Manufacturing Logistics Research: Taxonomy and Directions

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MANUFACTURING LOGISTICS RESEARCH: TAXONOMