lund University (DME) to approach this problem by the means of discrete-event simulation.

The initial system under investigation was an existing production line at BTP's Mjölby plant, shown in Figure 9.1. The line produces a large number of parts for fork-lift trucks, and features a combination of automated and manual tasks, including CNC machining, robotized welding, and automated painting. The material flow featured a large number of crossing flows and hundreds of different parts. A perceived bottleneck was seen as the primary problem.

The simulation objectives of the first project were therefore to:

- perform a flow analysis with the primary purpose of bottleneck detection,
- assess whether additional investments were necessary.

Additional objectives for BTP were to:

- try out discrete-event simulation as a technology,
- have BTP employees trained in simulation technology and methodology, mainly by DME.

The additional objectives for the DME researchers were to receive input from and study the methodological and integrational aspects pertaining to the project.

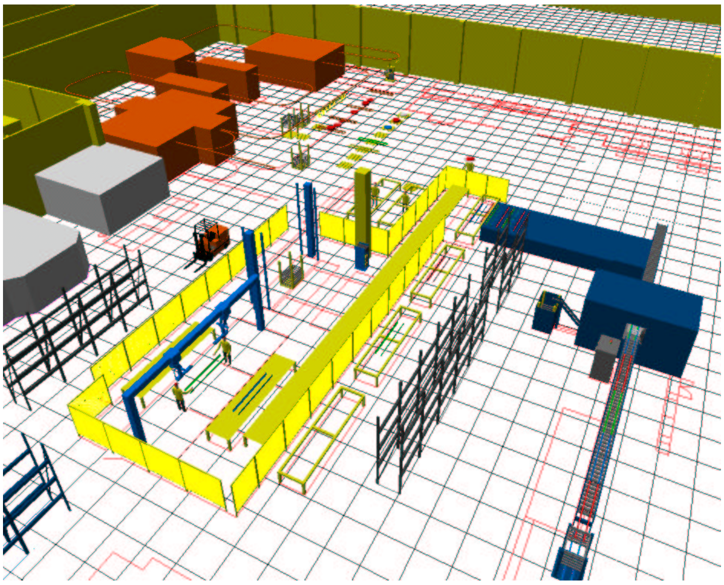


Figure 9.1 *Simulation model from the first project at BT Products. The simulation models in both projects were built in QUEST, a 3D discrete-event simulation software from Delmia Corporation.*

The second simulation project extended the scope to a planned investment in a new system, shown in Figure 9.2. The planned system was to form part of the flow of the first system. These two systems also shared structural components. The objectives of this project were to:

- validate the planned system in terms of annual capacity,
- perform a flow analysis to assess possible bottlenecks,
- test other what-if scenarios.

Both projects were carried out on multiple geographical sites – Lund and Mjölby – and on two different computer platforms – IRIX (Silicon Graphics) and Windows NT (Microsoft). The model translation phase was carried out using an incremental and modular approach to modeling, and throughout the project as a whole both modeling and documentation were supported by a configuration management (CM) system.

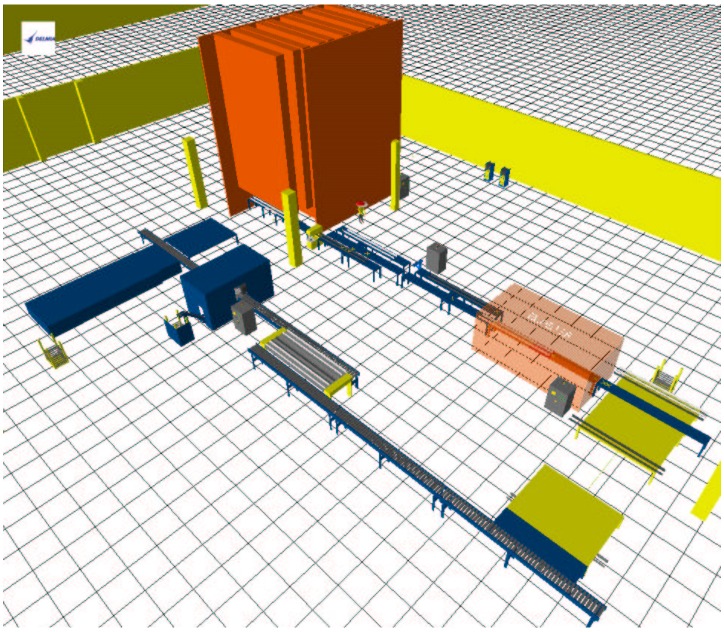


Figure 9.2 *Simulation model from the second project at BT Products.*

The results of the first project were judged as highly successful from the views of both BTP and DME. The model could be validated against the existing system, and the objectives were met. Also, additional benefits were realized since the perceived bottleneck was proved to have sufficient capacity. A capital intensive investment could thus be avoided. BTP also reported less tangible benefits such as improved communication between logistics and production, and increased system knowledge. BTP gained the necessary confidence to carry on with simulation, and a decision was taken to increase in-house competence of discrete-event simulation.

The second project is yet to be validated against the real system, since it was recently built and is currently in the ramp-up phase. Despite this, the project objectives were met and a number of results have been reported in company-internal documents.

Other results from this project have been reported in Randell, Holst and Bolmsjö (1999*a*), Randell et al. (1999*b*), and Randell et al. (2000), and a forthcoming publication by these authors will make the simulation experiences underlying the proposed methodology more explicit.

10

Japanese Industry

The results from the studies of Japanese industry are based upon two visits to Japan. The first study was made during May and June 1999 and included visits to seven large Japanese manufacturing companies. Results from this visit have been reported in Holst, Randell and Bolmsjö (2000) and Holst and Bolmsjö (2001*b*). The second study was made during March and April 2000, and included visits to five medium-sized and large manufacturers. Two of the companies had been previously visited in the first study. The findings from this study have not been published. The methodology was near identical in both studies, and will be briefly described in the next section.

10.1 Methodology

In both studies, the visits combined factory tours and interviews with people from various functions. The majority of interviewees were from the production engineering department, with significant representation from R&D and marketing. The visits also included talks to middle and senior managers. A questionnaire was sent out to the companies prior to the visit, featuring questions in both English and Japanese. The purpose of the questionnaire was to better prepare both parties for the interviews, and make the time spent at the companies more efficient. The questions were a mix of open end questions and questions where alternative answers were measured using five point Likert-like scales. Preliminary drafts of the questionnaire were discussed with Japanese researchers to assess its content validity and for translation. A pilot test with a Japanese firm was then conducted to improve the comprehensiveness, clarity, and relevance of the questionnaire.

The questionnaire was slightly different between the two studies. Feedback from the first study had indicated that too much time was required to answer the questions, and that the questions spanned several competence areas and thus could not be answered by a single person. In addition, some questions were perceived as vaguley formulated. After the first study, the number of questions was reduced, some questions were added, and others were rephrased for increased clarity.

In the first study, a total of 20 questionnaires were sent out to companies chosen *ad hoc* from a Japanese university professor's personal network, and visits were then made to 12 of these companies. Of these 12 companies, three did not return the questionnaire whereas two visits were judged as non-successful in terms of the amount and quality of the information received. Thus, five of the visited companies were excluded from the study, which left a final sample of seven. The sample size has not made it meaningful to perform a statistical analysis of the data obtained, nor allowed comparison of the answers. Instead, the results from the questionnaires have been used as a basis for discussion. Consequently, no external data validation has been performed, although the findings have been compared to the work of Umeda and Jones (1997) where possible. This and earlier work by the same authors are the only similar empirical studies available.

In the second study, a total of 20 questionnaires were sent out to companies chosen as in the first study, and visits were then made to nine of these companies, two o which had been visited in the first study. Two of these nine companies did not return the questionnaire whereas two visits were judged as non-successful in terms of the amount and quality of the information received. Thus, a total of four of the visited companies were excluded from the study, which left a final sample of five, with the two previously visited companies remaining. The questionnaires were used as in the first study.

As noted above, several companies that were visited in these two studies were excluded from the final samples and have not been explicitly reported. However, they have acted as input to the general findings and conclusions made here. In addition, they have been used by the author for external validation of these general findings.

10.2 First Visit

The industries represented by the visited companies in this first study are automobiles, trucks, buses, machine tools and electronics. They include component manufacture and final assembly, and use a wide range of production technologies. Their sales cover domestic as well as international markets, demand patterns include stable, cyclic and fluctuating, and customers range from industry to consumers. The visited companies can therefore be considered to represent a broad spectrum of Japanese manufacturing industry. All the visited companies are classified as large, both in terms of employees and capital (for a definition, see Holst and Pozgaj, 1997). Their turnover and gross profits were at the time of research among the top ten within their respective industries.

A brief outline of these companies follows next (note: companies have been given fictitious names from the Chinese animal zodiac. Any similarity to names of actual companies is unintentional).

Rat Corporation is one of the world's largest manufacturers of machine tools, with about 1,500 employees in total. Their products, most of which are made according to specific customer requirements, include lathes, machining centers, grinders, and systems. Visits were made to two factories; one old and one new. The company does not use DES.

Ox Motor Corporation, the third company in the automotive industry, was visited twice. The first visit was made to a plant belonging to the car division, the second to a plant within the truck and bus division. Ox ranks among the largest in Japan in its category, has several plants in Japan and also manufactures overseas, yet DES was used in neither of the two divisions visited.

Tiger Motor Corporation is another very large automobile manufacturer and makes extensive use of various simulation techniques, including DES. The visit was made to a unit responsible for drive-train design at the company's technical development center.

Rabbit Electric is an electronics division within one of Japan's largest corporations. The division employs more than 3,000 people, and makes various high-frequency based communications and imaging products. DES is not used.

Dragon Motor Corporation is one of the world's largest automobile manufacturers. It is almost the model company when it comes to using simulation as an integrated part of manufacturing system development, and conversely uses DES on a regular basis.

Horse Machines makes machine tools and automotive parts, and provides automation solutions. It is a first tier supplier to Dragon Motors, but supplies to other companies in the automotive industry as well. It employs more than 4,000 people and does not use DES.

10.3 Second Visit

This second visit is described in a working paper and has not yet been published. For these reasons, it will not be further outlined here. In short, however, and this is an important reason to include it here, this second visit supports the findings of the first study, albeit with a smaller sample size.

10.4 Summary

In summary, the two studies of Japanese industry showed that a majority of the visited companies did not use DES, let alone had integrated the use of this technique into their development process. On a more general level, this view was supported during talks with managers and engineers at one of the two companies that did use DES in the first study. They were aware of only one other major Japanese corporation that had introduced a company wide virtual manufacturing program similar to theirs. The two companies that used DES reported on several positive experiences. The most frequent purposes of use are planning and evaluation, communication and discussion of ideas and decision support. The future role of simulation is seen by these companies in the areas of design of manufacturing systems, added-value in production, virtual reality (VR) applications and reduced time-to-market.

Based on the findings from this study and general characteristics of the Japanese manufacturing industry, a number of simulation success factors specific to Japanese companies were identified. These are factors specific to Japanese companies, and should act as advantages in future use and integration of simulation. Perhaps surprisingly, they have not been explicitly mentioned in connection with previous research on simulation. These factors are usually not seen as directly connected to simulation, and conversely have been overlooked in most simulation research. The three most important success factors are described here. However, there also exists a number of push factors, or internal and external environmental drivers which are believed to push the companies in the direction of increased simulation use. Several push factors were identified, but only three are accounted for here. An attempt was also made to identify factors that act as entry barriers to simulation use and integration. Some of these are briefly mentioned in the article, although several more exist and need to be further explored. The push factors and barriers to entry are a combination of factors that are specifically Japanese and factors common to manufacturing enterprises in a global context.

10.4.1 Success Factors

Success factor 1 – Knowledge Creating. As several researchers have showed (Kusunoki and Numagami, 1998; Sobek, Liker and Ward, 1998; Nonaka and Takeuchi, 1995; Clark and Wheelwright, 1993; Womack et al., 1990), personnel, including engineers and other technical staff, are frequently and systematically transferred within a Japanese company. It is generally agreed upon that this is a key factor in explaining competitive advantages of Japanese industrial enterprises (see for instance Jacobs and Herbig, 1998). Also, as Sobek et al. (1998) showed in their extensive study of Toyota, only senior managers rotate broadly and frequently across functions. Engineers below the *buchō* level - corresponding to the head of a functional division - are primarily transferred within their function and at longer intervals than the typical product cycle. This is in essence supported by Kusunoki and Numagami's findings, which e.g. show that more than 70% of the third transfers are in the middle or late career stage, while fourth or later transfers are concentrated to the late career stages.

This study extends these findings to be the case at all the visited companies, although it cannot be said for certain that the frequencies of rotation are consistent with those reported by Sobek et al. (1998). However, the implications of these practices were strikingly evident when talking to engineers and managers at all levels in the visited companies. The impression was that of a very good general knowledge about business processes and functions in all parts of the organization. In fact, this study confirmed these transfer activities to be practiced at all the visited companies. Such rotating of engineers increases system knowledge at the factory level and employees' ability to communicate with each other.

As argued by Kusunoki and Numagami, this may even lead to cross-functional integration derived from the above mentioned multifunctional knowledge obtained through hands-on experiences in different functional areas, rather than through intensive and extensive communication. The first success factor derived from this study is therefore that this interfunctional transfer at managerial levels and intrafunctional rotation at engineering levels, supports and increases the quality of networking, engineering communication, cross-functional coordination and interfunctional knowledge across the organization, on both an explicit and a tacit basis. For engineers, it further reduces the amount of communication and supervision, trial and error, misunderstanding, unrealistic expectations, and confusion. These are substantial advantages to successful simulation projects.

Success factor 2 – Statistical Competence. This leads us to the second success factor, namely Japanese engineers and shop floor workers generally good knowledge of statistical analysis methods. In addition to the interfunctional transfers mentioned above, delegated responsibilities and problem solving activities have a long tradition in Japanese companies, and are aided by large amounts of information regarding the production processes and their performance measures (Holst and Pozgaj, 1997; Womack et al., 1990).

During the visits made as part of these studies, such statistics were frequently encountered on in virtually all parts of the factories, canteens not excluded. And this data is not only there for show: workers and managers on the shop floor regularly meet around these spreadsheets and diagrams to evaluate and discuss the latest and coming production performance. This greatly helps in identifying disturbances and undesired variations in the production, and provides a powerful way of jointly solving these problems.

Because simulation output data is a set of random estimates of several input parameters, one crucial phase in a simulation project is the interpretation and use of this data (Eriksson, 1997). Good results depend upon an intelligent design of experiments and analysis methods, knowledge that is highly specialized. Although the findings of Umeda and Jones suggest otherwise, the competence regarding experimental design methods and statistical output data analysis was perceived as high at the visited companies. The second success factor derived from this study is therefore that this "shop floor information system" and well established use of statistical process control methods in Japanese manufacturing firms greatly increases the likeliness of successful simulation projects.

Success factor 3 – Late-Mover Advantage. In many ways Japan seems to be lagging in ICT and 'e-manufacturing' investments, particularly in comparison to the U.S. (Kawai, 1998). This is perhaps mainly seen as a disadvantage, given the profound way these technologies are changing the way manufacturing companies do business. However, by studying reports on the considerable amount of unsuccessful implementations and failed investments, Japanese companies can learn from others' mistakes and much like they did with quality theory and practice in the 1950s and 1960s, companies can import, adapt and develop best practices from the U.S. and Europe, especially regarding strategic use of simulation.

Recent alliances and partnerships through mergers and acquisitions involving large Japanese and foreign companies, most notably Nissan–Renault, Ford–Mazda, Mitsubishi Trucks & Buses–Volvo Truck Corporation, Mitsubishi Motors–DaimlerChrysler and Toyoda Automatic Loom Work–BT Industries, suggest that this will be further supported through close relationships with companies that already have lots of experience in the field, successful as well as non-successful.

Two companies represent this trend in the first study; Tiger and Ox Motors both recently entered strategic alliances with non-Japanese automobile manufacturers. Thus, this late-mover advantage is the third success factor.

10.4.2 Push Factors

Push factor 1 – The Need for Flexibility and Lowering of Production Costs. Several researchers and analysts argue that a weakness of lean production is its inability to respond to the present situation with frequent and large variations in demand, regarding both volume and product mix (Katayama and Bennett, 1996)see e.g.. Even small changes in demand will often take production below the break-even point. Most analysts would agree that Japan currently exports too much from a high-cost manufacturing base in Japan. This trend is generally believed to become clearer, and is strongly supported by the findings of this study which show that lowering production costs is considered a major problem by all companies except one. The means to become agile and lower production costs, while maintaining labor stability, are numerous and constitute no easy task, but based on the authors' industrial experiences, as well as substantial amounts of other research, it is argued here that simulation is one feasible way which will present itself as a likely alternative, even when integration aspects are not considered. In this context, it should be noted that in the present debate several analysts of Japanese industry advocate further plant closures and work-force cuts. However, the authors believe that such measures are neither feasible nor likely to take place to the extent called for, and that market driven employment relations have a long way to go in Japan. It would be beyond the scope of this research to explore this further, but the reasons why the employment system will not change as much as some analysts seem to think would focus on cultural factors. This view is supported when looking into detail of those labor related restructuring measures that have taken place. These concentrate on such things as reduction of overtime and the number of female employees. Thus the general drive to curb production costs will push for further use of simulation.

Push factor 2 – Change in Supplier Networks. Loser keiretsu ties and more open supplier networks in general make it harder to control the quality of parts. Ox Motor particularly emphasized this, since they have seen considerable changes in their supplier networks in recent years. In particular, the number of independent companies, i.e. suppliers not belonging to their keiretsu, has increased. As described in the article (Holst and Bolmsjö, 2001*b*), these developments will push for an increased use of ICT, where simulation is believed to be one important component.

Push factor 3 – Globalization and Deregulation. As argued in previous sections, an increased competitive environment and deregulation of several sectors in Japan will call for an intensified use of technologies that can assist the concepts and strategies that will be pursued as an answer to these developments, just as in other parts of the world. Simulation, with the advantages outlined in this thesis, will be one key element in these efforts.

10.4.3 Entry Barriers

With the reservations mentioned in the article's discussion on Japanese simulation research (Holst and Bolmsjö, 2001*b*), this author is left with the impression that there is a relatively small amount of research in Japan focusing on the use of simulation technologies and related areas such as virtual manufacturing, information infrastructure, interoperability, etc. This seems particularly evident when looking for research on a more general level, taking into account strategic and operational issues. Dissemination of research results into industry is important, and perhaps best done through direct involvement by researchers in industrial projects. The fact that few researchers seem to exist in this field can therefore act as an entry barrier.

Japanese companies have a general preference towards simpleness – charts and diagrams are used extensively, QC activities, not consultants solve practical problems, and so on. As most would agree, this has undoubtedly played a major role in the success of Japanese manufacturing. In fact, concepts such as *poka yoke*, QC circles, 5S and the 7QC tools, just to mention a few, have been widely adopted by Western companies. However, to Japanese firms the step from such simpleness to full scale CIM and ICT implementation might be perceived as large, and may therefore act as another barrier to entry.

Furthermore, this study and others have mentioned simulation knowledge and competence as important factors in successful simulation projects. Arguments such as high initial investments, lack of competent personnel, etc, were mentioned by most of the visited companies that did not use simulation and DES. Also, many companies were not sure whether they would use simulation repeatedly, reflecting a lack of support for the need of integrating simulation into the development work. Some managers seemed to consider simulation as neither a tool to save costs nor increase income. The authors believe that part of the problem lies in the fact that in successful simulation projects, many costs are avoided rather than saved. Thus, the generally low level of simulation knowledge is also likely to act as an entry barrier.

Finally, a widespread use of several incompatible and dated stand-alone technologies with data spread in various sources and in inconsistent data formats will further adversely affect integration and access to and collection of input data for simulation models.

In conclusion, Japanese companies using simulation report on successful experiences. However, even for these companies the full potential of simulation has not been realized. Integration problems remain, mainly attributable to a lack of common supportive infrastructure and interoperability problems. Simulation appears to be far from an integrated part of manufacturing system development, and several barriers to entry exist. Simulation, in particular discrete-event simulation, has not yet gained an industry wide acceptance as an important decision support tool in Japanese industry.

11

Analysis and Conclusions

In summary, the case studies have provided insight into:

- approaches to manufacturing system development in Swedish and Japanese industry,
- differences and similarities between Swedish and Japanese industrial practice,
- the role of discrete-event simulation in manufacturing system development.

The first case study at S&S provided valuable insight into real issues in the development process in a Swedish manufacturing firm. Due to the multi-faceted composition of the research team and the commitment of S&S to provide the team access to a wide range of information and personnel, in-depth knowledge of actual development activities was gained through several perspectives.

The second case study at BTP also offered substantial insight into the engineering process of a manufacturing company. BTP's operations and market conditions were different than those studied at S&S and thus complemented the first case study well. Moreover, the two years spent working with BTP fuelled creative thinking and reflection on a majority of the issues underlying the herein proposed methodological framework. In brief, the successful results and realized benefits were judged by this author as strongly related to *integration*, just as a lack of integration was seen as the cause of several of the problems encountered along the way. However, although BTP went through a gradual increase in their level of integration of simulation in their manufacturing system development process, it was neither a structured approach nor a process that ended with the highest possible level of integration. As a result, the process was seen as having potential for improvement. The twists and turns and the ultimately successful outcome have therefore been important inputs to this research.

Turning to Japanese industry, there seems to be a widespread idea that it is in crisis. Based on visits to more than 40 Japanese manufacturers of various size, this author does not agree. The problems that have faced the Japanese economy since the early 1990s are mainly due to macroeconomic conditions largely beyond the control of the manufacturing industry, including but not limited to the effects of the so-called *bubble economy* which has left Japanese banks with enormous amounts of bad loans, a heavily regulated economy governed by conservative and powerful bureaucrats (Fingleton, 1997), failure on behalf of the Japanese government to carry through structural reforms, and declining levels of consumer spending in the important Japanese home market At the time of writing, deflation continues to weaken spending by increasing the real burden of debt (The Economist, 2001*c*), and as a result, the Japanese manufacturing industry's dependence on exports is increasing.

This is not to say that certain Japanese manufacturers are not in crisis. They are, but just as the entire Japanese industry was not uniformly successful in the 1970s to 1990s (Womack et al., 1990), so there are differences within the industry now. The bottomline is that we can still learn a lot from Japan. The real change is perhaps that Japan is back in a position where it too can learn from others. In this respect, Japan has become much like any other industrialized nation. The effects of globalization are beginning to show in Japan as well. Deregulation is attracting a growing number of foreign companies, large Japanese firms are increasingly cooperating, merging, or forming strategic alliances with foreign companies, and Internet access and the number of Japanese travelling or studying abroad is steadily increasing (Kawai, 1998). As a result, the global economic slowdown is seriously affecting Japan, and companies in the Japanese industry are now sharing several problems with their Asian, European and Northern American counterparts. As in many other countries, particularly Asian economies with a large dependence on the U.S. market for their exports, Japanese manufacturers are faced with overcapacity which is also having the effect of reducing investments and temporary employment. Many other changes are also evident. For instance, as Japanese companies' suppliers are becoming more independent, the industrial structure in Japan will increasingly resemble that in the West. As a result, cooperation and information sharing becomes harder to manage for Japanese manufacturers too. As a result of all this, Japanese companies have been forced to restructure. The last years have seen frequent media reports of large Japanese manufacturers plans to cut jobs, often by the thousands. Although these measures are still carried out in a very Japanese manner, there is considerable evidence that Japanese industrial structure is changing, as reported by e.g. Holst and Pozgaj (1997).

These insights, in combination with reviews of literature and own experience have lead the author to draw the following conclusions:

- neither the Swedish nor the Japanese manufacturing industry has realized the full potential of discrete-event simulation, although successful examples exist in both cases,
- although several problems exist, integrating DES into manufacturing system development can have several benefits for manufacturers, regardless of cultural or geographical factors
- further advantages (or success factors) can be realized if DES is combined with other methodologies and practices, such as those typically found in Japanese industry,
- current trends in the manufacturing industry can be seen to act as simulation push factors, suggesting a growing adoption and use of DES,
- despite the presence of these success and push factors, simulation can also be hindered by a number of entry barriers, some of which are general, and some which are culturally dependent, suggesting a limited future growth either because of non-adoption or unsuccessful use of DES.

As mentioned above, however, the findings from Japanese industry presented here are largely basd on the study presented in (Holst and Bolmsjö, 2001*b*), and to a lesser extent on the second study of five large Japanese manufacturing companies. Coming publications will extend the findings described here to that second study, which should provide for more reliable general conclusions. However, these studies have only touched upon several important areas, and further research is therefore needed. First of all, the empirical work of Umeda and Jones will need to be followed up (Umeda and Jones, 1997). For instance, in 1997 they stated that the use of simulation in Japan was modest but on the rise. No subsequent research has supported this prediction. If anything, the two studies discussed here have shown that simulation use is still modest in Japanese manufacturing firms. In line with that study, future work will also need to look more into details of simulation projects, which may reveal interesting differences between companies in expected and real outcome of simulation use.

In addition, more research is needed on the use of simulation in Swedish industry. As mentioned previously, few empirical studies exist that explore the reasons for use and non-use of DES in various parts of the world, including Sweden.

In connection with this, further work is also needed to explore the interrelationships between the strategic use of simulation and other management practices in Japanese and Swedish companies, as well the strategic role of manufacturing within these enterprises.

Part IV

RESULTS

The truth is rarely pure, and never simple.

– Oscar Wilde

12

Learning From Others

As Christensen (2001) argues, we must always look at what we do through the lenses of other disciplines. With this basic awareness in mind, and based on the problems outlined in Section 7.6, three primary areas of interest have been identified here:

1. Information and communication technologies
2. Information technology investment evaluation
3. Diffusion theory

Despite that these areas belong in the domains of other disciplines, a fact that holds some practical obstacles, they have been found to offer considerable value to the discipline of DES.

The following sections will motivate the choice of these areas and describe how the knowledge from them might be used in a simulation context.

12.1 Information and Communication Technologies

Many labels can be put on simulation; it is known as decision support, an analytical tool, and so on. However, it is one thing above all: *software*, or "the beast of complexity" (The Economist, 2001*d*).

As soon as a company attempts to adopt simulation, the software becomes, in one way or another, part of their information system. As a consequence, simulation software has come to suffer many of the problems associated with ICT investments in general.

So while previous sections argued that empirical material on simulation investments is rare, the point made here is that several studies of ICT investments could be used as a source of information on the reasons for the modest use of simulation.

A look at these studies show that they all indicate high failure rates of ICT investments, more or less regardless of type. More importantly, however, they attempt to explore the reasons behind this situation.

Starting with some hard figures, a frequently cited study showed that *75%* of information technology (IT) investments fail (Standish Group, 1995). A more recent study of IT investments in 400 large Swedish corporations and government agencies showed that more than *40%* of the projects failed to reach their objectives (Dagens Industri, 2001). Moreover, many of these projects turned out much more expensive than planned and got significantly delayed. According to Mats Röhfors, CEO of the Swedish branch of SAS Institute (2001), the company that ordered the study, these investments failed because companies focus on the wrong things when an IT investment is made. Often, the target is the kind of rationalization projects companies have been carrying out for the last 30 years. There is simply not that much left to gain from such efforts. Instead, firms should focus on “soft” investments that enable the right decisions to be made on the managerial level, i.e. strategic decision support. However, managers still favour investment appraisal expressed in strictly measurable performance. This is also supported by the study, which shows that *40%* of respondents find management’s competence inadequate. Interestingly, another study by the same company two years earlier shows similar results. If anything, matters have gotten worse. Furthermore, another study by Ewusi-Mensah (2000) found that a significant number of software projects are *abandoned*, and therefore never reported as failures.

Not surprisingly, we also see that the more complex the system, the less the value that can be realized from that investment. In a study of 100 large companies, it was found that only *ten* got any real value from implementing an enterprise resource planning (ERP) system (Davenport, 2000). Another testimony to this state of affairs is offered by James and Wolf (2000):

> For many businesses, installing ERP was traumatic. Following long, painful, and expensive implementations, some companies had difficulty identifying any measurable benefits. Those companies that were able to point to them thought they could have been achieved without the help of the computer system. One chief information officer concluded that "80 percent of the benefit that we get from our ERP system comes from changes, such as inventory optimization, which we could have achieved without making the IT investment.

This author believes that most people with simulation experience would agree that the above description holds true for DES as well, although the associated costs are less.

Not only can we learn from these related areas. There are also clear relationships between these and DES. In other words, the quality of simulation projects depends to a large extent on the quality of the underlying informational infrastructure. It is thus important to bear in mind that simulation has to rely on data from information systems which not only supply data in inconsistent formats, if at all, but have generally high failure rates in themselves (wmc99:p784). This is particularly true for ERP and MRPII systems.

Application Service Providers

In their 2001 software survey, *The Economist (2001*d*, p.3)* predicts that "the computer business will no longer revolve around writing big, stand-alone programs. Instead, it will concentrate on using software to create all kinds of electronic services, from simple data storage to entire business processes". Enter the *application service provider (ASP)*, a term devised for those companies that are going to provide these electronic services through the Internet. This trend can be motivated as follows (The Economist, 2001*d*, p.6):

> The way the [software] sector used to operate was fundamentally inefficient. Although a service at heart, it conducted itself like a manufacturing business. It put its programs on floppy disks or CD-ROMs, marketed them heavily and left the rest to the users. This created unhealthy incentives for software firms. Instead of developing software that works well and is easy to use, many of them concentrated on selling yet another upgrade with even more features[...] When software becomes an online service, the interests of vendors and customers become better aligned because the providers have to behave more like a utility.

The ASP concept thus centers on the simple principle that the software is to be regarded a *service* rather than a *product.* In other words, the ASP business can be desribed as "software for hire" (Far Eastern Economic Review, 2000, p.50). Rather than buying a piece of software, companies rent access to it, and the software and data are stored on the ASP's server. Popular free Web-based e-mail services, such as Hotmail and Yahoo! are examples of very simple ASPs.

The drawbacks of trusting ASPs with critical software may seem obvious: "If these programs, and the data they provide access to, were suddenly unavailable, many companies would be crippled" (Far Eastern Economic Review, 2000, p.50). Indeed, if employees one day switch on their computers to find no software, their company's operations are likely to be seriously affected. However, "the same is true of power, water or public transport" (*ibid.*), which usually works just fine. While still in its infancy, several analysts seem to agree (although several others disagree) that once ASPs (i) team up, and (ii) are able to rely on an improved Internet infastructure, demand for their services will seriously take off. Undoubtedly, there are major obstacles to overcome. One is the division of labor between servers and clients, e.g. the use of thin or intelligent clients. Another is the plethora of would-be standards, the indecisiveness of the computer industry to decide on which of these to use, and the complexity that has resulted. As an evidence, a formidable “alphabet soup” of acronyms has emerged, including XML, XAML, SOAP, eBXML, UDDI, and WSDL.[58]

As the authors of the software survey put it, “why should anyone care about this geeky stuff?” The answer is figures, i.e. the sheer size and growth rate of the software industry. In 1999 software accounted for *$157 billion* in sales and 15% in annual growth. Software spending in its turn influenced another *$800 billion* in hardware and services (The Economist, 2001*d*).

What about simulation in this context? Although simulation’s share of the software market is disappearingly small, simulation can be expected to ride the ASP wave in several ways. First, simulation software vendors will be able to exploit the technical developments now taking place within the area of information infrastructures. Second, once the technical issues have been solved, the expected general increase in awareness of the advantages of ASP is likely to affect simulation customers as well, thereby putting pressure on vendors to deliver.

However, if and when this ever happens remains to be seen. The concept as such is not brand new. In 2000, ASPs were one of the most talked about hypes in the software industry, and the fact that not much happened after that is to some a testimony of lacking potential. This author begs to differ, as do an increasing number of analysts who indeed see huge potential in ASPs. Although not an evidence in itself, some 500 ASPs in the U.S. alone shows that there are at least some companies that believe in the concept (The Economist, 2001*d*). Among these is the software giant Oracle. Larry Ellison, the firms CEO, predicts that in three years about *two thirds* of all applications will be delivered by ASPs (*ibid.*). In any case, the simple fact that simulation software has yet to appear as a service offered by ASPs should not rule this possibility out in the near future.

The most important point in this context, however, is that if ASPs become legio, simulation software has to fit into the resulting informational infrastructure whether or not “ASP” will be a column in listings of simulation software vendors. This will put very tough requirements on the availability and functionality of *standards* for interoperability and exchange of data. Apart from the standards and near-standards mentioned above, the Standard for the Exchange of Product Model Data (STEP) standard, which includes the information modeling language EXPRESS, is to be seen as important.

Highly related to ICT implementation issues is the problem of evaluation of these investments. As argued previously, this is also a problem area in simulation. Although the evaluation of such investments is strongly related to the implementation isssues described in this section, there is enough value in such investment appraisals in themselves to motivate a separation. In other words, looking at any one of these two areas by themselves is believed to have positive impacts on simulation investments, be it through less troublesome implementiation or more relevant and accurate investment analyses. However, considerable synergy could be attained through a unified aproach to these areas. Evaluation of information technology investments is the subject treated in the following section.

12.2 Information Technology Investment Evaluation

This is the problem: simulation, initially, does drive several highly *visible* costs; i.e. initial phases of simulation integration involve easily quantifiable costs for hardware, software, training and personnel, but few equally quantifiable cost reductions or revenue increases. In addition, those involved in simulation projects with a low level of integration are likely to perceive the added amount of time that has to be spent on input data collection, meetings, etc. as a burden.

The author would also argue that many times simulation is, wrongly, neither seen as a tool to reduce costs nor increase income. Part of the problem lies in the fact that successful simulation projects *avoid* rather than save costs. Also, costs are seemingly transferred to earlier stages in the development projects, when managers are traditionally very reluctant to deviate from the initial budget. Instead, problems are allowed to arise in later stages, thereby contributing to the cementation of simulation as a trouble-shooting tool.

Conversely, there is a wide gap between simulation investment and company ability to achieve the required or expected benefits from this investment. Evaluation or investment appraisal of discrete-event simulation is problematic because of the difficulties inherent in measuring the benefits and cost associated with such investments. It thus appears that discrete-event simulation shares these problems with information technology investment in general, and that this area is one from which simulation advocates have a lot to learn.

12.3 Diffusion Theory

In brief, diffusion theory and the aspects it looks into, divided into pre-adoption and post-adoption issues, is a missing piece of the puzzle in simulation research. The application of diffusion theory to the diffusion of DES in industry has not been reported so far in literature. With this basic awareness in mind, a forthcoming publication which is in the process of being written will describe a survey on the diffusion of discrete-event simulation conducted in Swedish industry during 2001 (Eriksson, Holst and Hallgren, 2001). This will be based on the work of Rogers (1983), Moore and Benbasat (1991) and Karahanna, Straub and Chervany (1999). The reader is referred to these sources for further material on the underlying theoretical framework and survey methodology.

Notes for Chapter 12

[58] This author will not delve any deeper into the world of these acronyms. The interested reader is referred to whatis.com (www) for more information.

13

Simulation Integration

To summarize the previous chapters in one sentence, we can say that the full potential of discrete-event simulation has not been realized in the manufacturing industry as a whole.

On a more general level, integration problems have been addressed within the extended enterprise manufacturing paradigm by the *enterprise engineering and integration (EE&I)* concept as described in Section 8.4 (Kosanke et al., 1998). Whilst this concept identifies production and process simulation as part of what is referred to as *business integration*, the second highest integration level, there are no explicit guidelines given as for how simulation should become integrated with the manufacturing system development process. Nevertheless, *simulation integration* should aim at being consistent with EE&I concepts and technologies to as large an extent as possible.

13.1 The Needed Directions in Simulation Integration

Three major research directions, which should be seen as fundamental guidelines for developing an integration framework and methodology, have been identifed here. These directions can be characterized as:

- **generic** as opposed to particular: the concept of simulation integration should be applicable across a wide range of manufacturing enterprises,
- **holistic** as opposed to reductionistic: simulation integration should consider integration from *all* aspects, just as the manufacturing system and product realization process should be seen from all its perspectives and over its entire life cycle.
- **structured** as opposed to *ad hoc*, unplanned, and evolutionary courses

of action: ways of implementing simulation integration should provide stepwise, easy to understand, easy to use, well-documented guidelines that are easily adaptable to a specific organization.

These are shown in Figures 13.1-13.3.

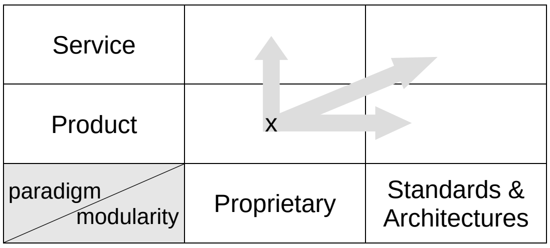


Figure 13.1 *The generic directions of simulation integration. The X indicates where most companies are today.*

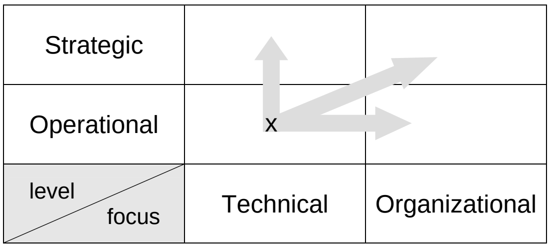


Figure 13.2 *The holistic directions of simulation integration.*

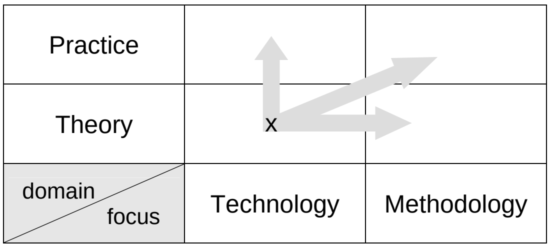


Figure 13.3 *The structured directions of simulation integration.*

13.2 Simulation Integration Defined

According to Vernadat (1996, p.23), “integration means putting together heterogeneous components to form a synergistic whole”. In this case, the goal is to make DES integral to the PRP by putting together all relevant components of DES with those of the manufacturing system development process.

Based on the above, and the systemic aspects defined by Hitomi (1996) and Seliger et al. (1987), simulation integration can be defined as:

> **Definition 13.1** SIMULATION INTEGRATION
>
> The integration of simulation from functional, structural, hierarchical, and procedural aspects into the manufacturing system development process, where development refers to the entire life-cycle of the system, i.e. the planning, design, redesign, development, reconfiguration, etc. of manufacturing systems.

While the above aspects relate to the system properties described previously, the lifecyle is captured by GERAM, as outlined previously.

13.3 Function, Information, Resource, and Organization

A manufacturing environment is so complex that it can be described in an almost infinite number of ways. To understand the conceptual difference between the building blocks of a manufacturing environment, i.e. the DOSE constructs, and the complex whole formed by these building blocks, some formalism that can serve to describe this complexion is necessary.

Based on the ideas outlined by Vernadat (1996), the particular feature of the enterprise views in the GERAM have been adopted. GERAM mainly builds on the CIMOSA, GIM, and PERA frameworks: the reader is referred to Vernadat (1996) for a detailed description of these frameworks.

These four views are (Vernadat, 1996; Berio and Vernadat, 1999):

1. **function**, which represents enterprise functionality (what has to be done) and behavior (in which order work has to be done, i.e. events, activities, and processes) including temporal and exception handling aspects,
2. **information**, which represents enterprise objects and their information elements,
3. **resource**, which represents enterprise means, their capabilities, and management (who/what does what),
4. **organization**, which represents organizational levels, units, authorities, and responsibilities, and may include other aspects, such as economic view, etc.

The primary purpose of these particular views (henceforth referred to as FIRO) is to adopt a semantic unification framework that seems to be gaining wide acceptance within the research community.

13.4 Issues to Reach Higher Levels of Simulation Integration

The present situation regarding simulation integration is illustrated in Figure 13.4.

Figure 13.5 attempts to show some of the issues in overcoming these problems, i.e. reaching higher levels of simulation integration: deciding what kind of data and information that needs to be shared and exchanged between the manufacturing system development process and the simulation/flow analysis; establishing who should be involved, i.e. resolving organizational issues; determining when, i.e. at what phases of the process that simulation shoud be employed; and agreeing on how simulation/flow analysis should be made a continous process instead of a set of separate projects. The herein proposed methodology aims to address aspects underlying several of these research issues.

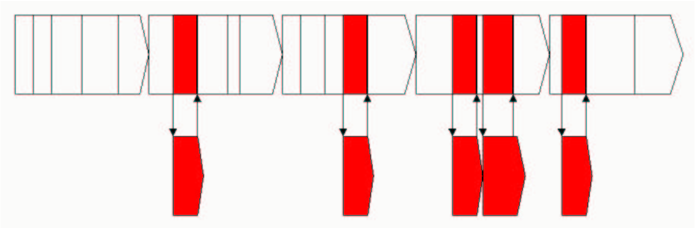


Figure 13.4 *Schematic view of the low level of simulation integration common in today's manufacturing enterprises. Note: upper part of the figure depicts the manufacturing system development process (process) and the lower part depicts the simulation/flow analysis (simulation). Hence, simulation activities are shaded.*

The cause of these problems, and hence the potential to successfully integrate simulation into the development process, can be found in those building blocks of the manufacturing environment that form the prerequisites for simulation integration. Thus, from a simulation perspective, these building blocks have been classified into four domains: data, organization, strategy, and enablers (DOSE).

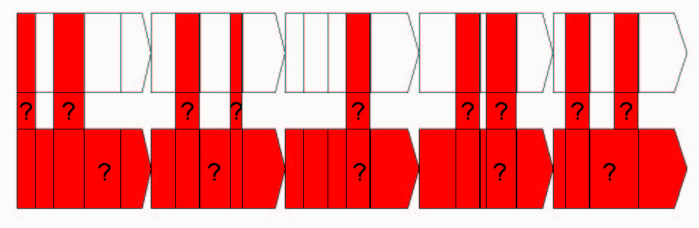


Figure 13.5 *Schematic view of research issues needed to reach simulation integration. Note: upper part of the figure depicts the manufacturing system development process (process) and the lower part depicts the simulation/flow analysis (simulation).*

13.5 Simulation Integration Domains

What attributes of the enterprise will create integration capabilities? Where does demand for integration arise? What conditions will decide a firms advantages and disadvantages regarding simulation use and simulation integration? How do different factors interplay to determine success or failure of simulation integration efforts?

Answering, or helping to answer questions like this has to be a fundamental capability of any integration framework. With this objective in mind, a model has been developed that attempts to . It is based on the diamond model developed by Porter (1990) as a means to explain factors behind the competitive advantage of a nation. Its strength is its simplicity and applicability to any country and any industry type.

Figure 13.6, which is modeled on Sölvell, Zander and Porter (1993, Figure 2.1) illustrates the model.

The remainder of this section will describe the four domains.

13.5.1 Data

The data domain refers to generation, collection, storage, sharing, exchange and availability of data. In other words, it deals with issues on data formats, interoperability, configuration management, communication and application protocols, and the underlying information infrastructure, such as databases. Problems here might be multiple data sources for the same type of data, e.g. cycle times, which may sometimes be found in both Manufacturing Resource Planning (MRPII) and process planning systems, and these two systems may even provide different data, none of which might be useful for simulation purposes (for example, data might be too aggregate for a simulation study). Another widely recognized problem arises when input data is unavailable. This

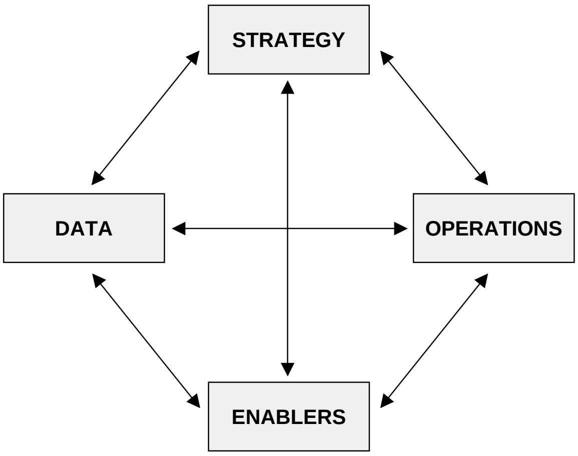


Figure 13.6 *The four integration domains.*

forces simulation engineers or other people involved in simulation studies to manually collect the needed data, make estimations, or even guess. These problems are common, since, in practice, any simulation study will need data from multiple sources.

While much research and development in this area remains, e.g. regarding the use of standards such as STEP and CORBA, and Web-based simulation, several important examples of data-level integration have been shown, such as integration of commercially available DES softwares with information sources (Bernard, 2000), with ABC (von Beck and Nowak, 2000), and with optimization software (Krug, 1997).

In this context, the main contribution of the methodology should be to provide management with a coherent and holistic view on data-related hardware and software issues across the organization, something that could result in synergetic effects with implementations of for instance ERP and activity-based management (ABM) systems.

The data aspect on integration is certainly where the largest amount of work has been done, both among researchers and practitioners. Here, the trend towards integration is clear, and evidenced e.g. by the solutions and software suites offered by vendors such as *Delmia Corporation* and *Tecnomatix* (Randell et al., 2001).

13.5.2 Operations

Within this domain, the basic awareness is that activities related to the development of manufacturing systems compete with each other mainly for the following three reasons:

1. they cross organizational boundaries by involving customers, partners, suppliers and sometimes even competitors,
2. they encompass organizational structures by involving different kinds of business processes, activities, functions and information, and
3. they have to share limited resources of time, money and people.

As a result, manufacturing and production operations demand or reject simulation activities in a number of different ways. To make simulation a successful winner in this competitive race and to "sell it" to the operations that need it, the organizational requirements on simulation integration have to be clearly understood and addressed, and the right decisions made on this basis. In other words, management must decide on how to best organize the (simulation) work, i.e. how to use their organizational resources in the most effective way. At the same time, every-day organizational issues such as making a new technique, working method, etc., accepted and implemented with confidence have to be dealt with. This raises questions such as: Which parts of the organization should simulation encompass? Should simulation integration be extended across the value chain of the product(s) and involve suppliers, partners and customers? And at what organizational levels should personnel be involved in simulation projects?

Here, it is important to assign explicit personal responsibilities based on well-defined and easily understood objectives, such as requiring the reduction of rework time and scrap for a production line by say 30 percent within six months. This triggers an ambitious problem-solving process which in turn can use simulation to validate different solutions to the problem.

13.5.3 Strategy

The previous paragraphs outlined two important aspects on integration. However, an overall strategic focus is also needed. In other words, there has to be a simulation strategy linked to a company's manufacturing strategy, which in turn should be part of the overall business and corporate strategy. This is the third integration domain, and one which is rarely addressed by companies using simulation. Mabrouk (1999), who has proposed a strategy for implementing DES as a decision support tool at the enterprise level, states that, "too often simulation projects are initiated at the wrong time and do not produce the results anticipated [...] the main cause for these problems is a lack of understanding, by executives, of how to best utilize this decision support tool". Some exceptions exist, however, including BT Products and Volvo Car Corporation in Sweden, see e.g. Klingstam and Johansson (2000).

As Wu (1994, p. 23) states, “to achieve competitiveness, a manufacturing company must have a coherent manufacturing strategy which corresponds to its market and matches its corporate strategy”.

Here, simulation is an important technique which can be used to analyze and develop manufacturing systems to support business objectives.

Again, we can turn to IT for a comparison. In a 1998 survey of IT’s contribution to corporate success in some 70 large manufacturing firms in Europe, the U.S., and Asia, it was found that top managers at the best performing companies (“IT stars”) spend about 45 hours per month on IT, compared with 20 hours for the worst performers (“IT laggards”) (Kempis and Ringbeck, 1998). A positive correlation between the number of executives assigned to IT management tasks and the time they spent on these tasks and performance was also found. Here, “the more the better” was found to be true. Furthermore, at IT laggards, business processes were seldomly linked to IT goals, and management’s expectations tended to be vague and unrealistic. By contrast, IT stars had clearly stated IT strategies broken down into concrete and measurable goals and workpackages, and they spent more time on training. The study concludes that, “information management must receive the attention of top management” (Kempis and Ringbeck, 1998, p. 141).

There are several aspects on the need to link simulation to higher-level strategic objectives. One is the way simulation can help evaluate how well certain strategic objectives are met, such as manufacturing lead time, flexibility, quality, delivery reliability, etc. Simulation can thus validate key factors that affect a manufacturing company’s competitive position. Issues here also include intra-enterprise and inter-enterprise integration. Another important argument here is that only by incorporating simulation into an overall manufacturing strategy can the critical mass of resources and managerial support be allocated to simulation and related activities. Consequently, simulation needs to be evaluated not only on financial premises, but also take into account strategic aspects, most of which are qualitative rather than quantitative. Finally, it should be noted that simulation in its role as a decision support and visualization tool may act as driver or enabler in translating the overall corporate strategy into a manufacturing strategy.

To give an example of strategic relevance, the author knows of one large Swedish manufacturer that started using simulation as early as 1993. Today, the company has reached a high level of simulation integration, but its initial commitment to simulation came to an abrupt halt when the simulation specialist left the company without being replaced. Certainly, core-competence personnel do leave organizations, but their function does not. The example suggests that simulation competence was not considered important to the company’s intellectual property at the time. This is a typical example of how a lack of strategic focus can adversely affect the adoption and integration of simulation (and any new technique or technology for that matter). Today, simulation is seen as a strategic resource at the company, and the need for a ‘critical mass’ of simulation competence has been acknowledged.

At the other end is BT Products, which was described previuosly. From the very start, management made a serious commitment to incorporating simulation into their manufacturing strategy, and attributing a certain importance to the technique. While the author argues that this is an unquestionable prerequisite, such an initial commitment must soon translate into relevant and real amounts of resources, competence and support devoted to the simulation project. At BT Products, however, it did. It is important to note here that by first choosing to simulate an existing system, model performance measures could be compared to measures from the real system. This validation proved successful in the first simulation project at BT, and also turned out to be crucial in that it supported a decision to continue with the project. The second project was an explorative study of the existing system to improve it. This resulted in cost-avoidable suggestions for substantial improvements of throughput. This was important since the results further consolidated BT’s belief in simulation as a decision support tool, and thus increased the general acceptance of the technique.

13.5.4 Enablers

Basically, enablers are all the standards (e.g. STEP), methods (e.g. for performance measurement), models (e.g. GERAM), tools, techniques (e.g. optimization), systems (e.g. MRPII, ERP), measures (e.g. the existence of performance measures), and resources such as hardware (e.g. computers), software (simulation or other supportive software), people, and networks that enable or drive the transformation from the real world "building blocks", i.e. data, organizational, and strategic issues to their corresponding desired functional, informational, resource, and organizational (FIRO) issues, which are described in the following section.

The components of these domains need to be transformed to a complex whole that not only meets the requirements and constraints on the system itself, but that is also adaptable to the adoption and integration of simulation into the system development process.

Finally, integration should aim at providing an integrated view on the various “flows” in manufacturing (Hitomi, 1996; Berio and Vernadat, 1999):

- material flow,
- information flow,
- decision/control flow, and
- cost flow.

The methodology, described in the next section, which aims at integrating simulation with the manufacturing system development process, should present benefits within both these areas. As stated by Klingstam (1999), there are basically two fields of knowledge related to simulation: *simulation* knowledge, and *process* knowledge.

From these two perspectives, integration should lead to the following benefits on the process side:

- reduced overlapping of activities,
- shorter lead times,
- better correspondence between planned and real outcome of strategic and operational objetives, and
- better informed decisions;

and on the simulation side:

- strengthened managerial support,
- increased relevance of cost and benefit analysis,
- fewer resources consumed in simulation projects,
- more realistic expectations on simulation, and
- support for continuous use of simulation.

The simulation and process views could be further divided into process, content, problem, and project aspects, where process in this context relates to the manner in which a study is planned, conducted, and completed (Pidd, 1998).

Notes for Chapter 13

[58] This author will not delve any deeper into the world of these acronyms. The interested reader is referred to whatis.com (www) for more information.

14

Methodological Framework

Though this be madness, yet there's method in it.

– William Shakespeare

We have seen that today, DES can be applied to a wide range of manufacturing system development activities. However, DES use is in many respects still modest. Often it is used on a 'one-shot' basis only, troubleshooting specific problems such as bottlenecks, or as a stand-alone tool, both of which reflects a low level of integration. On the other hand, a majority of companies do not use simulation at all (Eriksson, 2001*a*; Heitmann et al., 1997; Hlupic, 2000; Holst and Bolmsjö, 2001*b*; Klingstam, 1999; Umeda and Jones, 1997).

These companies seem to lack clear guidelines for adopting simulation and increasing their level of simulation integration in their manufacturing system development process. At the same time, research on integration aspects often deals with specific functional or data-level issues, such as developing various tools for integrating and connecting simulation to other systems, rather than general structural, hierarchical, and procedural integration aspects as part of a methodological approach. Conversely, research that takes a holistic and systemic view on simulation integration into manufacturing system development is scarce, or researchers only implicitly report on how simulation in practice should be integrated.

As Vernadat (1996, p. 11) states:

> …it must be stressed that integration is a never-ending process. First, because it is a goal. Second, because the enterprise is in a permanent process of change. In consequence, its introduction

> must be carefully planned and documented by a master plan, and once started, procedures for continuous improvements must be put in place.

Two things will be stressed from this statement: (i) the view on integration as a continuous process and (ii) the need for a plan, i.e. a structured approach. This leads us to the question of how the levels of integration can be raised.

14.0.5 Raising the Levels of Integration

The various forms of integration were explored in Chapter 8. It was argued previously that to realize the full potential of simulation, a company needs to raise its level of integration. So the question is, how? Basically, there are three various ways:

1. experience,
2. simple methods and rules of thumb, and
3. structured approaches.

Today, this process is based on experience and simple methods, developed *ad hoc* and usually in very particular context.

To paraphrase Kidd (1994), "what we need is a holistic methodology with supporting tools, which will allow us to deal with all aspects of discrete-event simulation, the interrelationships and the difficult process of planning and managing change". Basically, a methodology[59] is a set of instructions provided through methods, models, tools and guidelines that are to be used in a structured way. The next section will look at its main objectives.

14.1 Objectives

This thesis has aimed to suggest a methodological framework for integrating discrete-event simulation into manufacturing system development. This implies that the level of simulation integration neeeds to be raised, either from scratch or from lower levels. We refer to this as *adoption* and *integration*, and the process of continuously raising the levels of integration as the *integration realization process (IRP)*. The objective of the methodology can therefore be stated simply as:

- To raise the levels of simulation integration over the adoption and the integration realization process.

The methodology is to help companies manage adoption and integration of DES (simulation) into their manufacturing system development process (process). The methodology will thus provide:

- a coherent and holistic view on the scope of simulation integration
- practical guidelines for adoption and integration

14.2 Requirements

A number of requirements on the methodology have been defined based on theoretical findings and industrial experience.

In general terms, this methodology should be:

- **generic** as opposed to particular: it should be applicable across a wide range of manufacturing enterprises,
- **holistic** as opposed to reductionistic: the methodology should consider integration from *all* aspects, just as it should see the manufacturing system from all its perspectives an over its life cycle.
- **structured** as opposed to *ad hoc*, unplanned, and evolutionary courses of action: the methodology should provide stepwise, easy to understand, easy to use, well-documented guidelines that are easily adaptable to a specific organization.

Based on this, a set of more formal requirements can be formulated. The methodology should:

- assess, inform and guide decisions regarding adoption and integration of simulation into manufacturing system development,
- increase the relevance of requirements and trade-off analysis of adoption and integration of simulation,
- establish by quantitative and qualitative means the worth of simulation to the organization,
- provide practical guidelines for adoption and integration of simulation, and
- be well-documented and simple to use.

The methodology does not provide a complete set of tools and models. Rather, it should be applied in connection with existing tools and models.The remainder of this section will briefly outline the six questions describing the focus areas of the methodology.

14.2.1 Questions Answered

The methodology should answer the following questions:

Why? – This is the first question that needs to be answered, and it is highly strategic in its character: Why do we need simulation and what can it do for our company? Promoting such discussion, and indeed providing answers to these questions has to be the basis of any methodology that tells industry to embark upon the potentially costly and complicated task of integrating simulation into an already complex and resource-consuming process. The primary issue is to decide whether simulation should be used at all. As Hicks (1999, p.1215) states, “the most crucial stage of any project that involves problem solving and decision making is the formulation of the problem itself and the selection of which tools and technologies to attack the problem with. When one knows an issue is a "simulation" problem, one can proceed with established methodologies. When one knows it is not, one can select a different approach”. These basic issues need to be carefully resolved before any further action is taken in order to ensure managerial support and committment. However, several problems exist in this area, such as the lack of financial measures of successful integration projects, and the non-monetary and qualitative character of several of the benefits of simulation integration.

What? – This question centers on the basic requirements for adopting simulation and/or proceeding to a higher level of integration. Examples include requirements on competence, training, hardware, software, models, tools, etc. and are strongly connected to the other questions. Much like the question of "Why?", this is fundamental to gaining an enterprise-wide understanding and acceptance of starting or continuing the process of simulation integration. In the industrial case at BT Products, much of the success was attributed to the fact that this question was answered from within the organization over the the course of the initial project. Breaking down this question prior to commencing on the integration process should help focus attention on the right issues.

Who? – A question with several dimensions and levels. As mentioned previously, activities related to the development of manufacturing systems compete with each other for several reasons. This raises questions such as which parts of the organization simulation should encompass? Should we extend simulation integration across the value chain of our products and involve e.g. our main suppliers? At what organizational levels should we involve personnel in the simulation projects?

When? – This question emphasizes the importance of mapping phases of the manufacturing system development process that should be supported by simulation, as well as defining what kind of information and data that needs to be exchanged between these two processes, and when. It is important in this context to realize that simulation should be seen as part of a wider concept, where the authors support the term *flow analysis*, and conversely that simulation on the one hand might not always be the right tool for the job, and on the other hand, might need to be preceded by or work in parallel with other methods, models and tools.

“When?” emphasizes the importance of mapping the different phases of the manufacturing system development process that simulation should support, as well as defining what information and data that needs to be exchanged between these two processes and when. It is important in this context to realize that simulation should be seen as part of a wider concept, where the authors support the term *flow analysis*, and conversely that simulation on the one hand might not always do the trick, and on the other hand, might need to be preceded by or work in parallel with other methods, models and tools. As Hicks states, ‘the most crucial stage of any project that involves problem solving and decision making is the formulation of the problem itself and the selection of which tools and technologies to attack the problem with. When one knows an issue is a "simulation" problem, one can proceed with established methodologies. When one knows it is not, one can select a different approach’ (Hicks, 1999, p.1215).

There is no doubt, however, that integration should enable continuous simulation support in manufacturing system development, not only in the operational phases, as the case often is today, but throughout the system life-cycle. Particular emphasis should be placed on the early phases of system development, where the largest impact on future costs and revenues exists.

This necessitates keeping the models updated, or rather evolving, which can have substantial spin-off effects in that it can support continuous improvements, or kaizen activities. It brings up, however, a certain number of questions such as the delegation of responsibilities for reporting changes and collecting data from the real world, etc.

Where? – This question relates to where (physically) in the virtual or real organization simulation should be applied. Here the aim should be to address issues on modeling different manufacturing concepts, types of production, and manufacturing systems with various size and complexity, etc. Typical examples would be the difference in modeling a push and a pull system (e.g. a kanban production system), and modeling the entire factory vs. some smaller part of it. And should simulation be extended to include logistic flows? It also deals with deciding the appropriate level of detail, ‘one of the most difficult issues when modeling a complex system’ (Law and McComas, 1999, p.57).

How? – This is the structured sum of answers to all the previous questions, sequenced in a chronological order and provided as well-documented practical guidelines. A related concern here is to what extent integration should be achieved through either one of three ways: consultants, partners or in-house competence, or a combination thereof. The authors would argue that this outsource vs. insource approach can greatly affect the long-term outcome of simulation integration. In the project described here, BT Products mainly relied on a partner, and the authors would (subjectively) argue that the outcome of the project would have been another if the company had chosen a different approach.

Finally, the question of how also concerns whether integration should be achieved through either one of three ways; consultants, partners or in-house competence, or a combination thereof. Clearly, this important aspect touches on all three integration domains. Here, the authors would argue that this outsource vs. insource approach can greatly affect the long-term outcome of simulation integration.

14.3 Methodology Phases

The following eight phases have been defined:

1. **Process and simulation knowledge** Understand the process and the requirements and constraints it puts on simulation (Note: "understanding the process" has several implications, including a thorough knowledge of the system, its performance measures, and so on).
2. **Quantification** Determine the performance measures that are relevant to the simulation activities, and assess whether there is a need for simulation. If no, other approaches should be considered. If yes, proceed with the next phase.
3. **Strategy** Formulate a simulation strategy including a desired level of integration based on process and simulation knowledge and higher level strategic objectives, i.e. those emanating from manufacturing, business and corporate strategies.
4. **Identification & Analysis** Identify DOSE constructs that are relevant to the organization.
5. **Mapping** Map previously identified DOSE constructs to reference architecture, taking into account manufacturing system life-cycle specific issues, and assess the perceived level of integration with respect to real world conditions and strategic objectives.
6. **Activity Based Analysis** Analyze costs, benefits and trade-offs taking into account the life cycle analysis of the methodology, and reassess the level of integration.
7. **Definition** Define an action plan for adoption and integration of simulation in the form of well-documented guidelines for all DOSE domains.
8. **Implementation** Execute the plan.

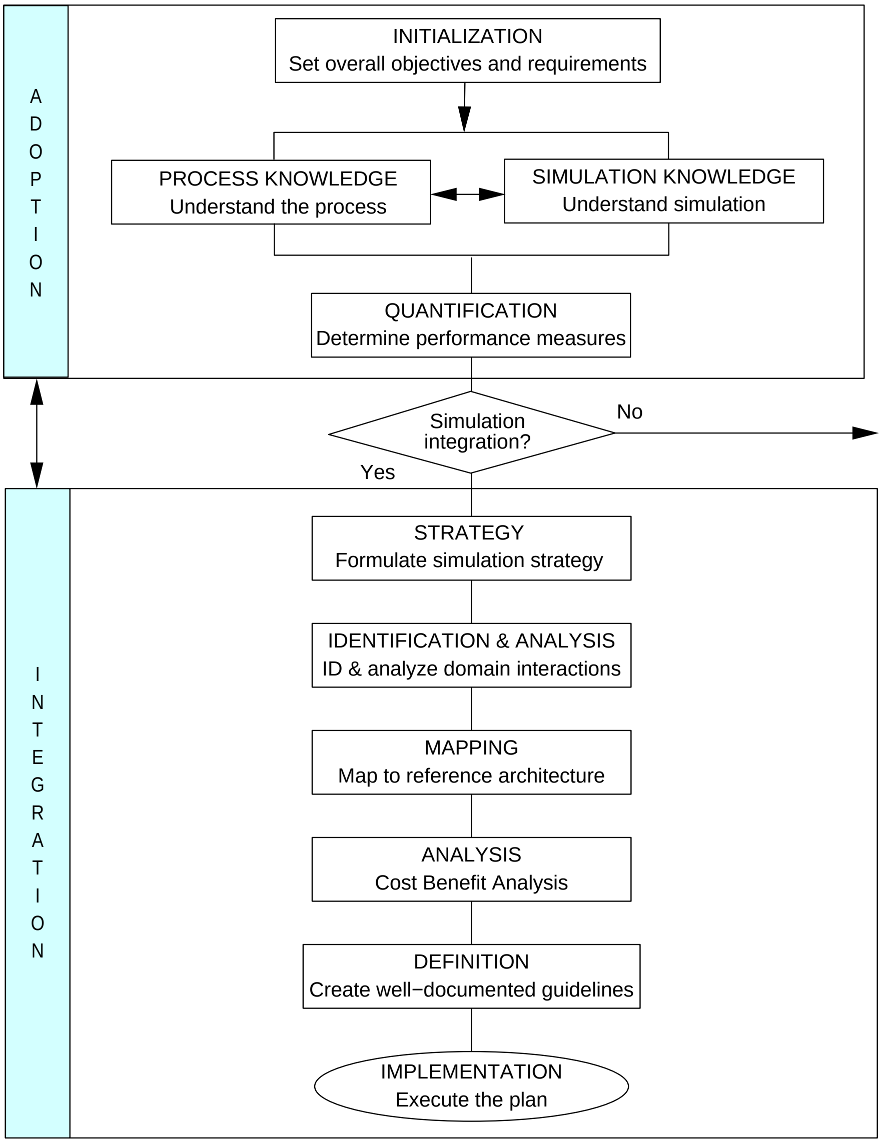


Figure 14.1 *An overview of the methodology phases.*

Validations, i.e. comparisons with the real world prior to the mapping phase have been left out on purpose since this would risk that the real world imposes unnecessary restrictions on the simulation integration process. After the mapping phase, an evaluation and a selection of simulation software (unless it has already been selected) should be carried out in conjunction with the analysis phase. Another separate task is time analysis, explained in Section 14.4. A note on the initial steps: it may be difficult assessing whether the organization has sufficient process and simulation knowledge, especially if there is nothing to measure against. This yardstick is in fact often made more explicit when performing a simulation study. Finally, it is important to see these seven phases as a continous loop to reflect changes in manufacturing strategy, the manufacturing system, etc. This should also provide for a continuously improved process and simulation knowledge. These methodology phases are shown in more detail in Figure 14.2.

14.4 Methodology Components

The main methodology components as shown in Figure 14.2 are the following:

- simulation integration framework (SIF),
- domain interaction model (DOSE),
- reference architecture (GERAM),
- activity-based simulation management (ABSIM), and
- life cycle analysis.

The simulation integration framework (SIF) and DOSE were outlined in the previous chapter. DOSE provides the underlying structure for the methodology as well as a theoretical description of how the different components of the integration process fit together. As argued previously, all issues connected to simulation integration can and should be classified into either one of these four domains. Future research should then aim at further decomposing each domain as well as to define and classify interactions and trade-offs. This section will briefly outline the remaining main methodology components.

14.4.1 Reference Architecture

The purpose of the reference architecture is to allow mapping of the DOSE constructs to a description of the manufacturing system development process.

One of the challenges for future development of the methodology is to detail the design and procedural aspects of this mapping phase.

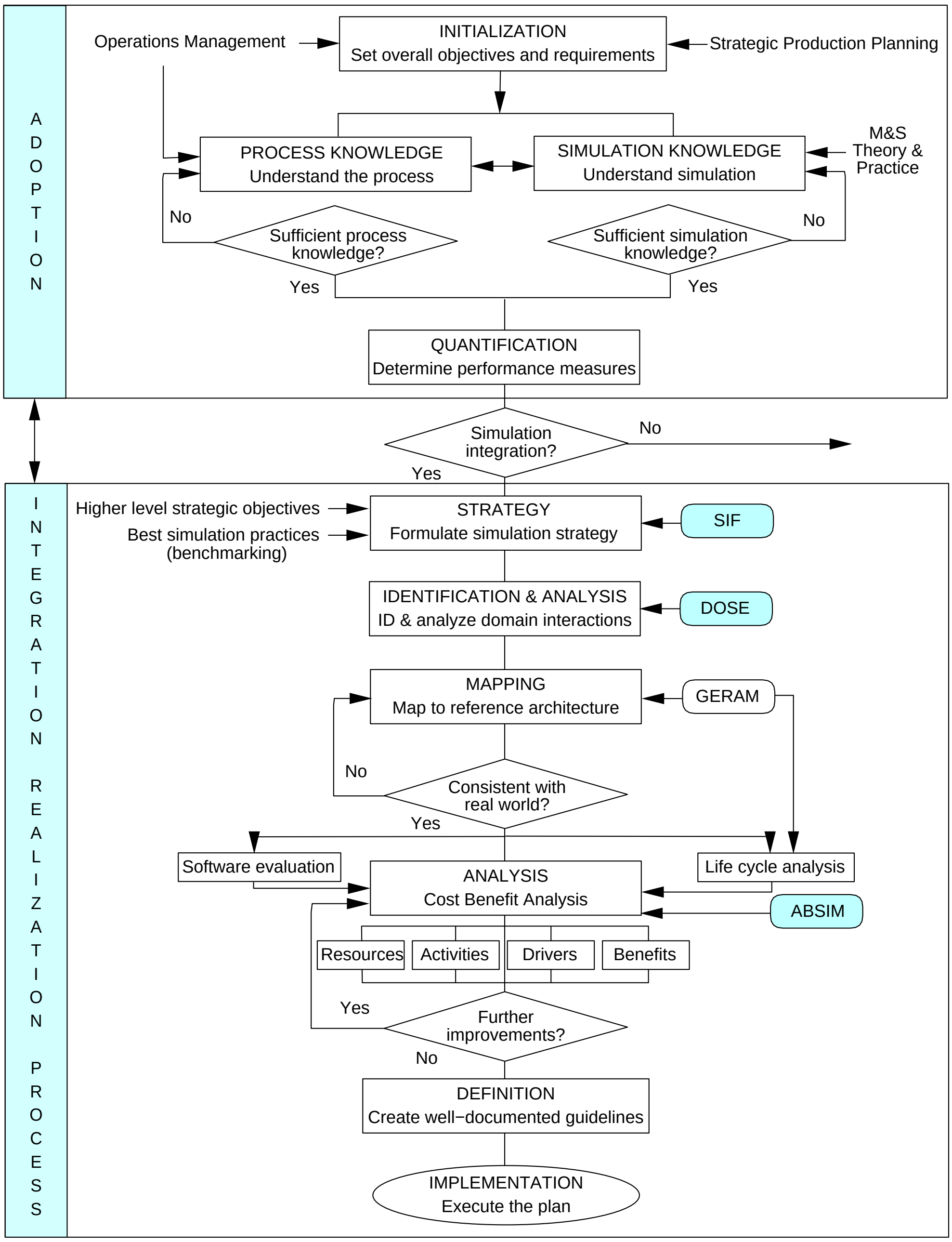


Figure 14.2 *State transition chart showing a detailed overview of the methodology phases and their inputs.*

14.4.2 Activity-Based Simulation Management

In short, activity-based simulation management (ABSIM) can be described as a model to communicate cost and benefits of discrete-event simulation projects. In this sense it fills a theoretical and practical gap. It applies the fundamental principles of ABM to simulation as a process, and is based on the one hand on activities, resources, and their related activity and process drivers, and on the other hand on qualitative and quantitative benefits.

ABSIM is still in the conceptual framework stage, and is further described in Holst and Bolmsjö (2001*a*), see Figure 14.3.

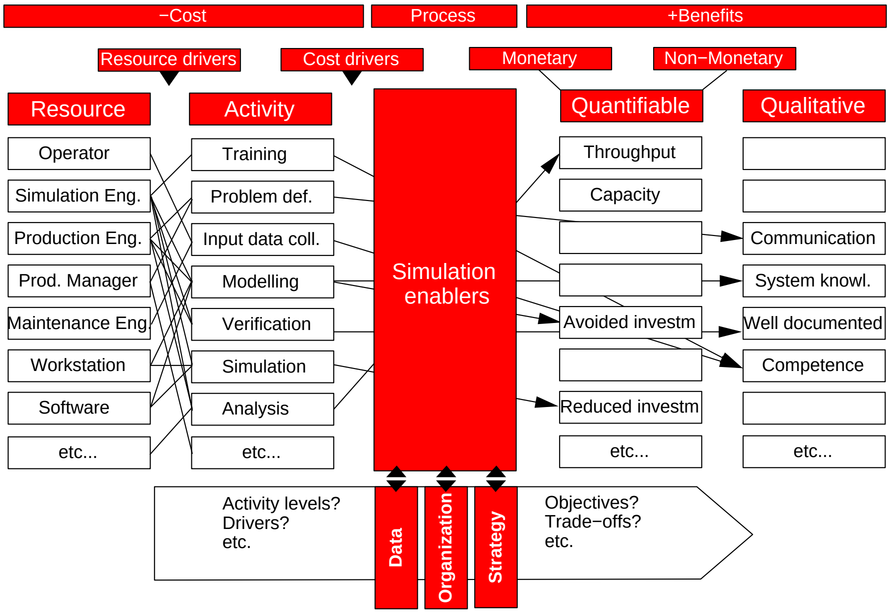


Figure 14.3 *The ABSIM framework (Note: content in white boxes are examples only and should not be seen as fixed components of the framework).*

When looking at reasons for the limited use of simulation, albeit with a less than satisfactory empirical base, a few common factors can be identified.

First, there is still a low level of simulation knowledge and competence in industry, which results in poor committment to simulation projects, or even worse, no simulation at all. Here the authors would argue that many times simulation is, wrongly, neither seen as a tool to reduce costs nor increase income. Part of the problem lies in the fact that successful simulation projects *avoid* rather than save costs. Also, costs are seemingly transferred to earlier stages in the development projects, when managers are traditionally very reluctant to deviate from the initial budget. Instead, problems are allowed to arise in later stages, thereby contributing to the cementation of simulation as a trouble-shooting tool.

More importantly though, simulation, initially, drives several highly *visible* costs. By this is meant that initial phases of simulation integration involve easily quantifiable costs for hardware, software, training and personnel, but few equally quantifiable cost reductions or revenue increases. In addition, those involved in simulation projects with a low level of integration might perceive the added amount of time that has to be spent on input data collection, meetings, etc. as a burden.

In other words, there is a wide gap (compare and illustrate with UEs diagram!) between simulation investment and company ability to achieve the required/expected benefits from this investment. Evaluation or investment appraisal of DES is problematic because of the difficulties inherent in measuring the benefits and cost associated with such investments (Hillam and Edwards, 1999). This results in an overestimation of the costs and an underestimation of the benefits.

The evaluation of these investments thus relies upon the satisfactory assessment of costs and benefits, and this assumes that the costs and benefits are well understood.

Connected to this is the fact that simulation is often bought as a consulting service, which keeps the company from gaining several qualitative benefits of keeping simulation in-house.

14.4.3 Life Cycle Analysis

The life cycle or temporal analysis component of the methodology deals with aspects related to the life cycle of the manufacturing system development *process* and the life cycle of the *simulation* studies performed as part of this, according to the following:

1. **Process** — Which phases of the development process should simulation support? There are different application areas in different system life cycle phases. As an example, several authors argue that particular emphasis should be placed on thr early phases of system development (see e.g. Klingstam and Johansson, 2000).

2. **Simulation** — What is the time needed for different phases and activities of the simulation studies and how does this relate to the process? Realistic expectations provide for the right amount of committed resources and increase the acceptance.

14.5 Summary

The methodological framework presented in this chapter is based on the four integration domains presented in Chapter 13 and the need to map the constructs of these domains to the representation of the real or desired manufacturing system development process, abstracted through the use of the generalized enterprise reference architecture and methodology (GERAM) views of function, information, resource, and organization.

Notes for Chapter 14

[59] Usage note: *Methodology* can properly refer to the theoretical analysis of the methods appropriate to a field of study or to the body of methods and principles particular to a branch of knowledge. In this sense, one may speak of *objections to the methodology of a geographic survey* (that is, objections dealing with the appropriateness of the methods used), or of the *methodology of modern cognitive psychology* (that is, the principles and practices that underlie research in the field). In recent years, however, *methodology* has been increasingly used as a pretentious substitute for *method* in scientific and technical contexts, as in *The oil company has not yet decided on a methodology for restoring the beaches.* People may have taken to this practice by influence of the adjective *methodological* to mean "pertaining to methods". *Methodological* may have acquired this meaning because people had already been using the more ordinary adjective *methodical* to mean "orderly, systematic". But the misuse of *methodology* obscures an important conceptual distinction between the tools of scientific investigation (properly *methods*) and the principles that determine how such tools are deployed and interpreted (The American Heritage, 2000).

Part V

EPILOGUE

A goal is not always meant to be reached,
it often serves simply as something to aim at.

– Bruce Lee

15

Discussion

Not everything that can be counted counts,
and not everything that counts can be counted.
– Albert Einstein

The overall objective of this thesis has been to “suggest a methodological framework for integrating discrete-event simulation into manufacturing system development”. This framework was to be based on knowledge gained by answering the question:

> How can manufacturing companies fully integrate discrete-event simulation into their manufacturing system development process?

After giving an account of the fundamental fields of knowledge behind this research, *manufacturing system development* in Chapter 6 and *discrete-event simulation* in Chapter 7, the last chapter of the frame of reference, Chapter 8: *Integration*, tried to sketch the fragmented picture that is perceived to exist in the area of simulation and integration. In the knowledge creating process preceding and accompanying the writing of this thesis, it was input from all these areas that eventually led to the belief that companies should follow holistic and structured approaches to integration. This was based on the complexity, dynamics, and change characteristics of manufacturing systems, and the large number of applications of discrete-event simulation in the development of these systems. Just as the systems view was claimed to be fundamental when studying and modeling manufacturing systems, so it came to be seen as a prerequisite for any attempt to develop approaches to integration.

Regarding simulation integration, this concept was defined and explored in Chapter 13, and the benefits and problems were outlined in the same chapter.

Based on the case studies reported in Chapters 9–11, and the declaration in Chapter 12 of disciplines that could fill knowledge gaps in simulation adoption and use, Chapter 14 then attempted to meet the ultimate objective of this thesis – a methodological framework. To some extent this objective was based on an axiom, namely that a methodology is needed. This assertion has not been validated. Also, the methodological framework presented in this thesis is far from complete. It is based on the assumption that methodologies for simulation and manufacturing system development exist, which is not strictly true. Although much research is being performed within these areas, practitioners have yet to take these methodologies to their hearts. However, whilst acknowledging current research within the above areas, it was necessary for the development of the herein described methodology to take a manufacturing system development methodology as more or less given. This is not to say that this is actually the case. On the contrary, it is important to further explore existing state-of-the-art methodologies in these areas in order to adapt the herein proposed methodology to the terminology and concepts contained in these. The methodology of primary interest here seems to be Axiomatic Design (AD). A few common issues and connections between this methodology and the proposed integration methodology have already been identified.

The four integration domains presented here form the basis of what has been referred to as an integration framework. However, the research presented here is not meant as a criticism of previous and current research carried out within separate subsets of the four integration domains. Focused research efforts within these domains are highly needed. Rather, it has been argued that there is a need for a unified approach to integration, linking these four domains together through the use of reference architectures such as GERAM. Integration as outlined here is thus intended to draw on existing results rather than reinvent the wheel.

Perhaps one of the primary benefits of this holistic and methodology-based view on simulation integration will be to make management more aware of the problems related to integration, rather than actually telling them how to do it. Nevertheless, the question of how has been addressed to an extent that should provide for some ideas of how to develop an integration methodology further.

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Conclusions

We can be knowledgable with other men's knowledge,
but we cannot be wise with other men's wisdom.

– Michel de Montaigne

This thesis has been based on the assertion that discrete-event simulation, if used correctly, is a powerful technology that can be applied to a large number of manufacturing system development activities. Alone or as part of a wider virtual manufacturing concept, simulation can support correct decisions that lead to the fulfillment of the quality, cost, time, and flexibility objectives. However, the full potential of this technology has not been realized. Problems exist in three areas – manufacturing system development, simulation technology, and integration.

They exist in manufacturing system development because complexity, dynamics, and globalization make performance objectives harder to meet. As a result, the manufacturing system and its development process have difficulties handling customer requirements, environmental constraints, uncertainty and change.

They exist in the area of discrete-event simulation because there is a lack of competence and knowledge of how to use it properly, and because simulation is software that has to fit into an enterprise's existing informational infrastructure.

Finally, they exist in the field of integration because there is a lack of comprehensible and easy to use standards, and although industry trends point to higher levels of integration, problems exist here because the view on different forms of integration is fragmented and confusing.

In summary, these problems are related to *fragmented*, *reductionist* views on and *unstructured* approaches to discrete-event simulation integration.

Reviews of literature, the study of findings from empirical research (although in limited amounts) and own case studies from Swedish and Japanese industry support these views.

The first case study at Segerström & Svensson provided valuable and in-depth insight into the engineering process of a medium-sized Swedish manufacturer acting in a competitive and turbulent environment. The study found a large potential for improving Segerström & Svensson's internal business processes with the help of simulation and structured approaches.

The ultimately successful outcome and experiences from the simulation projects carried out at BT Products showed that there are several benefits to adopting simulation as an integrated part of the manufacturing system development process. In addition, a large potential to improve operations by further integration was perceived as remaining at BT Products. This was an important motivation for proceeding with this research.

Conversely, from this author's perspective there are three solutions to these problems: (i) focused efforts on gaining missing knowledge from other disciplines, (ii) adopting a holistic view on integration, and (iii) following a structured approach to integration. The holistic view is realized through the development of an integration framework. The concept of simulation integration has been introduced and defined in this thesis as a collective name for this framework. The structured approach has been outlined as a methodology.

The structured approach and the underlying view on integration presented here are seen as an important basis for a framework that will result in a more detailed and comprehensive methodology for adopting simulation and raising the levels of simulation integration.

However, while these positive experiences and the results presented indicate a step in the right direction, the proposed framework and methodology need further development and more explicit links to existing enterprise engineering and integration work, including international and European standards. Industrial acceptance of this thinking is the final and greatest challenge.

17

Future Research

> *Leaving something incomplete makes it interesting,*
> *and gives one the feeling that there is room for growth.*
>
> – Kenkō

So, what is there left to do? And where is this research going next? Here, two main questions will be addressed. First, what does this author intend to do next, apart from taking some well-deserved time off? And second, what can others do?

First a few notes on the likely future directions of this research. As this author believes, the methodological approach outlined here has presented a holistic view on the complexity and diversity of issues related to the adoption and integration of simulation into the manufacturing system development process. A structured approach to deal with these issues has been suggested in the form of a methodological framework which fulfills the generic, holistic and structured requirements put on it. However, a need for further research on all these aspects of the framework remains.

First, in the terminology of GERAM, future development of the methodology will need to follow the instantiation dimension, from the generic to the particular, by looking into more detail at the various phases and their tasks. In other words, the methodology phases need to be further decomposed in order to provide for more specific instructions on how to carry them out. However, research will also need to travel in the reverse direction of the instantiation dimension, so as to accomplish the objective of genericity and thereby increase the overall quality of the methodology.

Second, the methodology needs to more specifically position itself in the manufacturing system development life cycle, by addressing simulation and information activities at the task level. These combined efforts should increase the generic and holistic qualities of the framework.

Third, the structured quality of this approach needs to be refined through a combination of theoretical and practical studies. The next step in this context will be for the author to truly learn from the other disciplines outlined in this thesis, starting with the application of diffusion theory. Here, an investigation of DES diffusion in Swedish industry is being planned with other researchers. After feedback from this study and continued research, the methodology will be evaluated in an industrial pilot test.

Finally, the overall quality of the methodological framework also needs to be enhanced by increasing its *standards relevance* and making the links to related standards, particularly GERAM, more explicit (see below).

This concludes the actions that this author plans to take over the short- to medium-term. The following will suggest some future research areas that should be of general interest.

First, more investigation of related standards in this area should be made, such as ENV 40003 (1990), ENV 13550 (1999), ENV 12204 (1995) and GERAM (ISO 15074, 1998), as well as work carried out under ISO/TC 184/SC 5/WG 1 (1990). While not directly applicable, certain components and models of these should be seen as useful in the context of this and related research areas. A challenge here is to transform the rather abstract and incomprehensible structure and terminology of, for instance, GERAM into more practical guidelines for modeling enterprises. Dealing with these standards, however, is in itself an enormously complex task.

Second, and more specifically it has been suggested in this thesis that the choice of insource vs. outsource simulation strategy has different implications on a number of parameters over the short- and long-term. These need to be carefully examined and weighted against each other through focused research efforts.

Finally, and again more generally, the impacts of higher levels of simulation integration on the way manufacturing systems are developed need to be explored. This strongly relates to the interaction between product and process developers, i.e. concurrent engineering aspects, as well as virtual manufacturing technology. Future research should look into these interrelationships and their implications.

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Glossary

Application Protocol (AP) In order to define implementable standard information models for specific industry needs, the STEP standard contains a construct called Application Protocol (AP). The AP defines the context and scope for how to interpret and use the data models defined in the Integrated Resources (Johansson, 2001).

Arena A discrete-event simulation software from Systems Modeling.

Artifact (also Artefact) Etymology: Latin *arte*, by skill, and Latin *factum*, something made: An object produced or shaped by human craft, especially a tool, weapon, or ornament of archaeological or historical interest (The American Heritage, 2000); a man-made object (Princeton University, 1997), something created by humans usually for a practical purpose (Merriam-Webster OnLine, www).

Business Engineering Business Engineering can be defined as the *integral* design of organizational processes and the information systems to support them (Giaglis, 1999).

Business Process The chain of activities that create value for the customers of an organization (Bruzelius and Skärvad, 1995). A sequence (or partially ordered set) of enterprise activities linked by precedence relationships, execution of which is triggered by some event(s) and will result in some observable or quantifiable end result (Vernadat, 1996).

Business Process Re-engineering (BPR) The process of simplifying enterprise processes to reduce excessive delays or costs in the enterprise operations (Vernadat, 1996).

Business Process Simulation BPS software is designed to emulate the dynamics of processes and display them graphically, thus indicating visually problems whithin the system (Eatock et al., 1999). Business Process Simulation (BPS) has proven to be a useful technique for validating a Business Process Re-engineering (BPR) study (Vernadat, 1996).

Computer-Aided Manufacturing System Engineering (CAMSE) The use of computerized tools in the application of scientific and engineering methods to the problem of the design and implementation of manufacturing systems (McLean, 1993).

Computer Aided Production Engineering (CAPE) A concept similar to Computer-Aided Manufacturing System Engineering (CAMSE).

Computer Simulation The discipline of designing a model of an actual or theoretical physical system, executing the model on a digital computer, and analyzing the execution output (Fishwick, 1995).

CORBA (Common Object Request Broker Architecture) Allows applications to communicate with each other no matter where they are located or who has designed them. CORBA 1.1 was introduced in 1991 and defined the Interface Definition Language (IDL) and the Application Program(ming) Interface (API) that enable client/server object interaction within a specific implementation of an Object Request Broker (ORB).

Capacity Requirements Planning (CRP) An examination of the possibilities of assembling products and of machining parts in relation to the capacity of production facilities(Hitomi, 1996, p. 69). Usually performed as part of the material requirements planning (MRP) procedure.

Discrete-Event Simulation (DES) Defined as "the modeling of systems in which the state variable changes only at a discrete set of points in time" (Banks et al., 1996, p.13) .

Discrete-Event System Specification (DEVS) A formal approach (formalism) to discrete-event simulation developed by Zeigler (1976).

Domain A functional area achieving some goals of the enterprise. It is made of a collection of stand-alone core processes (called domain processes) and interact with other domains by the exchange of requests (events) and objects (Vernadat, 1996).

Enterprise A large collection of concurrent business processes executed by a set of functional entities (or resources) that contribute to business objectives (Vernadat, 1996, p.19).

Future Event List (FEL) A list of event notices for future events, ordered by time of occurrence (Banks et al., 2000).

Firm An institution that hires factors of production and that organizes those factors to produce and sell goods and services (Parkin et al., 1997, p. 203).

Gross Domestic Product (GDP) Based on Gross National Product (GNP) but adjusted to remove the value of profits from overseas investments and the ‘leakage’ of profits accruing to foreign investors (Knox and Agnew, 1994, p.426). See Gross National Product (GNP).

GERAM (Generalized Enterprise Reference Architecture and Methodology) Methods, models and tools which are needed to build and maintain the integrated enterprise, be it a part of an enterprise, a single enterprise or a network of enterprises, i.e. virtual or extended enterprises (Vernadat, 1996).

Gross National Product (GNP) A measure of the market value of the production of a given economy in a given period (usually a year). It is based on the market price of finished products and includes the value of subsidies; it does not take into account the costs of replacing fixed capital (Knox and Agnew, 1994, p.426).

Hypothesis Etymology: Greek *hupothesis*, proposal, supposition: (i) A tentative explanation for an observation, phenomenon, or scientific problem that can be tested by further investigation; (ii) Something taken to be true for the purpose of argument or investigation; an assumption (The American Heritage, 2000); (i) A proposal intended to explain certain facts or observations; (ii) A concept that is not yet verified but that if true would explain certain facts or phenomena (Princeton University, 1997).

IDEF (I-CAM DEFinition) IDEF are graphical modeling notations to graphically depict business activities (processes), the data structures of a business, and for describing the behavior of a system. See also I-CAM.

IDEF$_0$ IDEF$_0$ is a method designed to model the decisions, actions, and activities of an organization or system. IDEF$_0$ is useful in establishing the scope of an analysis, especially for a functional analysis. As a communication tool, IDEF$_0$ enhances domain expert involvement and consensus decision-making through simplified graphical devices. As an analysis tool, IDEF$_0$ assists the modeler in identifying what functions are performed, what is needed to perform those functions, what the current system does right, and what the current system does wrong. Thus, IDEF$_0$ models are often created as one of the first tasks of a system development effort (Knowledge Based Systems, Inc., 2001). IDEF$_0$ is based on the Structured Analysis and Design Technique (SADT), of which IDEF can be said to be an extension (Vernadat, 1996).

IDEF$_3$ The IDEF$_3$ Process Description Capture Method provides a mechanism for collecting and documenting processes. IDEF$_3$ captures precedence and causality relations between situations and events in a form natural to domain experts by providing a structured method for expressing knowledge about how a system, process, or organization works (Knowledge Based Systems, Inc., 2001).

Integration Etymology: Latin *integer*, whole or entire: means putting together heterogenous components to form a synergestic whole (Vernadat, 1996, p.23).

Layout Planning (also Plant layout) A plan of, or the act of planning an optimum arrangement of industrial facilities including personnel, operating equipment, storage space, materials-handling equipment, and all other supporting personnel, along with the design of the best structure to contain these facilities (Moore, 1959).

Lead Time The total time a customer must wait to receive a product after placing an order. When a scheduling and production system are running at or below capacity, lead time and throughput time are the same. When demand exceeds the capacity of a system, there is additional waiting time before the start of scheduling and production, and lead time exceeds throughput time (Womack and Jones, 1996, p. 307). See also *throughput time*.

Manufacturing Etymology: Latin *manu factum*, made by hand: A series of interrelated activities and operations involving the design, materials selection, planning, manufacturing production, quality assurance, management and marketing of the products of the manufacturing industries (CIRP (1983) via Hitomi (1996, p. 4)).

Method Etymology: Latin *methodus*, method; Greek *methodos*, pursuit, method: (i) A means or manner of procedure, especially a regular and systematic way of accomplishing something; (ii) The procedures and techniques characteristic of a particular discipline or field of knowledge (The American Heritage, 2000).

Methodological Adjective form of *methodology*.

Methodology A body of practices, procedures, and rules used by those who work in a discipline or engage in an inquiry; a set of working methods; the study or theoretical analysis of such working methods (The American Heritage, 2000).

Manufacturing system A complex whole formed by a group of interacting, interrelated, and interdependent elements with the purpose of executing all the activities and operations needed to put a product on the market.

Model A representation of a system for the purpose of studying the system (Banks et al., 2000, p.13).

Modeling Etymology: Latin *modus*, measure, standard; To make or construct a model of (The American Heritage, 2000); (Fine Arts) The act or art of making a model from which a work of art is to be executed (MICRA, Inc., 1998).

National Bureau of Standards (NBS) See National Institute of Standards and Technology (NIST).

National Institute of Standards and Technology (NIST) An agency of the U.S. Commerce Department's Technology Administration. Formerly named National Bureau of Standards (NBS).

Operations Research and Management Science (OR/MS) Also known as Operational Research (OR), OR/MS looks at an organization's operations and uses mathematical or computer models, or other analytical approaches, to find better ways of doing them (The Operational Research Society, www). Members of the OR/MS profession thus apply scientific tools and methods to improve systems and operations and to assist in managerial decision making. OR/MS is a discipline that integrates and extends the principles and techniques of engineering, mathematics and the physical, information, and social sciences (INFORMS, 2001).

Paradigm Etymology: Late Latin *paradigma*; from Greek *paradeigma*, from *paradeiknunai*, to compare: A set of assumptions, concepts, values, and practices that constitutes a way of viewing reality for the community that shares them, especially in an intellectual discipline (The American Heritage, 2000); The generally accepted perspective of a particular discipline at a given time (Princeton University, 1997).

Processing Time The time a product is actually being worked on in design or production and the time an order is actually being processed. Typically, processing time is a small fraction of throughput time and lead time (Womack and Jones, 1996, p. 309).

Production Etymology: Latin *producere*, lead forward (the English term first appeared in 1483): The making of something new – either tangible (products) or intangible (services that disappear in the very act of their creation). Today, intangible "ideas" are also included under the heading of production. Thus, production is to be considered as an input-output system, converting resources of production into economic goods, thereby creating utilities (Hitomi, 1996, p.3).

PROPER (Programme for Production Engineering Education and Research) A long-term national effort to achieve excellence in areas of strategic importance for Sweden. PROPER has established cooperation between industry, the five Swedish technical universities, and the Swedish Institute of Production Engineering Research (IVF). PROPER receives its main funding from *the Swedish Foundation for Strategic Research (SSF).* Additional funding is provided by Universities, IVF, and Industry.

QUEST (Queuing Event Simulation Tool) A discrete-event simulation software with 3D animation capabilities from Delmia Corporation.

Simulation Assessment Validation Environment (SAVE) A comprehensive simulation concept developed by Lockheed Martin within the Joint Strike Fighter (JSF) program, an R&D program involving the JSF Program Office, the United States Air Force (USAF) Materials and Manufacturing Directorate, and the Lockheed Martin SAVE Team. The objective is to integrate and implement modeling and simulation tools into a virtual manufacturing environment to reduce JSF life cycle cost

Science Etymology: Latin *scientia*, from *sciens*, present participle of *scire*, to know: The observation, identification, description, experimental investigation, and theoretical explanation of phenomena (The American Heritage, 2000); Any domain of knowledge accumulated by systematic study and organized by general principles (Princeton University, 1997); Ascertained truth of facts (MICRA, Inc., 1998).

Supply Chain Management (SCM) Supply Chain Management is the management of material and information flows both in and between facilities in the chain, such as vendors, manufacturing plants, and distribution centers (Umeda and Jones, 1998).

Simulation Etymology: Latin *simulatio*, pretence: The imitation of the operation of a real-world process or system over time. Whether done by hand or on a computer, simulation involves the generation of an artificial history of a system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system (Banks et al., 1996, p.3).

Simulator An apparatus for reproducing the behavior of some situation or system; especially one that is fitted with the controls of an aircraft, motor vehicle, etc., and gives the illusion to an operator of behaving like the real thing (Banks et al., 2000).

STEP (Standard for the Exchange of Product Model Data) ISO10303 STEP is a set of ISO standards which provide for the exchange of engineering product data. These standards can be grouped into infrastructure components and industry specific information models. STEP covers a wide range of application areas and each area has its own part of of the standard application protocols. STEP also provides a method for implementation in file exchange and database access (Johansson and Rosén, 1999).

System A group of interacting, interrelated, or interdependent elements forming a complex whole (The American Heritage, 1996),

Theory Etymology: Late Latin *theoria*, from Greek *theoria*, from *theros*, spectator: (i) A set of statements or principles devised to explain a group of facts or phenomena, especially one that has been repeatedly tested or is widely accepted and can be used to make predictions about natural phenomena; (ii) The branch of a science or art consisting of its explanatory statements, accepted principles, and methods of analysis, as opposed to practice

(The American Heritage, 2000); The philosophical explanation of phenomena, either physical or moral (MICRA, Inc., 1998).

Throughput Time The time required for a product to proceed from concept to launch, order to delivery, or raw materials into the hands of the customer. This includes both processing and queue time (Womack and Jones, 1996, p. 311). See also *processing time* and *lead time*.

Virtual Manufacturing (VM) The use of computer models and simulations of manufacturing processes to aid in the design and manufacturing of products (Lin et al., 1995).

Winter Simulation Conference (WSC) The world's leading simulation conference, held every December in the U.S. (Winter Simulation Conference, www).

Acronyms

ABC	Activity-Based Costing
ABM	Activity-Based Management
ABSIM	Activity-Based Simulation Management
AD	Axiomatic Design
AGV	Automated Guided Vehicle
AMHS	Automated Material Handling System
AMS	Advanced Manufacturing System
AMT	Advanced Manufacturing Technology
ANOVA	Analysis of Variance
ANSI	American National Standards Institute
AP	Application Protocol
API	Application Program(ming) Interface
API	Application Protocol Interface
ASCII	American Standard Code for Information Interchange
ASEAN	Association of South-East Asian Nations
ASP	Application Service Provider
AS/RS	Automated Storage and Retrieval System
BCL	Batch Control Language
BE	Business Engineering
BFD	Business Function Diagram
BOM	Bill of Materials

BP	Business Process
BPR	Business Process Re-engineering
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAM	Computer Aided Manufacturing
CAM-I	Consortium for Advanced Manufacturing International
CAMSE	Computer-Aided Manufacturing System Engineering
CAPE	Computer Aided Production Engineering
CAPP	Computer-Aided Process Planning
CE	Concurrent Engineering
CIM	Computer Integrated Manufacturing
CIMOSA	Computer Integrated Manufacturing–Open Systems Architecture
CIMS	Computer Integrated Manufacturing System
CIS	Central Information System
CM	Configuration Management
CMS	Cellular Manufacturing System
CONSENSUS	Coordinated and Structured Development of Manufacturing Systems
CORBA	Common Object Request Broker Architecture
CRP	Capacity Requirements Planning
CVS	Concurrent Versions System
DBMS	Database Management System
DEDS	Discrete-Event Dynamic Systems
DES	Discrete-Event Simulation
DEVS	Discrete-Event System Specification
DFA	Design for Assembly
DFM	Design for Manufacturing

DFMA	Design for Manufacturing and Assembly
DIS	Distributed Interactive Simulation
DMS	Distributed Manufacturing Simulation
DOE	Design of Experiments
DVE	Distributed Virtual Environment
EDI	Electronic Data Interchange
EE	Extended Enterprise
EEI	Enterprise Engineering and Integration
ERP	Enterprise Resource Planning
EUROSIM	Federation of European Simulation Societies
EWS	Enterprise-Wide Systems
FAS	Flexible Assembly System
FEL	Future Event List
FEM	Finite Element Analysis
FMS	Flexible Manufacturing System
FTM	First To Market
FY	Fiscal Year
GASP	General Activity Simulation Program
GDP	Gross Domestic Product
GERAM	Generalized Enterprise Reference Architecture and Methodology
GIGO	Garbage In, Garbage Out
GNP	Gross National Product
GPSS	General Purpose Simulation System
GUI	Graphical User Interface
HLA	High Level Architecture
I-CAM	Integrated Computer Aided Manufacturing
ICT	Information and Communications Technologies

IDEF	I-CAM DEFinition
IDL	Interface Definition Language
IID	Independent and Identically Distributed
IIS	Internet Information System
IMDE	Integrated Manufacturing Design Environment
IMS	Integrated Manufacturing System
IMTR	Integrated Manufacturing Technology Roadmapping Initiative
INFORMS	Institute for Operations Research and the Management Science
IPPD	Integrated Product and Process Design
IPPED	Integrated Product, Process and Enterprise Design
IS	Information System
ISO	International Organization for Standardization
IT	Information Technology
IVF	Institutet för Verkstadsteknisk Forskning (The Swedish Institute of Production Engineering Research)
LCC	Life Cycle Cost
MBOM	Manufacturing Bill Of Material
MDT	Mean Down Time
MFSS	Manufacturing Subsystem
MPS	Master Production Schedule
MRP	Material Requirements Planning
MRPII	Manufacturing Resource Planning
M&S	Modeling & Simulation
MSD	Manufacturing System Development
MSE	Manufacturing Systems Engineering
MTO	Make to Order
NGM	Next-Generation Manufacturing

NGMF	Next-Generation Modeling Framework
NIE	Newly Industrializing Economy
NIST	National Institute of Standards and Technology
NUTEK	Närings- och teknikutvecklingsverket (Swedish National Board for Industrial and Technical Development)
OEE	Overall Equipment Effectiveness
OLP	Off-Line Programming
OR	Operational Research
ORB	Object Request Broker
OR/MS	Operations Research and Management Science
PADS	Parallel and Distributed Simulation
PDM	Product Data Management
PERA	Purdue Enterprise Reference Architecture
PLC	Programmable Logic Controller
P&S	Planning and Scheduling
PPC	Production Planning and Control
PPR	Product, Process, and Resource
PROPER	Programme for Production Engineering Education and Research
PRP	Product Realization Process
QFD	Quality Function Deployment
QUEST	Queuing Event Simulation Tool
R&D	Research & Development
R&D	research & development
RD	Robust Design
SADT	Structured Analysis and Design Technique
SAVE	Simulation Assessment Validation Environment
SCL	Simulation Control Language

SCM	Supply Chain Management
SIMAN	Simulation Language for Alternative Modeling
SIMSIG	Simulation Special Interest Group
SIS	Simulation of Information Systems
SISO	Simulation Interoperability Standards Organization
SLAM	Simulation Analysis
SME	Small and Medium-Sized Enterprise
SMED	Single Minute Exchange of Die
S/N	Signal-to-Noise
SPL	Simulation Programming Language
SQA	Simulation Quality Assurance
STEP	Standard for the Exchange of Product Model Data
TTC	Time To Customer
TTM	Time To Market
VM	Virtual Manufacturing
VSOP	Visualization, Simulation, Off-line Programming, and Production
V&V	Verification & Validation
VV&A	Verification, Validation & Accreditation
VV&T	Verification, Validation & Testing
WIP	Work-in-Process
WSC	Winter Simulation Conference

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Part VI

APPENDED PAPERS

Paper I

Integrated Development of Manufacturing Systems Using Simulation – Proposing the Fundamentals for a Joint Research Project

Lars Holst, Lars Randell, Gunnar Bolmsjö

In Proceedings of the 33rd CIRP International Seminar on Manufacturing Systems: The Manufacturing System in its Human Context - A Tool to Extend the Global Welfare, 5-7 June, 2000, Stockholm, Sweden.

Integrated Development of Manufacturing Systems Using Simulation – Proposing the Fundamentals for a Joint Research Project

Lars Holst, Lars Randell, Gunnar Bolmsjö

Abstract

This paper outlines a methodology for development of future manufacturing systems, where modeling and simulation are naturally integrated components, supporting all business decisions and stretching beyond their traditional application areas. The research described here has two objectives: (i) to provide a basis for joint research efforts within this area, and (ii) to contribute with integration of simulation into such a methodology. Developing such a methodology will be necessary to deal with an increasingly complex and competitive global business environment, characterized by change and uncertainty. It will be crucial in the realization of enterprise integration, and virtual and extended enterprises. The methodology aims at building on work already done in this area, and to use established standards to as large an extent as possible.

Keywords: Manufacturing system development, Integration, Simulation

1 Introduction

With today's focus on services, information technology and telecommunications, it is important to remember that the heart of an industrialized nation's economy still lies with the manufacturing industry. As we all know, tough customer requirements, shorter product life cycles and an increasingly complex and competitive global business environment, characterized by change and uncertainty put focus on the design and development of manufacturing systems to meet these requirements.

A lot of the necessary decision making and evaluation of different solutions has traditionally relied on the experience and skill of the people involved, as well as that indefinable notion of 'feeling'. Rapid changing, uncertain environments and fierce global competition are not just something researchers routinely write in their papers, or an overly dramatic picture painted by Peter Drucker (Drucker, 1995) and other management gurus. These conditions are facts of life for enterprises all over the world, which in the last decade have seen their competitive advantages diminish substantially. In few areas of business has this been more evident than in the manufacturing industry.

Moreover, activities related to the development of manufacturing systems compete with each other, mainly for three reasons:

1. They cross organizational boundaries by involving customers, partners, suppliers and sometimes competitors.
2. They encompass organizational structures by involving different kinds of business processes, activities and information.
3. They have to share limited resources of time, money, equipment and people.

In this situation, it becomes increasingly difficult to combine a large number of people, processes, activities, systems, technologies, etc. acting in different organizational structures and corporate cultures, so that the right people and the right processes have the right information and the right resources at the right time. This, however, is necessary for successful development of manufacturing systems.

2 Problem

The development described in the introduction is putting pressure on manufacturing enterprises to, on the one hand, reduce time-to-market and deal with shorter product life-cycles and unpredictable changes in volume and product-mix, and on the other hand, meet increased demands on price, quality and delivery times/reliability. This requires the manufacturing system to be agile, or hyper-flexible, and limits the time available for designing and developing new systems or reconfiguring existing.

To assist in this development, new manufacturing philosophies, strategies and concepts are in an ongoing evolutionary development. However helpful for organizations they may be, the vast number of methods, tools and standards resulting from the above measures taken in areas related to manufacturing system development, have faced management and other decision makers with an infinite number of alternative actions and trade-offs, operational as well as strategic. In addition, an enormous amount of information has to be managed and. Furthermore, methods, models and tools need to be fully integrated into the development of manufacturing systems.

The 1990s saw a number of such methodologies being developed, proposed and even used. These ideas have also been conceptualized as a new business paradigm called Integrated Product, Process and Enterprise Design (IPPED) (Wang, 1997). Despite some promising attempts (see for instance Yien (Yien and Tseng, 1997), Wu(Wu, 1994), Bellgran(Bellgran, 1998)) most methodologies are too abstract and difficult to use in practice. Some require highly specialized consulting, others may work under certain conditions only.

Moreover, a great deal of the research being carried out in this area is done by a large number of more or less independently working research groups, often small in size and narrow in scope. This does not adequately reflect the high degree of complexity and large number of interdependencies between different kinds of research fields prevailing within manufacturing system development. There are of course practical reasons for these limitations, but the authors believe that improvements can be made mainly in two ways: (i) by contributing with own research in the field of integrating simulation into manufacturing system development, thus taking advantage of the core competence of their affiliation, and (ii) by using research networks and partnerships, built up within the Program for Production Engineering Research (PROPER) and VSOP for CONSENSUS, as well as other networks, to overcome the above described limitations.

There was also an increase in the use of simulation as a tool to cope with the conditions described in the introduction, where one of the overall objectives was to integrate market, design and production activities by supporting and increasing the efficiency of the exchange of information through the use of advanced simulation tools (Bolmsjö and Gustafsson, 1998). Simulation is very well suited to cope with these conditions because it can act as a decision support tool in the context of manufacturing system development. It can also support, increase (where needed) and improve the efficiency of the information flow between different activities including market, sales and customers, thereby making activities more concurrent and thus shortening the design and development lead time. It can also significantly improve system knowledge throughout the organization. This research aims at integrating simulation into the proposed methodology for the development of manufacturing systems.

3 Objectives

The research described in this paper has the following objectives:

- To participate in developing a methodology for integrated design and development of manufacturing systems by integrating simulation into the methodology.
- To apply simulation-related parts of this methodology in an industrial case study, and use this for validation of the proposed methodology.

The paper in itself has the following objectives:

- To outline a methodology for development of manufacturing systems where the use of advanced simulation techniques is one fundamental part.
- To provide a basis for discussion and joined research efforts on such a methodology.

4 Scope

Developing a methodology that covers all aspects and phases of manufacturing system development, is an enormously comprehensive and complex work. If the result is to be useful and relevant, several different research areas must be integrated, something that requires the participation of a large number of researchers and industrial companies.

Still, the most important purpose of the development of this methodology is that it aims at doing exactly that; connecting all relevant research areas needed for manufacturing system development. This is reflected in the title of the paper, which focuses on the integrated development of manufacturing systems as a whole. Simulation is placed last, thus indicating that it is only one important part of the methodology.

Every researcher involved in the development of the proposed methodology should contribute with their respective specialized research results, thus focusing on core research competencies already established.

Since simulation represents the research area of the authors, the research described in this paper consequently focuses on the use of simulation in the manufacturing industry, particularly on discrete-event simulation applied on models of production systems for development and analysis of manufacturing systems. The proposed methodology aims at using established methodologies, methods, models, standards and architectures to as large an extent as possible.

5 Simulation

5.1 Introduction

The introduction of computers in simulation, and the decreasing cost of computing power, has made possible analysis of more complex problems. The most commonly found applications in the manufacturing industry today include business processes, costs and work in progress levels, material handling systems, automated storage and retrieval systems, assembly operations, ergonomic studies, layout designs, flow of products, off-line programming, motion and collision control, and shifts and labor movement.

Computer simulation has been applied to manufacturing for some 40 years (Savén, 1995). However, for most of that time it has been the domain of a few specialists, distanced from the system and manufacturing engineers. This is still true, although the gap is getting smaller. Also, while the design process has been using computer-aided tools like CAD/CAM for many years and production equipment has been programmed and controlled with computers for a long time, the development and use of computer-aid in production engineering has lagged considerably (Klingstam and Gullander, 1999).

Yet the importance of simulation is increasing as manufacturing systems become more dynamic and complex, as material flow and logistics become more complicated, and as business processes are reorganized to meet with environmental changes.

5.2 Recent developments

Consequently, in the last six or seven years, the use of simulation in the manufacturing industry has increased, particularly in the U.S. where large users are now found within the automotive, aerospace and defense industries. The emergence of low cost computing capabilities and powerful software tools have been major reasons behind this development. Simulation software has also become user-friendlier, requiring less input from the user and featuring easy-to-understand graphical user interfaces (GUI) providing 3D visualization and animation. Trends toward modules for specific applications can also be discerned. Output analysis capabilities have been integrated into many software packages, reducing the specific knowledge required for analyzing statistical data (Eriksson, 1997).

Regarding the use of simulation, international statistics are hard to find. However, in a survey of 64 Swedish industrial companies of various size made in late 1997, 54% of the surveyed companies responded that they were using simulation whereas 31% were using discrete-event simulation (Jackson, 1998). In the same survey the companies were asked what year they started using simulation. The results differed according to type of simulation. Only 12% had used DES before 1985, while 65% said they had used it before 1995. Of the 64 responding companies, 12% had started using DES after 1995. The survey also indicated a correlation between turnover, i.e. company size, and type of simulation used. Whereas both large companies and SMEs used simulation, mainly larger companies used DES.

Another more recent survey on the use of simulation in Swedish industry by Eriksson (Eriksson, 2000), shows that the use of simulation varies greatly depending on the type of simulation. It also indicates that there is generally a low level of theoretical knowledge of simulation, and that it is only to a limited degree integrated as a natural part of manufacturing system development. Many times, simulation is bought as a consulting service. The situation is very much the same in another country like Japan with advanced manufacturing systems, as showed in Umeda and Jones (Umeda and Jones, 1997) and Holst et al. (Holst, Randell and Bolmsjö, 2000b).

Still, modeling and simulation have been identified as a crucial component in major recent work done on future manufacturing in the U.S., Europe and Japan, including the Integrated Manufacturing Technology Roadmapping Initiative (IMTR) (IMTR, 2000), which builds on the results from the well-known Next-Generation Manufacturing (NGM) project, stating that:

> ...modeling and simulation (M&S) will reflect a new way of doing business rather than a supporting technology. It will make virtual production a reality. All production decisions will be made on the basis of modeling and simulation methods, rather than on build-and-test methods. M&S tools will move from being the domain of the technologist, to being a tool for all involved in the product realization, production and business processes.

5.3 Relevant research areas

Simulation constitutes a fundamental part of the proposed methodology. Therefore, it is important to take a holistic view on simulation, and consider all relevant research areas needed for a successful future integration of simulation into manufacturing system development. These research areas include:

- Simulation methodology;
- Simulation support;
- Concurrent development of simulation models;
- Scalability of simulation models;
- Reusability of simulation models;
- Disruption analysis;
- Input data collection;
- Output data analysis;
- Optimization techniques;
- Embedding customer requirements.

Understanding and integrating these into the proposed methodology will be the focus of the authors' research.

6 Manufacturing System Development

Manufacturing system development should be seen in the context of the product realization process. However, the traditional placement of this activity in a sequential product realization process will be avoided. Instead, future research will aim to find new ways of structuring manufacturing system development in the context of other business processes and activities.

6.1 Current state

According to a survey on development, operation, and maintenance of manufacturing systems in Swedish companies by Gullander and Klingstam (Gullander, 1998), all companies use some kind of project management strategy, which give guidelines for how the project should be carried out. However, these guidelines are generally not documented and do therefore not provide information on how tasks should be performed; the working procedure mainly relies on experience from past projects.

6.2 The future

In the near future, manufacturing systems must be seen in the context of virtual and extended enterprises, or in other words: networks and partnerships of enterprises stretching further and deeper than the traditional customer-supplier relationships (an enterprise may consist of one or more organizations sharing a definite mission, goals and objectives to offer an output such as a product or a service (ISO 15704, 1998)). Virtual and extended enterprises are strategies focusing on enterprise partnerships, or temporary organizations, taking advantage of each others strengths and complementary product life-cycle phases in order to rapidly and efficiently satisfy a market need. In practice, these concepts will involve various manufacturing philosophies and technologies, information and communication technologies, and management and organization styles. This will put significantly higher requirements on co-operation and sharing of information between enterprises.

Therefore, a well-documented methodology for developing manufacturing systems will be crucial in ensuring efficient and fast exchange of information as well as smooth cooperation between people connected to this process. Such a methodology will help people belonging to different organizations and cultures to ’speak the same language’, and will provide a common platform for discussion and visualization of thoughts and ideas.

6.3 Problem areas

Simulation can be seen in the context of Computer-Aided Manufacturing System Engineering (CAMSE), which is defined by McLean as (McLean, 1993): 'the use of computerized tools in the application of scientific and engineering methods to the problem of the design and implementation of manufacturing systems'. The goal of this engineering process is to find a good solution to a problem given a set of requirements and constraints. However, the requirements on tools needed for CAMSE are extremely complex since they should make available information which is used in a number of disciplines, e.g. (based on McLean (McLean, 1993) and Randell (Randell, 2000)):

- manufacturing engineering;
- plant engineering;
- materials processing;
- environmental engineering;
- modeling and simulation;
- quality engineering and control;
- statistical process control;
- economic and cost analysis;
- computer science;
- management science.

Most of this information is currently spread in different sources and different mediums, ranging from books and binders to different kinds of databases. Most of these sources of information are badly organized, highly specialized, or store the information in inconsistent data formats. Consequently, they are not able to share information or work together. Thus, organizations have difficulties coping with these problems within their own limits. Yet, the requirements on integration will only be driven to higher levels by the emergence of extended and virtual enterprises. Enterprise integration is therefore of high relevance to the development of the proposed methodology.

Moreover, simulation in this context has mainly been applied as a stand-alone tool when certain aspects of an existing manufacturing system have been studied, e.g. bottlenecks or other logistics issues in the case of discrete-event simulation (Klingstam, 1999). This can be described as a rather traditional use of simulation.

The cases where simulation has been used as a planned and organizationally well supported tool, integrated with other activities in the product realization process, are rare.

Yet simulation models provide analysis, description and evaluation capabilities and a common understanding of system functionality; functions which are needed for decision making. In addition, simulation supports collaborative work across organization boundaries.

The above mentioned research results, as well as the authors' own experience, show a need for a well documented methodology, which is easy to use and understood and supported by all people involved. Furthermore, the authors believe that simulation should be made an integrated and crucial part of this methodology.

7 Outlining the Methodology

A methodology is basically a set of instructions provided through methods, models, tools and standards that are to be used in a structured way (Vernadat, 1996).

The proposed methodology should cover all phases of system development, i.e. from a real or estimated customer need to a running system (note: this does not imply all phases of the system's life cycle).

In concordance with the requirements in ISO 15704 (ISO 15704, 1998), it should enable manufacturing system developers to determine and follow a course of action that is complete, accurate, flexible with respect to unpredictable environmental changes, and carried out with a minimum of resources.

It is an integrated methodology from two aspects:

1. Interorganizational – Integration of value adding activities across the entire value chain of the product, stretching through traditional organizational boundaries and involving suppliers, partners and customers, sometimes even competitors.
2. Intraorganizational – Integration of value adding activities across business processes within the boundaries of the traditional organization, involving different departments and functions.

Ten requirements on the methodology have been specified. The methodology in turn is based on five pillars. The ten requirements should be seen as guiding principles that are to be adhered to when developing the methodology (see section 7.2). The five pillars, on the other hand, apply to the finished methodology, and should be seen as essential parts of this (see section 7.3).

7.1 Basis of the methodology

The methodology aims at using already developed or proposed methodologies, as well as using established standards, models, architectures, protocols, etc, to as large an extent as possible, and where applicable. First of all, the proposed methodology should comply with the International Standard ISO 15704 (ISO 15704, 1998) as well as other relevant standards, which will be defined in later stages of the work.

An enterprise-reference architecture (type 2 architecture) deals with the structural arrangement (organization) of the development and implementation of a project or program (ISO 15704, 1998), such as the product realization process. The main basis of the herein described methodology is the work done by Klingstam (Klingstam, 1999), which in turn is based on the Generalized Enterprise-Reference Architecture and Methodology (GERAM) (ISO/TC 184/SC 5/WG 1, 1998). The eight life-cycle phases defined in the GERA component of GERAM are decomposed into eight Main Project Features (MPFs), which provide a more detailed description on how to carry out various tasks. More specifically, the MPFs provide guidelines for using the different methodology components; methods, models, tools and architectures.

A system architecture (type 1 architecture) deals with the structural arrangement (design) of a system (ISO 15704, 1998). Regarding the actual development of manufacturing systems, this methodology is based on the thoughts of the Extended Enterprise Open System Architecture (EE-OSA) (Zhang and Browne, 1999), which in turn is based on the well-known Computer Integrated Manufacturing Open System Architecture (CIM-OSA) (ENV 40003, 1990) (GERAM is partly based on CIM-OSA). In addition to this, other work in this area will be studied. This includes the Next-Generation Manufacturing (NGM) project and the Integrated Manufacturing Technology Roadmapping Initiative (IMTR) mentioned previously, as well as the European prestandard ENV 13550 (ENV 13550, 1999).

7.2 Methodology requirements

The methodology should be:

1. Integrated – there are several aspects on integration. A general way of describing it is that all methods, models, tools, processes, activities, systems and equipment connected to the development process should be natural parts of the methodology, and be linked via an information infrastructure that delivers the right information to the right place at the right time, every time.

2. Simple – easy to understand and use.

3. Specific – all necessary instructions should be clearly specified, including activities, people, decisions, documents, etc. and how and when models and tools should be used.
4. Connected – the models used should be connected to the real world systems, allowing e.g. easy update of the simulation model of a manufacturing system when changes occur in the physical system.
5. Customizable – useful for different types of manufacturing industries.
6. Reusable – easily transferable from one project to another.
7. Compatible – regarding data formats, software, tools, etc, the primary concern should be to maintain consistency and interoperability. The use of ISO standards, such as STEP (Johansson and Rosén, 1999) should be investigated.
8. Scalable – easily adaptable to different project and organization sizes by allowing multiple levels of abstraction.
9. Agile – in addition to being flexible, the methodology must be able to handle unpredictable events, i.e. adapting to an undefined range of requirements.
10. Life-cycle supportive – the methodology should support the overall phases of a manufacturing system life-cycle: from requirement specification to design, implementation, operation and maintenance.

There are of course several facets to each of these requirements, each requiring thorough specification of what is actually meant and covered by each requirement. For example, should customization apply to all kinds of manufacturing, or should it be limited in scope? These questions need to be answered in concordance with other researchers, and will not be further specified at this point. The final requirements on the methodology will thus be decided in later stages of the project.

7.3 The five pillars

The methodology rests on five pillars, which are to be seen as fundamental building blocks constituting the basis for all activities carried out during all phases of manufacturing system development. These are closely related to each other and need to be compatible with each other:

1. Documentation – the methodology should be documented, and the documentation should be easily available at any time.

2. Structural approach – system elements, activities, processes, etc. all have multiple interdependencies with each other, which need to be represented, e.g. with graphics. Process mapping is one structural approach, where even a simple visualization of the work helps in understanding and analyzing processes.

3. Standardized information models – interoperability aspects such as data format, collection and storage are crucial aspects to consider if information is to be shared efficiently. Ideally, data should be open and independent from the computer applications, allowing applications to create and access data independently (Johansson and Rosén, 1999).

4. Configuration management – data need to be managed in an efficient way. Configuration management is originally a discipline for controlling the evolution of software systems (Babich, 1986), which is due to the fact that software developers faced the size, complexity, and concurrent development problems on an early stage. Configuration management can, however, be used more generally to control and manage any set of documents (usually data files) for some specific purpose, e.g. CAD/CAM. Product Data Management (PDM) is a tool that helps manage both product data and the product development process. PDM systems keep track of data and information required to design and manufacture, as well as support and maintain products.

5. Human factors – the major part of the methodology is a structured approach that should define not only the steps or phases to be followed in the development of manufacturing systems, but also a way of involving the people working with or otherwise connected to this process as much as possible, and gaining their acceptance of the use of the methodology. By doing this, the acceptance of the system will be improved. Another success factor should be to involve the system users in the development process in order to ensure the best possible placement of these in the system. As Ilar (Ilar and Kinnander, 1999) among others has showed, human factors can even be integrated into the technical processes, e.g. by modeling the learning factor, or increase in skill of operators working with a certain process over time. As Ilar states, ’the absolute productivity...is determined by the synergetic interaction of main (technical) and supporting (human/organizational) processes’.

7.4 Levels and views

The modular reference framework of CIM-OSA, also known as the CIM-OSA cube, and used in EE-OSA as well, has three dimensions: architecture levels, modeling levels and views.

Architecture levels refer to the building blocks of the extended enterprise models, and have three levels: generic, partial and specific. *Modeling* levels refer to the steps in the modeling process, and can be seen as design principles. *Views* refer to the possibility of representing different views of the models of the manufacturing system, i.e. analyzing it from different perspectives. According to ISO 15704, at least four views should be included: function, information, resource and organization.

The proposed methodology should support these different levels and views. They will, however, not be further specified at this point.

7.5 Future work

Regarding the continued development of the methodology, the following steps will be taken next:

1. Mapping of relevant research.
2. Discussions with potential partners.
3. Establishment of a partnership for the development of the proposed methodology.
4. Establishment of a common glossary, definitions and references.
5. Setting of common objectives.
6. Development of the methodology.

The last step will be further decomposed after the objectives have been set.

7.6 Industrial case

The research project described in this paper is done in cooperation with two companies in the Swedish manufacturing industry. The part of the methodology dealing with production flow simulation is to be tested and validated at one of these companies; BT Products AB in Sweden, a world leading manufacturer of electrical warehouse trucks.

8 Conclusions

This paper proposes a twofold integrated methodology for development of manufacturing systems, where one important aspect is the integration of simulation into the development process. In addition to the research on simulation, the usefulness and success of the methodology will depend upon joint research efforts in several related fields. The results of such a joined research effort should constitute an important basis for further use and research of the proposed methodology for integrated development of manufacturing systems. They should also increase the awareness among scientists in related fields and decision-makers in manufacturing enterprises of the importance and usefulness of simulation as an integrated part of manufacturing system development.

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Paper II

Simulation integration in manufacturing system development: a study of Japanese industry

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Simulation integration in manufacturing system development: a study of Japanese industry

Lars Holst and Gunnar Bolmsjö

Abstract

This article focuses on the integrated use of simulation tools, particularly discrete-event simulation, in the design and development of manufacturing systems in Japanese industry. The results are based on questionnaires and visits to seven large Japanese manufacturers and show that most of the visited companies don't use simulation to any large extent, particularly not discrete-event simulation. Some of the reasons for this are general, while others are specific for Japan. However, the use of simulation is believed to increase in Japanese industry. Furthermore, this paper argues that there is a large potential for increased use of advanced simulation techniques in Japanese manufacturing companies, mainly for two reasons; (i) as a means to integrating activities related to the design and development across the entire value chain of a product, i.e. from supplier to customer, and thus support and increase the efficiency of the information flow between these processes, and (ii) as a means to integrating activities within the enterprise, i.e. between market, product and process activities, and thus act as a control and decision support tool. This would result in improved communication, reduced time-to-market and higher flexibility in volume and product-mix.

Keywords: Japanese industry, Manufacturing system development, Discrete event simulation, Integration.

1 Introduction

With today's tendencies to look on services and information technology as stand alone sectors, it is important to remember that the heart of an industrialized nation's economy still lies with the manufacturing industry. This is true for Japan as well, where manufacturing accounts for 27% of real GDP and more than 70% of exports (Kawai, 1998). In Japan, the manufacturing industry as a whole has been recovering during the much talked about sluggish domestic business conditions since the burst of the bubble economy in 1990. For example, since its trough in 1993, the industrial production index increased steadily until 1998, when it slumped as a result of a renewed recession caused by the financial crisis that hit Asia in 1997, only to regain momentum in the following year. The same applies to labor productivity in manufacturing (Kawai, 1998; Japan Information Network, 2000b; The Japan Institute of Labour, 2000). In many ways, Japan's manufacturing industry remains strong and competitive, although, as we will see, things are changing. Several factors have contributed to this strength. Among these is the fact that 'the Japanese approach to industrial organization and national economic policy is distinctly different, based upon a particular mixture of state-oriented values and political collectivism...it proves more effective at accumulating capital' (Knox and Agnew, 1994, p. 117). Japan thus enjoys a stable political/administrative framework, where as Fingleton (1997) argues, the Ministry of Finance's informal powers play a key role, and *keiretsu* networks still dominate the industrial structure (Holst and Pozgaj, 1997). This has allowed cartelisation and resulted in relatively high profit margins on several products. Combined with a large and protected domestic market and low interest rates and dividends, this has generated huge profits that have been reinvested in R&D. It has also kept outsiders out and made possible risk-spreading and long-term focus, as well as other advantages for large companies (Holst and Pozgaj, 1997; Gerlach, 1997; Sazanami, Urata, Kawai and Hufbauer, 1995; Anchordoguy, 1990; Johnson, 1990).

However, despite these favorable conditions, the manufacturing industry has been forced to restructure in recent years, including closing down plants and shifting production overseas. Japanese transplants' operations are increasingly competing with those of their domestic factories, and reducing the latters' reliance on exports to maintain high production volumes. Domestic and Asian demand has been weak as a result of the Asian financial crises of the late 1990s. Moreover, deregulation and globalization of the Japanese economy, among other things, threaten to reduce Japanese industry's access to capital, increase the competition and reduce the amount of domestic sales profits that can be reinvested in R&D, all important factors in explaining the 'Japanese Miracle' (Carlile and Tilton, 1998; Fingleton, 1997; Hane, 1996). Also, as a result, the Japanese market is slowly opening up to foreign companies.

Thus, crucial mechanisms such as ever expanding market shares and favorable domestic business conditions are no longer working, while competitive pressure and increasingly tougher customer demands remain. Companies have started laying off workers on a scale previously unthinkable of within the Japanese lifetime employment system (although that system was never based on formal contracts). Combined with small and medium-sized enterprises' bankruptcies (most of which are in the construction, retail and wholesale industries), this has led to record high post-war unemployment rates.

In addition, suppliers as well as their parent companies increasingly cooperate with companies outside their traditional keiretsu network. More importantly, the keiretsu networks are loosening up, see e.g. Steffensen (1998), and confirmed also by this study where companies rate their keiretsu ties as looser than before. The suppliers add more value too. In this study, when asked about changes during the last five years, it was particularly evident in many companies that the amount of work done by suppliers had increased, even when the total number of suppliers had remained virtually the same.

On top of all this, Japanese society as a whole is undergoing several changes. Among the most talked about is the ageing population. Estimates put Japan at the top of the league of countries with people over 65 somewhere between the year 2020 and 2025 (Japan Information Network, 2000a; The Japan Institute of Labour, 1996). By then, more than 25% of the population will belong to this age group, which among other things will result in a future shortage of labor for industry, rather than unemployment. This will make matters worse than they already are, particularly at SMEs where younger workers already avoid so-called *3K* jobs; *kitanai, kitsui, kiken* – dirty, hard, dangerous (Holst and Pozgaj, 1997). At the same time, values in the Japanese society are reported to be changing; more people change jobs because they want to, they demand that the seniority system omnipresent in several areas of Japanese society changes in favor of one based on skill and performance, and they increasingly value family and free time as more important than work.

Notwithstanding the undisputed success of Japanese manufacturing practices, there has been considerable debate in recent years concerning the future of Japanese manufacturing, focusing on issues such as changing demand patterns, production costs, robustness, flexibility, over-capacity, information and communications technologies, global networks, extended enterprises and virtual manufacturing.

Finally, and as mentioned previously, the dual structure of Japanese industry in which small businesses have absorbed many of the negative costs of large enterprises is changing. With more independent suppliers and looser bonds within keiretsu networks, the reliance on SMEs as safe targets for shifting cost-cuts and unwanted employees, particularly high-cost managers, will be a thing of the past.

Thus, several structural changes now underway are increasingly reducing manufacturing firms' ability to rely on anyone but themselves to succeed. These large corporations will have to critically review their own organization and strategy more than ever. This will undoubtedly call for several 'simple' cost-cutting measures, such as reducing overhead personnel, but more importantly it will put further focus on the manufacturing strategy itself as a means to competitive advantage.

This study was done with the basic awareness in mind that simulation of manufacturing systems as well as integration of simulation with other systems, softwares and activities will be a key component in future manufacturing strategies for companies all over the world. To what degree this awareness was evident at the companies during the visits will be described in this article, and the results and findings of this study should be seen in the context of a situation in which Japan, perhaps more than the rest of the world, is experiencing profound structural transformation.

2 Background

For manufacturing enterprises, the design of the manufacturing system is a key strategic activity mainly for two reasons; first, the manufacturing system still adds most of a product's value, and is critical to the quality of products and services; secondly, a manufacturing system is capital intensive and its development and operations connected to other activities to such an extent that its design is the key to efficient and effective coordination of resources, releasing or tying up money, time and people from other business processes depending on the degree of success of its design. Improvements in manufacturing performance thereby 'enhance overall business performance by supporting innovative, strategical and competitive competencies and capabilities' (Small, 1999, p. 267).

However, due to its complexity and dynamics, the development of manufacturing systems requires a great deal of information to be dealt with, efficiently, accurately and fast, by a great number of people. At the same time, environmental developments force manufacturing enterprises to reduce time-to-market and deal with shorter product life-cycles and unpredictable changes in volume and product-mix. They also face increased demands on price, quality and delivery times. This requires agile, or hyper-flexible manufacturing systems, and limits the time available for designing and developing new systems or reconfiguring existing systems (note: design, development, redesign, reconfiguration, etc. of manufacturing systems will henceforth be collectively referred to as development of manufacturing systems).

Moreover, activities related to the development of manufacturing systems compete with each other, mainly for three reasons: (i) they cross organizational boundaries by involving customers, partners, suppliers and sometimes competitors, (ii) they encompass organizational structures by involving different kinds of business processes, activities and information, and (iii) they have to share limited resources of time, money, equipment and people. For instance, as Japanese companies' suppliers become more independent, cooperation and information sharing becomes harder to manage.

In this situation, it becomes increasingly difficult to combine a large number of people, processes, activities, systems, technologies, etc. acting in different organizational structures and corporate cultures, so that the right people and the right processes have the right information and the right resources at the right time. This, however, is necessary for successful development of manufacturing systems.

The manufacturing industry is trying to deal with this in various ways; through the use of more advanced manufacturing technologies, information technology and new management and manufacturing philosophies, strategies and concepts, including concurrent engineering, enterprise integration, modularization and outsourcing of activities, virtual and extended enterprises, virtual manufacturing or other strategic and tactical measures.

The 1990s saw an increase of the use of simulation as a tool to cope with these conditions. The authors believe it was for a good reason: as will be further explained later on in this article, simulation is a technique well suited to deal with high degrees of complexity and dynamics, and an almost infinite number of alternative decisions.

In addition to what can be termed as traditional use of simulation, one of the overall objectives was to integrate market, design and production activities by supporting and increasing the efficiency of the exchange and sharing of information through the use of advanced simulation tools (Bolmsjö and Gustafsson, 1998).

Moreover, the authors strongly support the view that simulation is a technique that should be made integral to future manufacturing system development. However, it is also recognized that many problems still remain. Studies show that the use of simulation, much like industrial information technology and computer integration in general, is neither widespread nor always successfully implemented and used in industry (Beach, Muhlemann, Price, Paterson and Sharp, 2000; Eriksson, 2000; Jackson, 1998; Savén, 1995; Upton, 1995; Standish Group, 2000).

Furthermore, a vast array of Japanese industrial practices have been widely reported and diffused throughout the Western industrialized world since the early 1980s. However, there is considerable debate to the degree of success of these, see e.g. Kerrin (1998) and The Economist (June 20, 1998). Clearly, all aspects of these practices have not always been considered by non-Japanese managers in Western firms.

Moreover, this diffusion is no longer stemming *from* Japan only. There is considerable evidence indicating that Japanese industry is facing the same challenges as the rest of the international business community, and therefore will have to adopt, and indeed increasingly is adopting non-Japanese practices and concepts such as agile manufacturing, down-sizing and re-engineering. Japanese managers are also looking into new technologies to process information and improve communications and means of linking factories together into worldwide networks (Far Eastern Economic Review, July 27, 2000; Steffensen, 1998; Debroux, 1997; Katayama and Bennett, 1996; The Economist, June 24, 1995). These developments are mainly attributable to international competition dynamics driven by the globalization of the world economy and the rapid progress in information and communication technologies (ICTs).

Given the above, the purpose of this article is to assess the level of, as well as shed light on a scarcely reported practice: the use of simulation within the context of manufacturing system development in Japanese industry. Until now, there has really been only one study focusing on these issues (Umeda and Jones, 1997).

3 Objectives, scope and methodology

The objective of this article is to describe the use of simulation, particularly discrete-event simulation (DES), in the development of manufacturing systems in Japanese industry.

The article focuses on DES applied to models of production systems for development and analysis of manufacturing systems, and particularly looks into integration issues.

The results are based upon visits to seven large Japanese manufacturing companies in Japan, made during May and June 1999. The visits featured factory tours and interviews with various people, usually from the production engineering department. A questionnaire was sent out to the companies prior to the visit, featuring questions in both English and Japanese. The purpose of the questionnaire was to better prepare both parties for the interviews, and make the time spent at the companies more efficient. The questions were a mix of open end questions and questions where alternative answers were measured using five point Likert-like scales. Preliminary drafts of the questionnaire were discussed with Japanese researchers to assess its content validity and for translation. A pilot test with a Japanese firm was then conducted to improve the comprehensiveness, clarity and relevance of the questionnaire. A total of 20 questionnaires were sent out to companies chosen ad hoc from a Japanese University Professor's personal network, and visits were then made to 12 of these companies. Of these 12 companies, three did not return the questionnaires whereas two visits were judged as non-successful in terms of the amount and quality of the information received. Thus, five of the visited companies were excluded from the study, which left a final sample of seven companies. The response frequency has not made it meaningful to perform a statistical analysis of the data obtained, nor allowed comparison of the answers. Instead, the results from the questionnaires have been used as a basis for discussion. Consequently, no external data validation has been performed, although the findings have been compared to the work of Umeda and Jones (1997) where possible. This and earlier work by the same authors are the only similar empirical studies available.

4 Simulation

4.1 Introduction

Simulation is an important problem-solving methodology for the solution of many real-world problems in the manufacturing industry. Three typical application areas can be identified: (i) explorative studies of existing systems to improve them, (ii) studies of existing systems with some changes made to them, similar to the first purpose but used to validate a specific alternative, e.g. a proposed investment, and (iii) design and validation of new systems. In practice, simulation projects are often a combination of these three applications. Simulation provides analysis, description and evaluation capabilities of systems, and if successfully applied can support collaborative work across organizational boundaries and thereby improve information and communication. In addition, simulation can be used for training and education purposes. By these means, simulation can significantly improve system knowledge, shorten development lead time and support decision making throughout an organization. Also, understanding systems behavior and the parameters that affect performance is vital in design, development and operations of manufacturing systems. In fact, discrete event simulation is fundamental to the assessment of a new manufacturing system design or operations management policy since many of the measures used are dynamic in nature, i.e. influenced by time dependent behavior. The authors have also found that simulation increases the awareness of performance measurements and emphasizes the importance of those measures to the people involved in the simulation projects. Simulation can also be extended to an important component in organizational learning, one central focus area in management theory of the 1990s. As Senge and Fulmer (1993, p.21) states, 'although mental models are rich in detail, they are deficient in critical ways. They focus deeply on particular parts of a business and are superficial regarding other…parts. They are predominantly static and do not clearly distinguish assumptions about structure, behavior, and expected outcomes of policy changes. Mental models are largely tacit, expressing themselves as intuitions…that are difficult to communicate and share' They conclude that 'through computer-simulation models…micro worlds could transform how organizations learn' (Senge and Fulmer, 1993, p.25) (N.B. Micro world is a term used in the article to describe an interactive computerized environment that simulates a real-world situation). The reader is referred to Banks (1999), Law and McComas (1999), Pidd (1998), Banks, Carson and Nelson (1996), and Law and Kelton (1991) for literature on simulation, particularly DES applied to manufacturing systems.

4.2 Practitioners vs researchers

The practical use of discrete-event simulation (DES) within the context of manufacturing system design and development has been slow to catch up with the state-of-the-art level of research carried out. This has been shown in work done in several highly industrialized countries, including Sweden, Germany, Great Britain and Japan (Eriksson, 2000; Hirschberg and Heitmann, 1997; Hlupic, 1999; Umeda and Jones, 1997). The reasons include, but are far from limited to deficiencies in functionality of commercially available software. On the other hand, research that focuses on the integration of simulation with activities connected to manufacturing system development is scarce, a few exceptions are reported by Feldmann and Schlögl (1999), on an industrial application, and Klingstam (1999), on a methodology outline.

Today, one of the largest application areas for simulation modeling is that of manufacturing systems (Banks, 1999). As shown by Umeda and Jones (1997), this is confirmed to be the case in Japan as well. The most commonly estimated performance measures by simulation include throughput, time in system for parts, time parts spend in queues, queue sizes, timeliness of deliveries and utilization of equipment or personnel.

According to Umeda and Jones's study, the largest application areas in Japanese industry are found within (in order of decreasing frequency of application) manufacturing systems, factory material handling systems, logistics and automated warehouses.

Still, regarding the use of simulation, international statistics are hard to find. However, in a recent survey of 150 companies on the use of simulation (including both continuous and discrete event simulation) in Swedish industry (Eriksson, 2000), less than *one tenth* of the companies use simulation frequently, whereas only *one third* are considering to use simulation more frequently in the future. Furthermore, as few as *one tenth* considered their competence regarding simulation to be adequate. Eriksson's survey further shows that the use of simulation varies greatly depending on the type of simulation. It also indicates that there is generally a low level of theoretical knowledge of simulation, and that it is only to a limited degree integrated as a natural part of manufacturing system development. Many times, simulation is bought as a consulting service.

With the exception of the results reported in Umeda and Jones (1997), similar surveys carried out in Japanese industry have not been found. Still, modeling and simulation have been identified as crucial components in major recent work done on future manufacturing in the U.S., Europe and Japan (Intelligent Manufacturing Systems, 2000; Consortium for Advanced Manufacturing International, 2000; Integrated Manufacturing Technology Roadmapping Initiative, 2000). Dissemination of research results into industry, as well as a continuous cooperation between industry and research organizations, are important contributions from such efforts. For this reason, it is relevant to look at the quality and amount of simulation research being carried out in Japan.

4.3 Simulation research in Japan

Assessing the level of research within a certain field is not an uncomplicated task. Looking through numerous conference proceedings and journal papers gives a general idea of contributions from certain research communities, but one has to bear in mind that gaining reliable quantitative results from such an empirical study would be a tedious task, while obtaining qualitative measures would be even more difficult since this would rely on subjective opinions. Despite this and some reservations mentioned below, the authors believe that such an approach does give some idea of the state of research, and to this end have looked at Japanese contributions to recent Winter Simulation Conferences (WSC) (Farrington, Black Nembhard, Sturrock and Evans, 1999; Benjamin, Erraguntla and Mayer, 1998; Andradóttir, Healy, Withers and Nelson, 1997).

At WSC'99, 246 papers were presented in virtually every area of simulation. Out of these, only *three* papers were written by Japanese researchers in Japan. Stepping back a year, the proceedings of WSC'98 contain only *two* Japanese papers out of a total of 236 papers. Similarly, WSC'97 featured *three* Japanese papers out of 200 papers and tutorials. At neither of these three conferences did any Japanese researchers take active part in the panel discussions. The question is to what degree a look at some 680 contributions reflects the actual amount and quality of simulation research being carried out in Japanese industry and academia. Most researchers in the field would probably agree that WSC is *the* place to present research results, since virtually anyone who is anybody in simulation attends or in other ways follow these conferences. Still, one should be careful to draw conclusions from such rough comparisons. For instance, such factors as financial reasons and language might play a role in this, since many Japanese researchers have to pay for conferences by themselves, while some have a limited proficiency in English. Undoubtedly, a large amount of research is available in Japanese only.

However, given the fact that Japan is the world's second largest manufacturing nation, it can hardly be questioned that there is an imbalance in research available in English in comparison to the U.S.

Of existing contributions, most seem to describe application development as opposed to basic research in simulation. There seems to be a large number of industry-authored articles and applications-oriented papers, suggesting that simulation is much more common in industry laboratories and systems engineering departments than in academic institutions. According to a review of a 1994 simulation conference held in Japan, most of the Japanese industry-authored papers described applications that were currently in use (Kahaner, 2000). This supports the above review of WSC papers, and is true of many of the academic and jointly authored papers as well.

Also, instead of simulation of manufacturing systems per se, the focus of Japanese researchers, and as we will see, practitioners, seems to be on scheduling, which occasionally involves simulation. Thus the focus is more on practical issues, as supported by the findings of Kotha and Swamidass (1998), who argue that Japanese use of advanced manufacturing technologies is blue collar oriented, i.e. focused on shop floor technologies rather than higher level technologies.

If overall trends in Japanese simulation research are to be identified, the authors would argue that these are focused on scheduling and distributed simulation, with some notable contributions in certain industrial application developments, occasionally in a virtual manufacturing context. This is also where the most interesting work has been done by Japanese researchers in recent years, see for instance Fujii, Kaihara and Tanaka (1998) and Fujii, Tsunoda, Yamane, Hirashima and Hirano (1994) in distributed simulation and Kubota, Sato and Nakano (1999) for an industrial application of manufacturing system design and supply chain integration.

4.4 Integration

The authors take as a fundamental stance the view that there are substantial benefits to simulation integration. Several research results and programs point to various aspects of the need to integrate simulation as well as other techniques into manufacturing system development (Holst, Randell and Bolmsjö, 2000a; Small, 1999; Giaglis, Paul and O'Keefe, 1999; Klingstam, 1999; Ball, 1995; Ball, Boughton and Love, 1994) and is recognized also by Japanese researchers, e.g. Fujii et al. (1998).

In particular, as Small (1999) found in an extensive survey, the full benefits of Advanced Manufacturing Technologies (AMTs) can only be realized with an extensive use of integrated technologies. While this refers to the integration capabilities of single technologies, another important aspect to integration is the interoperability and compatibility between various technologies and techniques. This is also the area where some of the major problems are present. These include inconsistent data formats, interoperability problems and the lack of a common information infrastructure. As Steffensen (1998, p.519) states, 'Japanese company groups have for years built up complex, costly, proprietary and customized information systems and software solutions. Simultaneously, a striking discrepancy between large manufacturers and small, lower-level subcontractors, has come into existence'. This was evident at most of the visited companies.

4.5 Future trends

Future manufacturing systems must be seen in the context of virtual and extended enterprises, or in other words: networks and partnerships of enterprises stretching further and deeper than the traditional customer-supplier relationships (Zhang and Browne, 1999). These enterprise partnerships, or temporary organizations, take advantage of each other's strengths and complementary product life-cycle phases in order to rapidly and efficiently satisfy a market need. In practice, this will involve various manufacturing philosophies and technologies, information and communication technologies, and management and organization styles. This will put significantly higher requirements on cooperation and sharing of information between enterprises.

To an even larger extent than today, value-adding features such as quality, functionality and materials will depend upon activities performed outside the traditional organizational boundaries of an enterprise.

Some would argue that this has been a reality in the Japanese automobile industry for some time now, as evidenced already by Womack, Jones and Roos (1990). There, indeed, a small number of very large first-tier suppliers manufacture much more complex and higher value-added products than just ten years ago; air bags, steering wheels, electrical systems and seats are some examples. However, what differs typical Japanese industrial networks from those of Western companies is that the former tend to be more closed and centralized, while terms and conditions to a larger extent are dictated by the large 'mother company' at the top of the network.

Future trends of software standardization, integration and open global networks will find many Japanese companies struggling to accommodate themselves since neither stability, geographical proximity and industrial policies, key factors in Japan's industrial development (Knox and Agnew, 1994), are particularly important in the new world (Steffensen, 1998).

This trend, expressed in the form of inter-regional sourcing strategies, became evident in 2000 when Toyota announced for the first time that it would buy non-Japanese components (stamped sheet metal body parts from Korea).

5 Visits

Taking a holistic view on simulation, several areas needed for a successful future integration of simulation into manufacturing system development need to be considered. How the visited companies approach some of these areas will be described in the following sections, which deal with what the companies actually do. What they don't do and why is accounted for in the discussion that follows. First, a general overview of the companies is given, including a note on whether or not they use DES for some purpose in the design of manufacturing systems.

The industries represented by the visited companies are automobiles, trucks, buses, machine tools and electronics. They include component manufacture and final assembly, and use a wide range of production technologies. Their sales cover domestic as well as international markets, demand patterns include stable, cyclic and fluctuating, and customers range from industry to consumers. The visited companies can therefore be considered to represent a broad spectrum of Japanese manufacturing industry. All the visited companies are classified as large, both in terms of employees and capital (see Holst and Pozgaj (1997) for a definition). Their turnover and gross profits were at the time of research among the top ten within their respective industries.

Note: companies have been given fictitious names from the Chinese animal zodiac. Any similarity to names of actual companies is unintentional.

5.1 Companies

Rat Corporation is one of the world's largest manufacturers of machine tools, with about 1,500 employees in total. Their products, most of which are made according to specific customer requirements, include lathes, machining centers, grinders, and systems. Visits were made to two factories; one old and one new. The company does not use DES.

Ox Motor Corporation, the third company in the automotive industry, was visited twice. The first visit was made to a plant belonging to the car division, the second to a plant within the truck and bus division. Ox ranks among the largest in Japan in its category, has several plants in Japan and also manufactures overseas, yet DES was used in neither of the two divisions visited.

Tiger Motor Corporation is another very large automobile manufacturer and makes extensive use of various simulation techniques, including DES. The visit was made to a unit responsible for drive-train design at the company's technical development center.

Rabbit Electric is an electronics division within one of Japan's largest corporations. The division employs more than 3,000 people, and makes various high-frequency based communications and imaging products. DES is not used.

Dragon Motor Corporation is one of the world's biggest automobile manufacturers. It is almost the model company when it comes to using simulation as an integrated part of manufacturing system development, and conversely uses DES on a regular basis.

Horse Machines makes machine tools and automotive parts, and provides automation solutions. It is a first tier supplier to Dragon Motors, but supplies to other companies in the automotive industry as well. It employs more than 4,000 people and does not use DES.

5.2 Concurrency and integration

Concurrent Engineering, or integrated product and process development, is a systematic approach to the integrated concurrent design of products and their related processes, including manufacture and support across the product life cycle. At Dragon Motors, concurrent engineering has been conceptualized as CASE – Computer Aided Simultaneous Engineering. It aims at making the different phases of the product realization process more concurrent by using computer aid in the entire process. On a regular basis, people involved in these activities meet in so-called CASE rooms, where 3D models can be shown on a 100 inch screen. These rooms were implemented as an integrated part of CASE in order to support communication and discussion. The people interviewed belonged to the development and planning department at the machines and tools engineering division as well as production engineering. In their view, the overall advantages of the CASE concept included early-stage improvements due to more sufficient evaluation capabilities, reduced number of reworks and shortened development periods. Another significant cost reduction benefit of CASE is that it helps in using existing lines by enabling the use of existing fixtures and tooling. Furthermore, existing part types and machining processes can to a greater extent be utilized. According to people from the production engineering department, all this is possible by managing information, improving communication and visualization, and evaluating alternatives through the use of simulation tools and databases. In one example presented, plant investment had been reduced by 83% through the use of CASE tools, mainly geometric simulation of clamps and fixtures. Great emphasis is put on the use of 3D models as a supportive tool in understanding and discussing various design and process features such as fixtures and clamps.

Tiger Motors recently (in 1997/98) initiated a program for concurrent engineering based on solid CAD data as a means of communicating designs and evaluating different design aspects. The move from 2D to solid 3D CAD modeling was a key factor in the transition process. So far, the experiences have been very good. One example given was from the engine cylinder head casting design process, where the lead-time had been reduced from two weeks to two hours. This exemplifies the benefits of information sharing between designers and production engineers. Building an engine requires an extensive amount of tests and evaluations to be made. Simulation is made of strength and rigidity, oil levels, casting, vibrations, noise, and 3D mockups are used for interference and clearance studies. At Tiger, however, data exchange with production starts only when the digital model reaches the prototype stage. From this point on, product designers and production engineers work together. Final assembly of the engine is not included in this process. However, at the time of the visit, adoption of CAE tools that would enable integration into the above mentioned process were being examined by the assembly unit.

5.3 Discrete-event simulation

Discrete-event simulation for designing manufacturing systems is only used by Dragon and Tiger. Although all of the remaining companies plan to use simulation for this purpose, only two plan to do so in the near future.

At Dragon Motors, production lines are considered important to simulate. For this purpose, DES models of the production lines are used. In addition to production line mock-ups, where such things as interference between material handling equipment and workability are checked, output data such as volume, lead-time and availability are of prime interest. Normally, in the kind of long straight-flow lines, which dominate Dragon's production, the aim is to balance the line by having the same cycle time in every operation. One successful result of production simulation presented showed a decrease of one such cycle time from 35.6 seconds to 33 seconds, mainly by modification of buffer sizes. During the manufacturing system development phase, the manufacturing system design is reviewed by a team of production engineers, plant engineers and operators who meet in CASE rooms. Here, considerations include buffer sizes and robustness to variation in product mix. Validation is also taken seriously, and current simulation accuracy was reported to be 95.5%, i.e. when comparing simulation output and actual production the error was 4.5% in terms of production volume. However, despite a recent and large investment in a family of state-of-the-art simulation software, including an advanced 3D DES package from a large U.S. vendor, the company still uses its in-house developed 2D software for its factory simulation. The reason, they say, is that their software is based on the general-purpose programming language C++, a well-known and open software, which makes modeling a lot easier than using the simulation programming language of the bought software. Additional animation and visualization capabilities are not required, since the simulation results are generally not presented to higher level managers. Instead, performance evaluation and predictions based on statistical calculations are the objectives.

At Rat, visits were made to two plants; one built in the early 1990s, the other in the late 1970s. Owing much to the age difference, these two factories represent two different poles in manufacturing system design. Although Japanese companies are famous for continuously developing their manufacturing systems through kaizen, there are large differences in performance: the new factory needs only 60 machines and three to four days to produce what the older factory would need 250 machines and one month to do. The old plant consistently suffers from bottlenecks and long waiting times in buffers. In fact, the interviewees were somewhat reluctant to show and even discuss that factory. Despite having obviously simulation targeted application areas in heavy need of attention, the company has never performed any simulation project on its own, neither for robot simulation nor production simulation. In recent years, however, integration of operations has increased. Activities have become more concurrent, and a PDM system was recently bought. In addition, subcontractors have been forced to use the same CAD software as Rat.

Rabbit Electric has a complex production mainly based on surface mount technology (SMT) and injection molding, and the problems include significant amounts of downtime. There are plans to start using production simulation, particularly for the design of new manufacturing systems. They say this will be necessary sooner or later, since their market requirements change so fast. However, the interviewees sensed some reluctance in other parts of the organization. The only simulation project to date had been for training purposes. The service was bought from a consultant, but the experiences were not good.

Ox and Horse have considered using production simulation, but had no such plans for the near future.

5.4 Input and output data

Input data collection is one of the key areas in simulation. The quality of output data, and consequently simulation results, are directly dependent on the accuracy and reliability of input data. This in turn depends upon how input data is collected, and is generally recognized as one of the major problems in simulation projects, see for instance Perera and Liyanage (2000). Interestingly, input data collection has not been integrated into Dragon's CASE concept. To gain access to data of good quality, manual collection would be necessary in most cases. Due to the size of the manufacturing system and the extensive amount of data that would be required, this is considered a practical problem. Instead, the company tries to find simpler methods to deal with the problem. For example, cyclical distributions of failures are used in the production simulation models.

As a manufacturer of machine tools that are ultimately the source, in some way or another, of input data for their customers simulation models, it was interesting to see how Horse was dealing with this problem. The general manager of sales planning and the general manager of manufacturing indeed recognized it as a problem, and both agreed that this was an important and at the same time difficult area that would need more attention in the future. Says one of the managers: ‘technically speaking, this is not a problem but our customers have not clearly expressed their needs, and standards are also missing’. In their own production, an in-house developed system is used for automatic data collection, albeit not for the purpose of feeding simulation models since DES is not used. Instead, the collected data is destined for scheduling and monitoring of parts.

5.5 Simulation competence

Interestingly, there seemed to be a correlation between companies that don't use simulation and their assessment of their knowledge of simulation. On a one to five scale, where one represented no knowledge and five very good knowledge, companies that didn't use DES rated it a three or less. For those companies that answered the questionnaire, this was also reflected in their ratings of what they thought simulation could be used for in the future. Their answers were vague and rated most application areas that were not integrated with simulation today as less likely to be so in the future. Rabbit Electric's seeming reluctance to start using DES, despite a high degree of complex flows and a plan to change the layout, probably has to do with the fact that their knowledge of simulation is not good; it rated it as a two on the same scale.

5.6 Time frame

Dragon and Tiger, both automotive companies and the only two companies in the study with extensive intra-organizational use of simulation, started using simulation as an integrated part of concurrent engineering within a rather narrow time span. Both companies initiated their latest company-wide concurrent engineering programs in 1997/98. One of their main competitors started building their concurrent engineering system for vehicle design and manufacturing tooling in 1996, but did not start the needed software installations until 1997. It is probably no coincidence, since all players in one of the worlds most competitive industries have to keep a close eye on each other in order to survive. Traditionally, Japanese companies have been particularly noted for always responding to competitors initiatives, rarely leaving actions unmet (Abegglen and Stalk, 1985). Keeping an eye on the action of others doesn't always mean acting though. The most striking example was the third automotive company that was visited; Ox Motors. At the time of the visit, no (official) plan for using DES for manufacturing simulation existed.

5.7 Planning and scheduling

Rat Corporation's newer plant is not only unusually automated, even by Japanese standards, but also extremely structured and clean in its layout. It is organized along three straight lines which manufacture parts according to their size. The shop floor is dominated by a relatively small number (considering the output) of highly advanced and flexible multi-operation CNC machines, and each line is directly connected to its own automated storage and retrieval system (AS/RS). Practically all material is moved between the different stations automatically, either by automated guided vehicles (AGVs) or through direct access to one of the AS/RSs. Each part is identified by a barcode label, while the boxes transported by the AGVs are identified by programmable ID badges. Thanks to the direct access to the AS/RSs, these act as buffers, totally eliminating the need for such on the shop floor. The whole shop floor area is enclosed on one side by a wall with two holes, each with a conveyor sticking through: one for input and one for output. Outside the input hole is the raw material delivery area, from which parts are placed on the in-conveyor. With few exceptions, this is the last time the parts are touched by human hand before they are transported through the out-conveyor as finished parts ready for assembly. The entire plant is controlled through a local area network (LAN).

This represents an interesting approach to manufacturing system design, not because it is novel or unique, but because it is very well suited to adapting to changes in product mix and demand by scheduling.

It also stands in clear contrast to Rat's older plant. The floor area is larger and the seemingly endless row of machines are placed very near each other in long rows separated by narrow aisles. The plant has turned into a manufacturing system dinosaur in view of the high number of product variants and flexibility required. The source of the problem is the unstable demand and high number of different products, since Rat, as a machine tool manufacturer, is highly dependent on the general business cycle.

Ox, in sharp contrast to Dragon and Tiger, albeit in the same industry, relies only on scheduling for production planning purposes. To this end they mainly do their planning manually using a simplified model of 50 part categories. However, they have installed a control system connected to the assembly line, which is used when large deviations from the predicted volumes occur. The company put priority on connecting the system only to assembly since production was considered too complex. The managers interviewed agreed that production had to be made simpler and more modern, particularly if simulation was even to be considered.

The above findings illustrate both a common problem and a common solution in Japanese industry: to minimize system losses during production with a high degree of product mix, the sequence of products needs to be carefully planned. Traditional lean production has solved this scheduling problem mainly by organizing the material movements in straight flows supported by short setup times, constant production rates, and a fairly stable product mix, all in large volumes. However, when straight flows are difficult to maintain due to a large and unpredictably changing variety of products in small volumes, the changes in product mix require the sequence of products to be changed quickly in order to avoid costly production disturbances. To solve this problem, scheduling simulation can be used to test various sequences (Katayama and Bennett, 1996; Xiaobo, Zhou and Asres, 1999).

As argued in the section on Japanese simulation research, scheduling is also one of the most commonly found application areas for simulation, and the requirements for future integration of simulation with planning and scheduling are supported by Umeda and Jones's findings.

5.8 Related areas

In addition to the use of DES in Dragon, working conditions are also being improved by the use of ergonomic and assembly simulation. Concrete examples included modifications of safety covers, wiring and piping and height of working areas.

Tiger does not make ergonomic simulations, but similar to Dragon makes use of simulation in virtually every other area of automobile production. Examples related to production include off-line programming of assembly robots, press forming and plastic mold flow. These simulations are all done prior to the prototyping stage.

Other than these two companies, a general picture emerges of limited use of simulation for other purposes than highly specialized and narrow (from an enterprise perspective) application areas. Neither Dragon nor Tiger or any other company used simulation for education or training purposes. It should be noted here that this study did not explicitly deal with logistics or supply chain simulation, and these areas were rarely touched upon by interviewees except at Dragon and Horse.

6 Discussion

Simulation, as focused on in this article, can be seen in the context of Computer-Aided Manufacturing System Engineering (CAMSE), which is defined as: 'the use of computerized tools in the application of scientific and engineering methods to the problem of the design and implementation of manufacturing systems' (McLean, 1993).

However, the requirements on tools needed for CAMSE are extremely complex since they should make available information used in a number of disciplines. In all of the visited companies, most of this information is currently spread in different sources and different mediums, ranging from books and binders to different kinds of databases. Moreover, when simulation is used in this context, it is mainly applied as a stand-alone tool when certain aspects of an existing manufacturing system are needed to be studied, e.g. bottlenecks or other logistics issues in the case of DES (Klingstam, 1999). In other words, simulation is not viewed as critical or strategically important, but rather as a troubleshooting tool. This can be described as a rather traditional use of simulation. Among the visited companies, there were no cases where simulation was used as a planned and organizationally well-supported tool, integrated with other activities in the product realization process. The companies that came closest were Dragon and Tiger.

Most importantly, these two companies which did use DES and various other simulation techniques, reported on positive experiences. Also, several examples that simulation investments had paid off at Dragon and Tiger were given. For instance, the mentioned reductions in investment and cycle times reported by Dragon have undoubtedly yielded substantial cost reductions as well as shortened development and production lead-time, and thus ultimately reduced time-to-market. Typical benefits sounded like: 'our engineers are able to work together more collaboratively, with fast, reliable access to engineering data', and, 'using a concurrent engineering approach helps us to communicate more effectively, reducing product development costs and time-to-market, and problems in production are avoided by interference and clearance checking'.

However, in neither of these in many ways state-of-the-art companies has integration come as far as planned. Tiger would ideally be able to use the product designers' 3D product models in die cutting CAM models. However, CAM puts requirements on the product that designers usually do not or cannot model in standard CAD software. Rather than modifying the CAD models, die designers build a new dedicated model for die cutting. They think this is easier than having to use the advanced functions of the product designers' software, which they don t know as well. This is a well known problem, but shows that there is a need for a common information infrastructure. This is particularly true if the present virtual manufacturing is to be fully extended to the production process. As the situation is now, there is no intra-organizational function responsible for software purchasing, and thus no overall responsibility for integration aspects including such fundamental factors as compatibility between different software. This common problem is usually solved by informal communication. However, it does show that the area needs more attention.

An overall impression is that the introduction of 3D CAD has been the major event in terms of computer aided engineering tools. True as it may be, the overwhelmingly positive and extensive reviews of 3D CAD use were probably, at least to some part, due to the fact that no examples of benefits from DES could be accounted for.

Moreover, when given ten choice areas that need additional attention in the future, simulation was placed last or second last by all companies. Yet, the full range of simulation functionality does not seem to be realized. One example is that simulation is rarely used for education and training purposes. Another is the practice at Dragon of using cyclical failure distributions, a surprisingly rough measure considering the high levels of other simulation application areas in Dragon. As one manager in production engineering says, there is a lack of central policy and understanding among higher level managers of simulation. This might be exemplified by the production engineering department's choice of sticking to their own software for production line simulation. They intend to continue designing their production lines with straight flows to as large an extent as possible, which will make improvements easier without having to rely solely upon simulation for such tasks as finding bottlenecks in production. A need for a common information infrastructure exists here as well. As one production engineer at Tiger states, it will be important to raise the CAD models' informational value, i.e. making the information inherent in product and other models available for various applications. Tiger specifically mentioned DES as one area that needs to be addressed.

Another possible explanation might be a long tradition of in-house developed applications, with fewer applications contracted to outside firms than in Western companies (Imai, 1986). As reported by some companies, this does usually improve the usability and acceptance of the application, but might also result in certain tasks being to difficult for the in-house developers to handle. One such area is clearly integration of simulation with other softwares and systems. Still, most commercial simulation software seem to be of U.S. and European origin, as confirmed by Umeda and Jones (1997).

A general conclusion based on questionnaire answers regarding factors considered as the largest problems to achieve profitability points at price of finished products, quality, domestic and foreign competition, downtime, bottlenecks, productivity, ramp-up time and time-to-market. Notable exceptions are Dragon, which doesn't consider down-time and bottlenecks in production as major problems. Most companies seem content with laws and regulations, and surprisingly labor cost.

The main interest in future use of simulation in the visited companies, based on high scores in the questionnaires and interviews, are logistics, production simulation, value-adding in production, decision support, communication support and Virtual Reality applications (mainly visualization).

As expected, virtually all companies mention reduced time-to-market, shortened ramp-up-time, shop floor control, etc as important future areas. They particularly seem to view reduced time-to-market as the main reason for investing in simulation software.

What generally seems to be missing is an awareness of the need for a related infrastructure, including e.g. configuration management.

On the positive side, Japanese companies seem to have closer intrafunctional links between R&D, product development, and operations departments. This should ease simulation application development considerably and support integration of simulation modeling with other information technology such as existing databases and other applications, provided that commercially available software systems have these capabilities. However, this is rarely the case. For example, most existing databases are structured to support individual tools, and various stages in manufacturing system development make use of different interfaces and a plethora of data formats. Perhaps illustrating this is the fact that only two of the companies use a PDM system, although another three plan to start using it in the near future. One company specifically mentioned the need for configuration management, an important component in simulation projects (Randell, Holst and Bolmsjö, 1999). Only one of the companies use an ERP (Enterprise Resource Planning) system, although two companies plan to do so. Interestingly, the one company that has both a PDM and an ERP system, Ox Motors, does not use discrete-event simulation.

7 Summary

A majority of the companies don't use DES, let alone have integrated the use of this technique into their development process. On a more general level, this view was supported during talks with managers and engineers at Dragon who were aware of only one other major Japanese corporation that had introduced a company wide virtual manufacturing program similar to Dragon's. The two companies that use DES report on several positive experiences. The most frequent purposes of use are planning and evaluation, communication and discussion of ideas and decision support. The future role of simulation is seen by these companies in the areas of design of manufacturing systems, added-value in production, virtual reality (VR) applications and reduced time-to-market.

The previously mentioned global trends of extended and virtual enterprises and increasingly complex manufacturing systems, the evident changes in supplier structure and other domestic structural changes, an increasingly uncertain environment, unpredictable demand and international competitive dynamics will certainly not leave Japanese companies unaffected. With this basic awareness in mind, the authors would argue that there is a large potential for increased use of advanced simulation techniques in Japanese manufacturing companies mainly for two reasons; (i) as a means to integrating activities related to the design and development across the entire value chain of a product, i.e. from supplier to customer, and thus support and increase the efficiency of the information flow between these processes, and (ii) as a means to integrating activities within the enterprise, i.e. between market, product and process activities, and thus act as a control and decision support tool. This would result in improved communication, reduced time-to-market, higher productivity and higher flexibility in volume and product-mix.

In addition, and based on the findings from this study and general characteristics of the Japanese manufacturing industry, a number of simulation success factors specific to Japanese companies have been identified. These are factors specific to Japanese companies, and should act as advantages in future use and integration of simulation. Perhaps surprisingly, they have not been explicitly mentioned previously in this article. These factors are usually not seen as directly connected to simulation, and conversely have been overlooked in most simulation research. The three most important success factors are described here.

However, there also exists a number of push factors, or internal and external environmental drivers which are believed to push the companies in the direction of increased simulation use. Several push factors have been identified, but only three are accounted for here.

An attempt has also been made to identify factors that act as entry barriers to simulation use and integration. Some of these are briefly mentioned, although several more exist and need to be further explored.

The push factors and barriers to entry are a combination of factors that are specifically Japanese and factors common to manufacturing enterprises in a global context.

7.1 Success factors

Success factor 1 – Knowledge creating. As several researchers have showed (Kusunoki and Numagami, 1998; Durward K. Sobek, Liker and Ward, 1998; Nonaka and Takeuchi, 1995; Clark and Wheelwright, 1993; Womack et al., 1990), personnel, including engineers and other technical staff, is frequently and systematically transferred within a Japanese company. It is generally agreed upon that this is a key factor in explaining competitive advantages of Japanese industrial enterprises, see for instance Jacobs and Herbig (1998). Also, as Durward K. Sobek et al. (1998) showed in their extensive study of Toyota, only senior managers rotate broadly and frequently across functions. Engineers below the *buchō* level - corresponding to the head of a functional division - are primarily transferred within their function and at longer intervals than the typical product cycle. This is in essence supported by Kusunoki and Numagami's findings, which e.g. show that more than 70% of the third transfers are in the middle or late career stage, while fourth or later transfers are concentrated to the late career stages.

This study extends these findings to be the case at all the visited companies, although it cannot be said for certain that the frequencies of rotation are consistent with those reported by Durward K. Sobek et al. (1998) at all companies. However, the implications of these practices were strikingly evident when talking to engineers and managers at all levels in the visited companies. The impression was that of a very good general knowledge about business processes and functions in all parts of the organization. In fact, this study confirmed these transfer activities to be practiced at all the visited companies. Such rotating of engineers increases system knowledge at the factory level and employees' ability to communicate with each other.

As argued in Kusunoki and Numagami (1998), it may even lead to cross-functional integration derived from the above mentioned multifunctional knowledge obtained through hands-on experiences in different functional areas, rather than through intensive and extensive communication. The first success factor derived from this study is therefore that this interfunctional transfer at managerial levels and intrafunctional rotation at engineering levels, supports and increases the quality of networking, engineering communication, cross-functional coordination and interfunctional knowledge across the organization, on both an explicit and a tacit basis. For engineers, it further reduces the amount of communication and supervision, trial and error, misunderstanding, unrealistic expectations, and confusion. These are substantial advantages to successful simulation projects.

Success factor 2 – Statistics. This leads us to the second success factor, namely Japanese engineers and shop floor workers generally good knowledge of statistical analysis methods. In addition to the interfunctional transfers mentioned above, delegated responsibilities and problem solving activities have a long tradition in Japanese companies, and are aided by large amounts of information regarding the production processes and their performance measures (Holst and Pozgaj, 1997; Womack et al., 1990).

During the visits of this study, such statistics were frequently encountered on in virtually all parts of the factories, canteens not excluded. And it's not only there for show: workers and managers on the shop floor regularly meet around these spreadsheets and diagrams to evaluate and discuss the latest and coming production performance. This greatly helps in identifying disturbances and undesired variations in the production, and provides a powerful way of jointly solving these problems.

Because simulation output data is a set of random estimates of several input parameters, one crucial phase in a simulation project is the interpretation and use of this data. Good results depend upon an intelligent design of experiments and analysis methods, knowledge that is highly specialized. Although the findings of Umeda and Jones (1997) suggest otherwise, the competence regarding experimental design methods and statistical output data analysis was perceived as high at the visited companies. The second success factor derived from this study is therefore that this 'shop floor information system' and well established use of statistical process control methods in Japanese manufacturing firms greatly increases the likeliness of successful simulation projects.

Success factor 3 – Late-mover In many ways Japan seems to be lagging in ICT and 'e-manufacturing' investments, particularly in comparison to the U.S. This is perhaps mainly seen as a disadvantage, given the profound way these technologies are changing the way manufacturing companies do business. However, by studying reports on the considerable amount of unsuccessful implementations and failed investments mentioned previously in this article, Japanese companies can learn from others' mistakes and much like they did with quality theory and practice in the 1950s and 1960s, companies can import, adapt and develop best practices from the U.S. and Europe, especially regarding strategic use of simulation.

Recent alliances and partnerships through mergers and acquisitions involving large Japanese and foreign companies, most notably Nissan–Renault, Ford–Mazda, Mitsubishi Trucks & Buses–Volvo Truck Corporation, Mitsubishi Motors–DaimlerChrysler and Toyoda Automatic Loom Work–BT Industries, suggest that this will be further supported through close relationships with companies that already have lots of experience in the field, successful as well as non-successful.

Two companies represent that trend in this study; Tiger and Ox Motors both recently entered strategic alliances with non-Japanese automobile manufacturers. Thus, this late-mover advantage is the third success factor.

7.2 Push factors

Push factor 1 – Need for agility and lower production costs. Several researchers and analysts argue that a weakness of lean production is its inability to respond to the present situation with frequent and large variations in demand, regarding both volume and product mix, see e.g. Katayama and Bennett (1996). Even small changes in demand will often take production below the break-even point. Most analysts would agree that Japan currently exports too much from a high-cost manufacturing base in Japan. This trend is generally believed to become clearer, and is strongly supported by the findings of this study which show that lowering production costs is considered a major problem by all companies except one. The means to become agile and lower production costs, while maintaining labor stability, are numerous and constitute no easy task, but based on the authors' industrial experiences, as well as substantial amounts of other research, it is argued here that simulation is one feasible way which will present itself as a likely alternative, even when integration aspects are not considered. In this context, it should be noted that in the present debate several analysts of Japanese industry advocate further plant closures and work-force cuts. However, the authors believe that such measures are neither feasible nor likely to take place to the extent called for, and that market driven employment relations have a long way to go in Japan. It would be beyond this article's scope to explore this further, but the reasons why the employment system will not change as much as some analysts seem to think would focus on cultural factors. This view is supported when looking into detail of those labor related restructuring measures that have taken place. These concentrate on such things as reduction of overtime and the number of female employees. Thus the general drive to curb production costs will push for further use of simulation.

Push factor 2 – Change in supplier networks. Loser keiretsu ties and more open supplier networks in general makes it harder to control the quality of parts. Ox Motor particularly emphasized this, since they have seen considerable changes in their supplier networks in recent years. In particular, the number of independent companies, i.e. not belonging to the keiretsu, has increased. As described elsewhere in this article, these developments will push for an increased use of ICT, where simulation is believed to be one important component.

Push factor 3 – Globalization and deregulation. As argued in previous sections, an increased competitive environment and deregulation of several sectors in Japan will call for an intensified use of technologies that can assist the concepts and strategies that will be pursued as an answer to these developments. Simulation, with the advantages outlined in this article, will be one key element in these efforts.

7.3 Entry barriers

With the reservations mentioned in the discussion on Japanese simulation research, the authors are left with the impression that there is a relatively small amount of research in Japan focusing on the use of simulation technologies and related areas such as virtual manufacturing, information infrastructure, interoperability, etc. This seems particularly evident when looking for research on a more general level, taking into account strategic and operational issues. Dissemination of research results into industry is important, and perhaps best done through direct involvement by researchers in industrial projects. The fact that few researchers seem to exist in this field can therefore act as an entry barrier.

Japanese companies have a general preference towards simpleness – charts and diagrams are used extensively, QC activities, not consultants solve practical problems, and so on. As most would agree, this has undoubtedly played a major role in the success of Japanese manufacturing. In fact, concepts such as *poka yoke*, QC circles and 5S, just to mention a few, have been widely adopted by Western companies. However, to Japanese firms the step from such simpleness to full scale CIM and IT implementation might be perceived as large, and may therefore act as another barrier to entry.

Furthermore, this study and others have mentioned simulation knowledge and competence as important factors in successful simulation projects. Arguments such as high initial investments, lack of competent personnel, etc, were mentioned by most of the visited companies that didn’t use simulation and DES. Also, many companies were not sure whether they would use simulation repeatedly, reflecting a lack of support for the need of integrating simulation into the development work. Some managers seemed to consider simulation as neither a tool to save costs nor increase income. The authors believe that part of the problem lies in the fact that in successful simulation projects, many costs are avoided rather than saved. Thus, the generally low level of simulation knowledge is also likely to act as an entry barrier.

Finally, a widespread use of several incompatible and dated stand-alone technologies with data spread in various sources and in inconsistent data formats will further adversely affect integration and access to and collection of input data for simulation models.

7.4 Suggestions for future research

This article has presented a general overview of simulation use in Japanese industry. During February and March 2000, a second study was done at another set of large Japanese manufacturing companies. Coming research will extend the findings described here to that second study, which should provide for more reliable general conclusions.

However, these studies have only touched upon several important areas, and further research is therefore needed.

First of all, the empirical work of Umeda and Jones (1997) will need to be followed up. For instance, in 1997 they stated that the use of simulation in Japan was modest but on the rise. No subsequent research has supported this prediction. If anything, this study has shown that simulation use is still modest in Japanese manufacturing firms. In line with Umeda and Jones's study, future work will also need to look more into details of simulation projects, such as the time spent on various activities/phases, e.g. input data collection, and so on. This may reveal interesting differences between companies in expected and real outcome of simulation use.

Since the authors believe that software functionalities and deficiencies to a large extent influence simulation use, the most popular features possessed by existing software, as well as the gap between features possessed and those features needed. While such studies have been made of software tools, see for instance McMurtrey, Teng, Grover and Kehr (2000), research focusing on simulation software is lacking.

On a more general level, this study has touched upon an interesting observation; that the successful use of simulation is highly contextual, i.e. dependent on a number of variables such as nationality, strategic view on manufacturing, view on technologies used, etc. In other words, introducing simulation in two similar companies will not be equally successful. This observation was confirmed regarding the nationality factor on a more general level by Kotha and Swamidass (1998) who compared the use of Advanced Manufacturing Technologies (AMTs) in the US and Japan. Although this may seem like a trivial observation, research in this area is scarce.

In connection with this, further work is also needed to explore the interrelationships between the strategic use of simulation and other management practices in Japanese companies, as well the strategic role of manufacturing within these enterprises.

Simulation aspects of personnel transfer and project management have also been described in this article. They provide interesting facets of simulation studies. However, research looking at advantages of this transfer of personnel from a simulation point of view is missing.

Finally, further research and dissemination of results within important related areas such as optimization, simulation methodology (including components such as model reutilization, documentation, modularization, etc), distributed simulation and Internet applications is needed.

8 Conclusions

The authors believe that there is great potential for an increased use of simulation in Japanese companies mainly for two categories of reasons. One applies to manufacturing companies regardless of geographical and cultural context. The other is due to conditions specific for Japan. Those companies using simulation report on successful experiences. However, even for these companies the full potential of simulation has not been realized. Integration problems remain, mainly attributable to a lack of common supportive infrastructure and interoperability problems. Simulation appears to be far from an integrated part of manufacturing system development, and several barriers to entry exist. Simulation, in particular discrete-event simulation, has not yet gained an industry wide acceptance as an important decision support tool in Japanese industry.

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Paper III

Integrating Simulation into Manufacturing System Development: A Methodological Framework

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Integrating Simulation into Manufacturing System Development: A Methodological Framework

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Abstract

Today, discrete-event simulation (DES) use in the manufacturing industry has become widespread, but far from all companies use this technology. Often simulation is used on a 'one-shot' basis only, or as a stand-alone tool, reflecting a low level of integration. At the same time, a majority of companies do not use simulation at all. It is argued here that these companies lack methodologies for adopting and integrating simulation into their manufacturing system development process. Also, simulation research on integration aspects often deals with specific functional, or data-level issues, such as integrating and connecting simulation to other systems and tools, rather than structural, hierarchical, and procedural integration aspects as part of a methodological approach. Furthermore, simulation use seems to lack strategic focus. Based on industrial experience, this paper presents the framework of a methodology for integrating discrete-event simulation into manufacturing system development.

Keywords: Manufacturing system development, Discrete-event simulation, Integration.

1 Introduction

Today, DES can be applied to a wide range of manufacturing system development activities. However, DES use is in many respects still modest. Often it is used on a 'one-shot' basis only, troubleshooting specific problems such as bottlenecks, or as a stand-alone tool, both of which reflects a low level of integration. On the other hand, a majority of companies do not use simulation at all (Eriksson, 2001*a*; Heitmann et al., 1997; Hlupic, 2000; Holst and Bolmsjö, 2001*b*; Klingstam, 1999; Umeda and Jones, 1997).

These companies seem to lack clear guidelines for adopting simulation and increasing their level of simulation integration in their manufacturing system development process. At the same time, research on integration aspects often deals with specific functional or data-level issues, such as developing various tools for integrating and connecting simulation to other systems, rather than general structural, hierarchical, and procedural integration aspects as part of a methodological approach. Conversely, research that takes a holistic and systemic view on simulation integration into manufacturing system development is scarce, or researchers only implicitly report on how simulation in practice should be integrated.

2 Problem

The few empirical studies that exist seem to indicate that discrete-event simulation use is still modest in the manufacturing industry, particularly outside the U.S., or as Busenius (2000) states, “it seems as if the optimistic forecasts by renowned companies and research institutes at the beginning of the 90s did not come true”. Even companies that report on successful and continuous use of simulation have not reached their current level of integration and acceptance overnight. At the same time, many organizations cannot devote the necessary resources, competence, and organizational support over enough time to reap the benefits of simulation integration. Certainly, a fundamental problem is that DES of manufacturing systems is a highly complex activity, touching upon several operational and strategic issues. At the same time, attention is drawn to several other means of improving the system development process other than simulation. More importantly, however, the simulation activities that do receive the attention of managers and other employees often send distorted signals about costs, benefits, and required resources.

When looking at reasons for this limited use of simulation, albeit with a less than satisfactory empirical base, a few common factors can be identified. First, there is still a low level of simulation knowledge and competence in industry, which results in poor commitment to simulation projects, or even worse, no simulation at all (Eriksson, 2001). In particular, there seems to be a focus on *costs* rather than benefits.

According to Banks (1999, p.10), however, “many managers are realizing the benefits of utilizing simulation for more than just the one-time remodeling of a facility. Rather, due to advances in software, managers are incorporating simulation in their daily operations on an increasingly regular basis”. While this may be true for the US, no empirical studies have been made to support that view. More importantly, few researchers have addressed the issue of *how* such a scenario should be realized. Certainly, advances in software alone are not enough.

In fact, several problems remain regarding adoption, usage, and integration of simulation into the manufacturing system development process. These problems regard such diverse matters as information sharing and exchange between different functions involved in manufacturing system development, interoperability and collection of data, organization of simulation activities, acceptance and other diffusion theory related issues, and several aspects on the strategic view on simulation. There also seems to be a wide gap between simulation investment and company ability to achieve the required or expected benefits from this investment. Evaluation or investment appraisal of DES is problematic because of the difficulties inherent in measuring the benefits (and to some extent the costs) associated with such investments. It is also argued here that the process of adopting and integrating simulation into the development process is today largely based on tacit knowledge, i.e. the experience and ideas of people, instead of explicit knowledge, formalized through a methodological approach.

The current situation seems to indicate a need for methodologies that can help companies manage adoption and implementation of simulation as an integrated set of activities in a manufacturing system development context. In other words, simulation engineers and manufacturing system developers need to share the same flow of information, the same view on process and content, and synchronize their working procedure of both the problem and project parts of their work to a much larger extent than is the case today[60]. This would provide for a more relevant view on the benefits of simulation as well as more efficient and effective adoption and usage of simulation.

3 Objectives and Scope

The objective of this paper is to outline a methodological framework for integrating simulation into manufacturing system development. The paper focuses on discrete-event simulation of production flows, and presents a structured approach for integration based on experience from Swedish industry, mainly two simulation projects that spanned two years and were carried out at *BT Products AB* in Mjölby, Sweden, a world leading manufacturer of electrical warehouse trucks, see Section 4.

4 Industrial Partner

BT Products AB (BTP) embarked upon an ambitious and comprehensive simulation program in late 1998, which included DES for flow analysis purposes. Prior to that, BTP had never used discrete-event simulation and there was no in-house competence or previous experience with this technology. With an increasingly complex production, and competitive and market pressure to reduce lead times, increase capacity, and introduce new products, BTP partnered with the Department of Mechanical Engineering at Lund University to approach this problem by the means of discrete-event simulation. The initial system under investigation was an existing production line at BTP's main factory in Mjölby, where a large number of parts for fork-lift trucks are manufactured. Subsequent simulation studies extended the scope to planned investments in new systems, and the projects were carried out over a two-year period. The herein proposed methodology is primarily based on experiences made during this work. Other results from this project have been reported in Randell, Holst and Bolmsjö (1999a), Randell et al. (1999*b*), and Randell et al. (2000), and a forthcoming publication will make the simulation experiences underlying the proposed methodology more explicit.

5 Simulation Integration

According to Vernadat (1996, p.23), "integration means putting together heterogeneous components to form a synergistic whole". In this case, the goal is to make DES integral to the PRP by putting together all relevant components of DES with those of the manufacturing system development process.

Based on the above, and the systemic aspects defined by Hitomi (1996) and Seliger et al. (1987), simulation integration can be defined as:

> *Simulation integration is the integration of simulation from functional, structural, hierarchical, and procedural aspects into the manufacturing system development process, where development refers to the planning, design, redesign, development, reconfiguration, etc. of manufacturing systems.*

Although integration seems to have become something of a general buzz-word in industry, much remains to be done when it comes to integration of modeling and simulation of manufacturing systems into the development process. As mentioned in the introduction, DES is often used on a 'one-shot' basis, trubleshooting specific problems such as bottlenecks, and as a stand-alone tool, not integrated with other applications and systems. Regarding for instance models used in FMS design, Borenstein et al. (1999, p.8) report that "these models present a unique common characteristic, they were developed as "stand-alone" models, in which the emphasis is on the application of the model to solve isolated problems". This isolated use shows in the form of poor documentation and a virtual "shut-down" of all simulation activities inbetween the solving of these isolated problems. The present situation regarding simulation integration is illustrated in Figure 1.

Figure 2 attempts to show some of the issues in overcoming these problems, i.e. reaching higher levels of simulation integration: deciding what kind of data and information that needs to be shared and exchanged between the manufacturing system development process and the simulation/flow analysis; establishing who should be involved, i.e. resolving organizational issues; determining when, i.e. at what phases of the process that simulation shoud be employed; and agreeing on how simulation/flow analysis should be made a continous process instead of a set of separate projects. The herein proposed methodology aims to address aspects underlying several of these research issues.

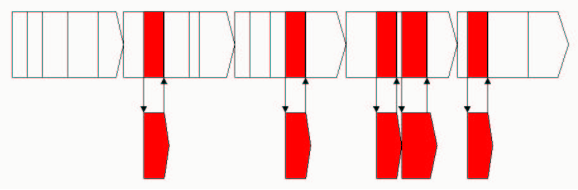

Figure 1 *A schematic view of the low level of simulation integration common in today's manufacturing enterprises. Note: upper part of the figure depicts the manufacturing system development process (process) and the lower part depicts the simulation/flow analysis (simulation). Hence, simulation activities are shaded.*

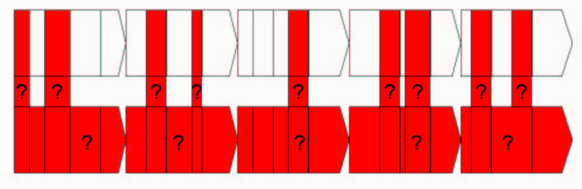

Figure 2 *A schematic view of the research issues to reach simulation integration. Note: upper part of the figure depicts the manufacturing system development process (process) and the lower part depicts the simulation/flow analysis (simulation).*

As for manufacturing system development in general, the need for simulation integration has been implicitly brought up by several researchers, e.g. Harrell and Tumay (1995) and Hibino et al. (1999), and more explicitly by Ball (1995) and Klingstam (1999).

Altogether, however, few researchers have focused on methodologies for reaching that integration, which, to paraphrase Kaplan and Cooper (1998, p.13) must be "based on concepts and theory, not just the ready availability of data and information". It should be noted, however, that with the large number of DES application areas and emerging integration capabilities mentioned above, the problem of simulation integration has become very complex, thus necessitating a holistic and well-structured approach to the problem. At the same time, in the manufacturing industry several factors work together to make the adoption and use of DES more time-consuming, more inefficient, less accepted, less accurate and less likely to succeed than would be necessary. In other words, problems connected to discrete-event simulation projects are present in several areas and at different strategic and operational levels. The cause of these problems, and hence the potential to successfully integrate simulation into the development process, can be found in those building blocks of the manufacturing environment that form the prerequisites for simulation integration. Thus, from a simulation perspective, these building blocks have been classified into four domains: data, organization, strategy, and enablers (DOSE), as proposed by Holst (2001b).

The components of these domains need to be transformed to a complex whole that not only meets the requirements and constraints on the system itself, but that is also adaptable to the adoption and integration of simulation into the system development process. The DOSE domains are further described in Section 5.1. A way of describing the "complex whole", i.e. the manufacturing system, is then described in Section 5.2.

On a more general level, the integration problem has been addressed within the extended enterprise manufacturing paradigm by the enterprise engineering and integration (EE&I) concept (Kosanke et al., 1998). Whilst this concept identifies production and process simulation as part of what is referred to as *business integration*, the highest integration level, there are no explicit guidelines given as for how simulation should become integrated with the manufacturing system development process. Nevertheless, *simulation integration* should aim at being consistent with EE&I concepts and technologies to as large an extent as possible. The general aims of enterprise integration are (Vernadat, 1996, p.20):

- to provide interoperability of IT applications,
- to enable communication among the various functional entities of the enterprise, and
- to facilitate coordination of functional entities for executing business processes so that they synergistically contribute to the fulfilment of enterprise goals.

The connection to the DOSE domains is evident, and the proposed framework can be said to be consistent with the overall objectives of EE&I. It follows from the above that simulation integration, while conceptually belonging with business integration, will have to deal with issues in all the three forms of integration defined by Vernadat (1996) as:

1. **system integration**, which esentially concerns systems communication, i.e. interconnection and data exchange by means of computer networks and communication protocols,

2. **application integration**, which concerns interoperability of applications on heterogenous platforms as well as access to common shared data by the various applications, and neccesitates e.g. API, standard data exchange formats, etc., and
3. **business integration**, which concerns integration at the enterprise level, i.e. business process coordination, and often requires to go deeper in the enterprise knowledge base to precisely model business operating rules.

Furthermore, integration should aim at providing an integrated view on the various “flows” in manufacturing (Hitomi, 1996; Berio and Vernadat, 1999):

- material flow,
- information flow,
- decision/control flow, and
- cost flow.

The methodology, which aims at integrating simulation with the manufacturing system development process, should present benefits within both these areas. As stated by Klingstam (1999), there are basically two fields of knowledge related to simulation: *simulation* knowledge, and *process* knowledge.

From these two perspectives, integration should lead to the following benefits on the process side:

- reduced overlapping of activities,
- shorter lead times,
- better correspondence between planned and real outcome of strategic and operational objetives, and
- better informed decisions;

and on the simulation side:

- strengthened managerial support,
- increased relevance of cost and benefit analysis,
- fewer resources consumed in simulation projects,
- more realistic expectations on simulation, and
- support for continuous use of simulation.

The simulation and process views could be further divided into process, content, problem, and project aspects, where process in this context relates to the manner in which a study is planned, conducted, and completed (Pidd, 1998).

The following section will outline the four DOSE domains mentioned previuosly: data, organization, strategy, and enablers.

5.1 Data, Organization, Strategy, and Enablers

Data – The data domain refers to generation, collection, storage, sharing, exchange and availability of data. In other words, it deals with issues on data formats, interoperability, configuration management, communication and application protocols, and the underlying information infrastructure, such as databases. Problems here might be multiple data sources for the same type of data, e.g. cycle times, which may sometimes be found in both MRPII and process planning systems, and these two systems may even provide different data, none of which might be useful for simulation purposes (for example, data might be too aggregate for a simulation study). Another widely recognized problem arises when input data is unavailable. This forces simulation engineers or other people involved in simulation studies to manually collect the needed data, make estimations, or even guess. These problems are common, since, in practice, any simulation study will need data from multiple sources.

While much research and development in this area remains, e.g. regarding the use of standards such as STEP and CORBA (Common Object Request Broker Architecture), and Web-based simulation, several important examples of data-level integration have been shown, such as integration of commercially available DES softwares with information sources (Bernard, 2000), with ABC (von Beck and Nowak, 2000), and with optimization software (Krug, 1997).

In this context, the main contribution of the methodology should be to provide management with a coherent and holistic view on data-related hardware and software issues across the organization, something that could result in synergetic effects with implementations of for instance ERP and ABM systems.

Organization – Here, the basic awareness is that activities related to the development of manufacturing systems compete with each other mainly for the following three reasons:

1. they cross organizational boundaries by involving customers, partners, suppliers and sometimes even competitors,
2. they encompass organizational structures by involving different kinds of business processes, activities, functions and information, and
3. they have to share limited resources of time, money and people.

To make simulation a successful winner in this competitive race, the organizational requirements on simulation integration have to be clearly understood and addressed, and the right decisions made on this basis. In other words, management must decide on how to best organize the (simulation) work, i.e. how to use their organizational resources in the most effective way. At the same time, every-day organizational issues such as making a new technique, working method, etc., accepted and implemented with confidence have to be dealt with. This raises questions such as: Which parts of the organization should simulation encompass? Should simulation integration be extended across the value chain of the product(s) and involve suppliers, partners and customers? And at what organizational levels should personnel be involved in simulation projects?

Strategy – The previous paragraphs outlined two important aspects on integration. However, an overall strategic focus is also needed. In other words, there has to be a simulation strategy linked to a company's manufacturing strategy, which in turn should be part of the overall business and corporate strategy. This is the third integration domain, and one which is rarely addressed by companies using simulation. Mabrouk (1999), who has proposed a strategy for implementing DES as a decision support tool at the enterprise level, states that, "too often simulation projects are initiated at the wrong time and do not produce the results anticipated [...] the main cause for these problems is a lack of understanding, by executives, of how to best utilize this decision support tool". Some exceptions exist, however, including BT Products and Volvo Car Corporation in Sweden, see e.g. Klingstam and Johansson (2000). There are several aspects on the need to link simulation to higher-level strategic objectives. One is the way simulation can help evaluate how well certain strategic objectives are met, such as manufacturing lead time, flexibility, quality, delivery reliability, etc. Simulation can thus validate key factors that affect a manufacturing company's competitive position. Issues here also include intra-enterprise and inter-enterprise integration. Another important argument here is that only by incorporating simulation into an overall manufacturing strategy can the critical mass of resources and managerial support be allocated to simulation and related activities. Consequently, simulation needs to be evaluated not only on financial premises, but also take into account strategic aspects, most of which are qualitative rather than quantitative. Finally, it should be noted that simulation in its role as a decision support and visualization tool may act as driver or enabler in translating the overall corporate strategy into a manufacturing strategy.

Enablers – Basically, enablers are all the standards (e.g. STEP), methods (e.g. for performance measurement), models (e.g. GERAM), tools, techniques (e.g. optimization), systems (e.g. MRPII, ERP), measures (e.g. the existence of performance measures), and resources such as hardware (e.g. computers), software (simulation or other supportive software), people, and networks that enable or drive the transformation from the real world "building blocks", i.e. data, organizational, and strategic issues to their corresponding desired functional, informational, resource, and organizational (FIRO) issues, which are described in the following section.

5.2 Function, Information, Resource, and Organization

A manufacturing environment is so complex that it can be described in an almost infinite number of ways. To understand the conceptual difference between the building blocks of a manufacturing environment, i.e. the DOSE constructs, and the complex whole formed by these building blocks, some formalism that can serve to describe this complexion is necessary.

Based on the ideas outlined by Vernadat (1996), the particular feature of the enterprise views in the GERAM have been adopted. GERAM mainly builds on the CIMOSA, GIM, and PERA frameworks: the reader is referred to Vernadat (1996) for a detailed description of these frameworks.

These four views are (Vernadat, 1996; Berio and Vernadat, 1999):

1. **function**, which represents enterprise functionality (what has to be done) and behavior (in which order work has to be done, i.e. events, activities, and processes) including temporal and exception handling aspects,
2. **information**, which represents enterprise objects and their information elements
3. **resource**, which represents enterprise means, their capabilities, and management (who/what does what)
4. **organization**, which represents organizational levels, units, authorities, and responsibilities, and may include other aspects, such as economic view, etc.

The primary purpose of these particular views (henceforth referred to as FIRO) is to adopt a semantic unification framework that seems to be gaining wide acceptance within the research community. The translation from the DOSE domains to the FIRO views is described in Section 6.2.

6 Outline of the Methodological Framework

To paraphrase Kidd (1994), "what we need is a holistic methodology with supporting tools, which will allow us to deal with all aspects of discrete-event simulation, the interrelationships and the difficult process of planning and managing change". Basically, a methodology is a set of instructions provided through methods, models, tools and guidelines that are to be used in a structured way. In this case, the methodological basis can be described as a set of questions that need to be addressed and answered: Why? What? Who? When? Where? and How?

The objective of the methodology is to help companies manage adoption and integration of DES (simulation) into their manufacturing system development process (process), and ultimately to answer the above questions. The methodology will thus provide:

- a coherent and holistic view on the scope of simulation integration
- practical guidelines for adoption and integration

A number of requirements on the methodology have been defined based on theoretical findings and industrial experience. The methodology should:

- assess, inform and guide decisions regarding adoption and integration of simulation into manufacturing system development,
- increase the relevance of requirements and trade-off analysis of adoption and integration of simulation,
- establish by quantitative and qualitative means the worth of simulation to the organization,
- provide practical guidelines for adoption and integration of simulation, and
- be well-documented and simple to use.

The methodology does not provide a complete set of tools and models. Rather, it should be applied in connection with existing tools and models, such as those for process mapping, organizational charts, etc. The remainder of this section will briefly outline the six questions describing the focus areas of the methodology:

Why? – This is the first question that needs to be answered, and it is highly strategic in its character: Why do we need simulation and what can it do for our company? Promoting such discussion, and indeed providing answers to these questions has to be the basis of any methodology that tells industry to embark upon the potentially costly and complicated task of integrating simulation into an already complex and resource-consuming process. The primary issue is to decide whether simulation should be used at all. As Hicks (1999, p.1215) states, “the most crucial stage of any project that involves problem solving and decision making is the formulation of the problem itself and the selection of which tools and technologies to attack the problem with. When one knows an issue is a "simulation" problem, one can proceed with established methodologies. When one knows it is not, one can select a different approach”. These basic issues need to be carefully resolved before any further action is taken in order to ensure managerial support and committment. However, several problems exist in this area, such as the lack of financial measures of successful integration projects, and the non-monetary and qualitative character of several of the benefits of simulation integration.

What? – This question centers on the basic requirements for adopting simulation and/or proceeding to a higher level of integration. Examples include requirements on competence, training, hardware, software, models, tools, etc. and are strongly connected to the other questions. Much like the question of "Why?", this is fundamental to gaining an enterprise-wide understanding and acceptance of starting or continuing the process of simulation integration. In the industrial case at BT Products, much of the success was attributed to the fact that this question was answered from within the organization over the the course of the initial project. Breaking down this question prior to commencing on the integration process should help focus attention on the right issues.

Who? – A question with several dimensions and levels. As mentioned previously, activities related to the development of manufacturing systems compete with each other for several reasons. This raises questions such as which parts of the organization simulation should encompass? Should we extend simulation integration across the value chain of our products and involve e.g. our main suppliers? At what organizational levels should we involve personnel in the simulation projects?

When? – This question emphasizes the importance of mapping phases of the manufacturing system development process that should be supported by simulation, as well as defining what kind of information and data that needs to be exchanged between these two processes, and when. It is important in this context to realize that simulation should be seen as part of a wider concept, where the authors support the term *flow analysis*, and conversely that simulation on the one hand might not always be the right tool for the job, and on the other hand, might need to be preceded by or work in parallel with other methods, models and tools.

Where? – This question relates to where (physically) in the virtual or real organization simulation should be applied. Here the aim should be to address issues on modeling different manufacturing concepts, types of production, and manufacturing systems with various size and complexity, etc. Typical examples would be the difference in modeling a push and a pull system (e.g. a kanban production system), and modeling the entire factory vs. some smaller part of it. And should simulation be extended to include logistic flows? It also deals with deciding the appropriate level of detail, ‘one of the most difficult issues when modeling a complex system’ (Law and McComas, 1999, p.57).

How? – This is the structured sum of answers to all the previous questions, sequenced in a chronological order and provided as well-documented practical guidelines. A related concern here is to what extent integration should be achieved through either one of three ways: consultants, partners or in-house competence, or a combination thereof. The authors would argue that this outsource vs. insource approach can greatly affect the long-term outcome of simulation integration. In the project described here, BT Products mainly relied on a partner, and the authors would (subjectively) argue that the outcome of the project would have been another if the company had chosen a different approach.

6.1 Phases

The following eight phases have been defined:

1. **Process and simulation knowledge** Understand the process and the requirements and constraints it puts on simulation (Note: "understanding the process" has several implications, including a thorough knowledge of the system, its performance measures, and so on).
2. **Quantification** Determine the performance measures that are relevant to the simulation activities, and assess whether there is a need for simulation. If no, other approaches should be considered. If yes, proceed with the next phase.
3. **Strategy** Formulate a simulation strategy including a desired level of integration based on process and simulation knowledge and higher level strategic objectives, i.e. those emanating from manufacturing, business and corporate strategies.
4. **Identification** Identify DOSE constructs that are relevant to the organization.
5. **Mapping** Map previously identified DOSE constructs to the DOSE-FIRO matrix, taking into account manufacturing system life-cycle specific issues, and assess the perceived level of integration with respect to real world conditions and strategic objectives.
6. **Analysis** Analyze costs, benefits and trade-offs taking into account the time component of the methodology, and reassess the level of integration.
7. **Definition** Define an action plan for adoption and integration of simulation in the form of well-documented guidelines for all DOSE domains.
8. **Implementation** Execute the plan.

The methodology phases are shown in Figure 3. Validations, i.e. comparisons with the real world prior to the mapping phase have been left out on purpose since this would risk that the real world imposes unnecessary restrictions on the simulation integration process. After the mapping phase, an evaluation and a selection of simulation software (unless it has already been selected) should be carried out in conjunction with the analysis phase. Another separate task is time analysis, explained in Section 6.2. A note on the initial steps: it may be difficult assessing whether the organization has sufficient process and simulation knowledge, especially if there is nothing to measure against. This yardstick is in fact often made more explicit when performing a simulation study. Finally, it is important to see these seven phases as a continous loop

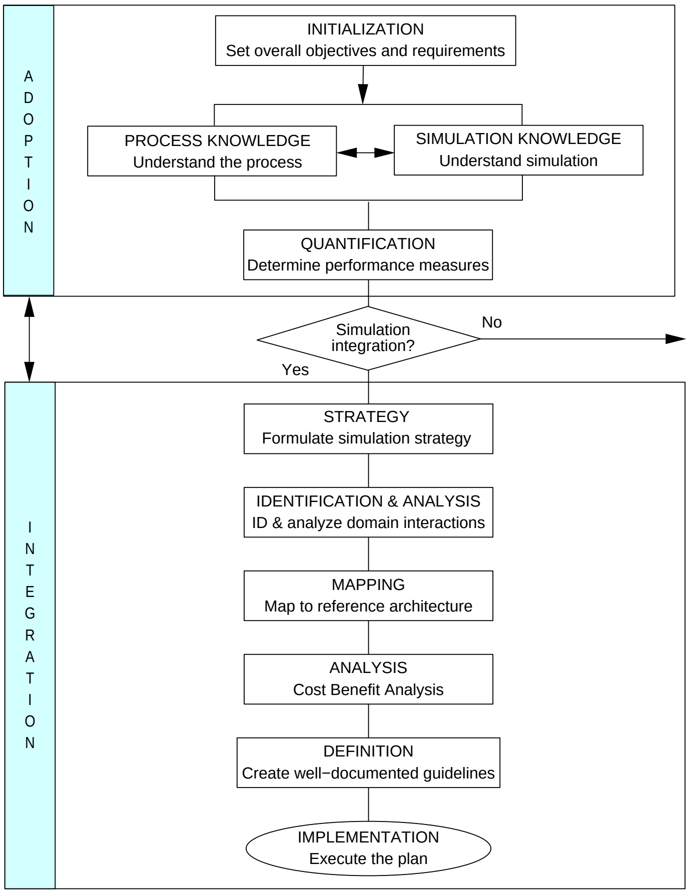

Figure 3 *State transition chart showing an overview of the methodology phases.*

to reflect changes in manufacturing strategy, the manufacturing system, etc. This should also provide for a continuously improved process and simulation knowledge.

6.2 Methodology Components

This section will briefly outline the following methodological components:

- the DOSE domains,
- the DOSE-FIRO matrix,
- activity-based simulation management (ABSIM), and
- time analysis.

The DOSE domains

DOSE provides the underlying structure for the methodology as well as a theoretical description of how the different components of the integration process fit together. It is argued here that all issues connected to simulation integration can and should be classified into either one of these four domains. Future research should then aim at further decomposing each domain.

The DOSE-FIRO matrix

The purpose of the DOSE-FIRO matrix is to link the DOSE constructs to a description of the manufacturing system development process, which is conceptually illustrated in Figure 4.

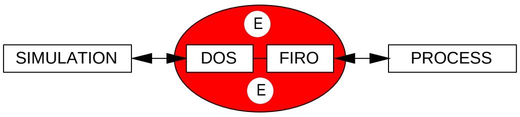

Figure 4 *A conceptual illustration of the DOSE-FIRO matrix.*

In practice, this process should be guided by answering four of the questions outlined in Section 6: Why, What, Who, and When, which is done in the Mapping phase, see Figure 5. One of the challenges for future development of the methodology is to detail the design and procedural aspects of using this matrix.

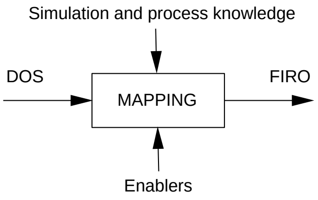

Figure 5 *An IDEF$_0$ view of the mapping phase.*

Activity-Based Simulation Management

In short, ABSIM can be described as a model to communicate cost and benefits of discrete-event simulation projects. In this sense it fills a theoretical and practical gap. It applies the fundamental principles of ABM to simulation as a process, and is based on the one hand on activities, resources, and their related activity and process drivers, and on the other hand on qualitative and quantitative benefits, see Figure 6. ABSIM is still in the conceptual framework stage, and is further described in Holst (2001a).

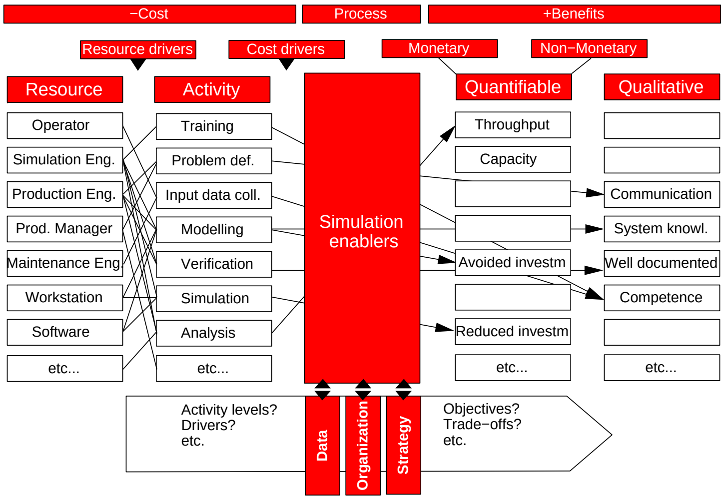

Figure 6 *The ABSIM framework (Note: content in white boxes are examples only and should not be seen as fixed components of the framework).*

Time analysis

The time analysis component of the methodology deals with the following time related aspects:

1. **Process** — Which phases of the development process should simulation support? There are different application areas in different system life cycle phases, and particular emphasis should be placed on early phases (Klingstam and Johansson, 2000).
2. **Simulation** — What is the time needed for different phases of the simulation study and how does this relate to the process? Realistic expectations provide for the right amount of committed resources and increase the acceptance.

7 Discussion

The authors believe that the methodological approach outlined here, although only briefly summarized, has presented a holistic view on the complexity and diversity of issues related to adopting and integrating simulation into the manufacturing system development process. While a structured approach to deal with these issues has been suggested, there is a need for further research. First, more explicit links to related standards in this area should be made, such as ENV 40003 (1990) and GERAM (ISO 15074, 1998) and work carried out under ISO/TC 184/SC 5/WG 1 (1990). While not directly applicable, certain components and models of these could be useful. Secondly, the general methodology phases need to be further decomposed in order to provide for more specific guidelines. Furthermore, it has been suggested here that the choice of insource vs. outsource simulation strategy has different implications on a number of parameters over the short- and long-term. These need to be carefully examined and weighted against each other. Also, what needs to be considered is how a higher level of simulation integration and more integrated use of flow analysis changes the way manufacturing systems are developed, as well as the interaction between product and process developers, i.e. concurrent engineering aspects. Certainly, integrating simulation into manufacturing system development will affect the development process itself. Future research should look into these interrelationships and their implications. Finally, the methodology will need to be evaluated in an industrial pilot test.

8 Conclusions

Successful results from the simulation projects carried out at BT Products show that there are several benefits to adopting simulation as an integrated part of the manufacturing system development process. The structured approach and the underlying view on integration presented here constitutes an important basis for a framework that will result in a more detailed and comprehensive methodology for adopting and raising the levels of simulation integration. However, while these positive experiences indicate a step in the right direction, the proposed methodology needs further development and more explicit links to existing enterprise engineering and integration work.

Acknowledgments

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APPENDIX

A

Manufacturing and Production

> "Manufactured in 1622"

While few, if any existing products can boast this label, 1622 is the year to which *manu factum*, the latin origin of the word manufacturing, can be traced (Hitomi, 1996). The history of artefacts goes back a lot longer than that though. Man-made objects have been around for as long as the modern man has existed. However, from its original 17th century meaning – *made by hand* – the word has taken on an immensely more complex meaning; it has formed a plethora of derivatives and compunds, one of which is used in the title of this work, and along the way there has arisen some confusion as to the meaning of these words. This chapter will try to state the author's view on the complex world of manufacturing and its connotations.

1 Manufacturing Defined

Traditionally, manufacturing was defined as the transformation of raw materials into useful goods. However, it can be broadened to the general transformation of all resources to meet human needs.

In fact, as Yien and Tseng (1997, p. 393) point out, there are now two different understandings of the term *manufacturing*. In a broader sense, manufacturing is understood as "the conversion of a design into a finished product" (Hitomi, 1996, p. 4). In a narrower sense, manufacturing means only the material transformation processes, i.e. the activities carried out on the shop floor (Yien and Tseng, 1997).

Here, it can be noted that one of the greatest sources of confusion in manufacturing literature seems to arise from the usage of the two terms "manufacturing" and "production". Although there is a difference, many authors, including Hitomi (1996), use them alternatingly. Conversely, this author holds the opinion that one should not pay too much attention to this; rather, the context should make it clear whether the term should be understood in the broad or in the narrow sense.[61]

In this thesis, however, the term *manufacturing* should be understood in the broader sense, while the term *production* will be used to denote shop floor activities. A *manufacturing system* and a *production system* carry analoguous meanings, as described in Section 6.2.

An appropriate definition of manufacturing in this context was stated by CIRP in 1983 as follows (Hitomi, 1996, p. 4):

> **Definition A.1** MANUFACTURING
>
> A series of interrelated activities and operations involving the design, materials selection, planning, manufacturing production, quality assurance, management and marketing of the products of the manufacturing industries.

In other words, manufacturing here refers to *all* the activities needed to put a product on the market. Although the areas of input and output are far wider than that of manufacturing by the traditional definition, the process is structurally similar to manufacturing in its traditional sense, only involving far more activities and business processes.

All these activities need to be performed both *effectively* and *efficiently*, an overall guiding principle that will be frequently mentioned in this thesis. Here, effectively relates to *doing the right things* whereas efficiently is to be understood as *doing things right*. This mirrors the understanding of strategic and operational views on business processes.

The "products of the manufacturing industries" in the above definition are known as *goods* and *services*. Goods are *tangible* – such as cars, computers, and television sets – and services are *intangible* – such as repair, technical support, broadcasting, etc.

Goods, the focus of this thesis, are broadly divided into *capital goods* and *consumption goods*.[62] Capital goods are used to produce other goods – such as commercial aircraft, machine tools, and trucks – and consumption (or consumer) goods are goods that are bought by households – such as cars, consumer electronics, and furniture – although several product types comprise both categories (Parkin et al., 1997; Wu, 1994). Consumption goods are further divided into *durable* consumption goods – products usually expected to last three years or more, such as refrigerators and bottle openers – and *non-durable* consumption goods – such as cheese and wine. This classification of products is shown in Figure 1. Sometimes, the terms "product" and "goods" are used with the same meaning – to denote tangible products.

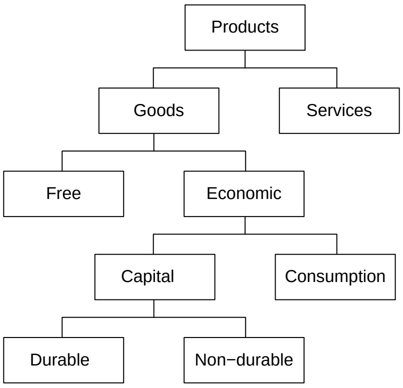

Figure 1 *A classification of products.*

Looking at *how* goods are produced, manufacturing can be classified as either *discrete-parts manufacturing* or *continuous processing.* Discrete-parts manufacturing is characterized by the making of individual parts that are clearly distinguishable, such as engine cylinders and screws; that is, what we normally think of as goods. Process industries produce continuously flowing products, such as oil and chemicals. However, these two manufacturing types occasionally overlap; for example, mass production of discrete parts shares many characteristics of process industries (Parkin et al., 1997). This thesis is written from the perspective of discrete-parts manufacturing.

Manufacturing can further be characterized as a *secondary* industry, as it processes raw materials supplied by the *primary* industry – agriculture, forestry, mining, and so on – into finished goods (Wu, 1994). Of course, there are innumerable such inputs and outputs within the manufacturing industry itself. As Wu exemplifies, the automotive industry uses as its inputs steel, rubber products, and machine tools, which are all secondary industry outputs. In the late 19th century the understanding of production was widened to include services, such as transportation, sales,trade, etc. With this terminology, the production of services is referred to as the *tertiary* industry.

What, then, is the purpose of all this? As Askin and Standridge (1993, p. 3) state:

> The purpose of manufacturing, at least idealistically, is to enrich society through the production of functionally desirable, aesthetically pleasing, environmentally safe, economically affordable, highly reliable, top-quality products.

We thus see that if manufacturing is at the heart of a nation's economy, *production* is at the heart of manufacturing. Before we move on to explore the concept of production further, however, we can take another view on manufacturing. Obviuosly, there is a need for a set of supporting activities of some sort, if the purpose of manufacturing is to be fulfilled. Here, Hitomi (1996) defines three kinds of *flows* that support effective manufacturing:

1. material flow,
2. information flow
3. cost flow.

These are shown in Figure 2. Hence, it can be said that material, information, and cost flow through all the business processes that make up the manufacturing enterprise.

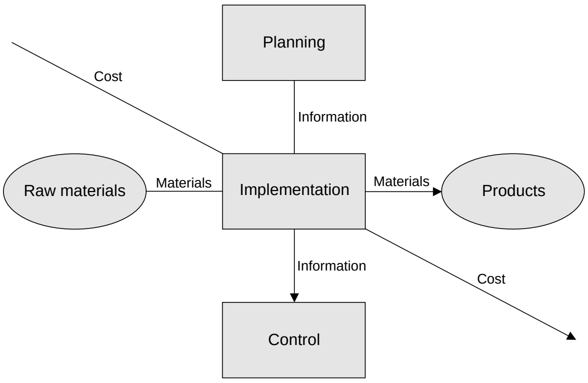

Figure 2 *Three supporting flows in manufacturing. Source: Hitomi (1996, p. 6).*

Seeing as all these flows relate to production, it is time to move on to the next section, which will also explain the nature of these relationships.

2 Production Defined

Production can be considered an input-output system, which through a series of activities[63] converts *resources of production* (land, labor, materials, equipment, money, and information)[64] into economic goods, thereby creating utilities[65] (Hitomi, 1996, p. 7). A formal definition based on Parkin et al. (1997, p. 46) and Hitomi (p. 14) can therefore be stated as:

Definition A.2 PRODUCTION

> The conversion of resources of production into goods and services, in particular raw materials into tangible products.

In this sense, production is to be seen as the very core of manufacturing. All other activities carried out by a manufacturing enterprise are done to support production. Conversely, the three supporting flows in manufacturing must also strongly relate to production. With this perspective, we can say that the material flow corresponds to the *production and logistics process*[66] itself, flowing from procurement to distribution, as shown in Figure 3.

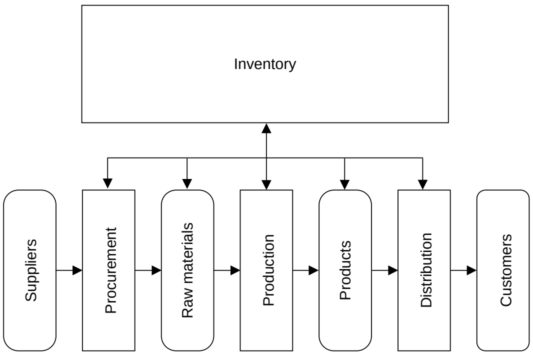

Figure 3 *Flow of material through typical production stages. Based on Hitomi (1996, Figure 1.2, p. 7).*

The information flow is handled by the *management function*, which conducts planning – the selection of the future course of action – and control.[67] According to the resulting plan, it is then *production* that executes practical activities to make products in a workshop, also referred to as *implementation* of the plan or schedule. Control is then the measurement and correction of the performance of these activities to ensure that management objectives are met (Hitomi, 1996).

The cost flow corresponds to the value-adding activities in the production process, i.e. the transformation of raw materials.

Out of these three, Hitomi stresses that the information flow is the driving force since it generates the flows of materials and cost, based on market needs. When these three flows work together, synergistic effects are realized that ensure high quality, low cost, and just-in-time deliveries.

Production operations can be further classified as being generally of either a *fabrication* or *assembly* nature, where fabrication (or parts manufacturing) refers to the removal of material from the raw stock or a change in its form for the purpose of obtaining a more useful form, and assembly refers to the combination of separate parts or raw stock to produce a more valuable combined unit (Askin and Standridge, 1993). More formally, we adopt the following definitions from Askin and Standridge (p. 5) and the CIRP Technical Scientific Committee (1990) respectively:

Definition A.3 FABRICATION

The removal of material from the raw stock or a change in its form for the purpose of obtaining a more useful form.

Definition A.4 ASSEMBLY

The combination of parts into composite structures; final products or subassemblies.

Notes for Chapter A

[60] The distinctions of process vs. content and problem vs. project are explained by Pidd (1998, p.25-28)

[61] It should be noted, however, that since manufacturing etymologically means *made by hand* and production means *lead forward*, it can be argued that for semantic reasons the understanding of manufacturing should be in the narrower sense and the understanding of production should be in the wider sense, i.e. contrary to the herein used definitions. The remainder of this dicussion, however, is left to the reader.

[62] Although manufacturing and production implies the distinction of tangible goods (products) as opposed to intangible (services), economists prefer the distinction of *free goods* and *economic goods*. Free goods are available in unlimited quantities at no cost, such as air and river water, and hence, need not be produced. Economic goods, on the other hand, need to be produced at a required time and place with expenditure, and are thus affected by scarcity (Hitomi, 1996).

[63] Production activities are also referred to as *production stages*.

[64] In macro economics, resources (also known as means or factors) of production are traditionally classified into land, labor, and capital. However, as Hitomi (1996) observes, this classification is not so suitable for analyzing production processes on a micro level, and proposes the following four categories as essential in a manufacturing system context: (i) production objects, (ii) production means, (iii) productive labor, and (iv) productive information. These categories are then further decomposed. See Hitomi (1996, pp. 9-11) for a more detailed account of these.

[65] Economically, utility is an index expressing the degree of satisfaction of a human want (Hitomi, 1996, p. 4).

[66] The production process is usually referred to as just *process*.

[67] Planning is sometimes referred to as *scheduling*, although the result of these activities – the *plan* and the *schedule* respectively – differ in their level of aggregation. It is therefore more correct to refer to these activities as *planning and scheduling*. This difference is further explained in Section 6.3.

B

World Views

World views, also known as *formal approaches* or *formalisms* are perhaps not always clearly and succinctly explained in simulation literature, yet they are fundamental to any simulation study. [68]

Here, Page (1994) offers one of the best explanations of world views:

> …many errors seem to arise as a result of a poor mesh between the models of problems as they form in the mind of a modeler and the representational capabilities provided by extant programming languages and techniques…The developers of simulation programming languages sought to close this conceptual distance through the provision of a *conceptual framework* (or “world view”) within the language. This provides the modeler with a means to construct a mental picture of the model.

Several world views exist. For example, Derrick (1988) classifies thirteen world views,[69] and identifies both positive and negative aspects of their influence on model representation. However, the following world views are to be seen as primary, and are conversely the most commonly encountered on in the simulation world:

1. Event-scheduling
2. Activity-scanning
3. Process-interaction

The principal differences of these world views are related to the different ways in which the behavior of a system can be modeled, or in other words, the different perspectives on system representation provided through varying *localities* (Page, 1994), namely those of:

1. **time**: the times at which things "happen" = event-scheduling,
2. **state**: a state precondition on the occurence of something happening = activity-scanning, and
3. **object**: the ordered sequence of actions performed on (or by) a given model object = process-interaction.

1 Event-Scheduling

Event-scheduling represents the first way simulations were developed, and was commonly used from the 1960s to the 1980s, partly because it was embedded within SIMSCRIPT, a widely used simulation language at the time (Pidd, 1998). It is based on moving the simulation along the time scale until an event occurs, update the system state, schedule new events, move on to the next event, and so on.

2 Activity-Scanning

Activity-scanning is closely related to event-scheduling, with the subtle difference that it allows *conditional activities* (also known as conditional events), i.e. activities that are not triggered by other activities but rather occur as the result of two or more conditions being satisfied. According to Trick (1996), this approach is the simplest to think about and formalize. Its main disadvantage is inefficiency, since the simulator has to keep scanning for the conditional activities. Although the disadvantages outweigh the advantages, Trick predicts that artificial intelligence and rule based systems (e.g. neural networks) will make this approach more viable. According to Banks (2000), however, modeling inaccuracies may occur with this approach, because discrete time slices must be specified. If the time slice is too wide, detail is lost. Banks predicts that this type of simulation will become less popular with increased computing power and decreased computing costs. [70]

3 Process-Interaction

Process-interaction differs from the two previous approaches in that it provides tools for the user to define system components and set their parameters, rather than thinking in terms of events. Thus, from the modeler point of view, events have no meaning; the system is modeled using basic building blocks which are then logically connected. From the simulator point of view, however, the model works the same way as with the event-scheduling approach: events are scheduled, the system state is updated, and the time is moved to the next event. Several authors agree that this approach has the most intuitive appeal (Banks, 2000; Trick, 1996).

As Pidd (1998, p.77) explains, however, “each [...] approach implies its own unique form of simulation executive and each requires the model logic to be expressed in a different way”. Conversely, the theoretical break-down of world views is mirrored by commercially available simulation software. As an example, the two 3-D packages AutoMod and Quest both take the process-interaction view. However, which approach a given software package takes is not always easy to see.

4 Summary

So how does one choose which world view to adopt?

As argued by Zeigler (1995, p.4), “no one formalism is best to represent the variety of behaviors in real systems of interest. [...] indeed, the same real system may be a variety of related models, expressed in different formalisms“. Acccording to Zeigler, influencing factors include the domain of application, the modeling objectives, and the level of abstraction.

Wainer and Giambiasi (2001, p.23) argue that “the formal specifications should be able to be translated into an executable model. In this way, the behavior of a conceptual model can be validated against the real system, and the response of the executable model can be verified against the conceptual specification”.

Page (1994), observing that using one particular world view for all cases may have drawbacks, states that, “the tendency to use the language best known by the modeler often results in a contrived "fitting" of the natural model description into the form provided by the SPL, serving only to recreate the original impedance problem once removed”. Here, Derrick (1988) argues that it is important to identify the need to *select* a world view suitable for a particular model and a given set of objectives.

In summary, several authors seem to agree that no one world view is universally correct. As Michel de Montaigne observed, “there never were in the world two opinions alike, no more than two hairs or two grains; the most universal quality is diversity”.

The reader is referred to Page (1994) and Pidd (1998) for a more detailed exposition of different world views.

Notes for Chapter B

[68] World views go under several different names and are also known in literature as *modeling structures*, *modeling methods*, *simulation approaches*, *conceptual frameworks*, and *weltansicht*. Here, the term “world view” is adopted.

[69] Derrick (1988) uses the term "conceptual framework" instead of world view.

[70] Activity-scanning is also known as the *two-phase approach*. In this context, there is a similar approach known as the *three-phase method*, which differs from the two-phase approach in its time-handling. According to some authors, most notably Banks (2000) and Pidd (1998), the three-phase method is to be seen as one of the four major world views present in the simulation community, the other three being the previously mentioned. However, the inaccuracy problems apply to this method as well (Banks, 2000).

Take us out of orbit, Mr Sulu. Ahead, warp factor one.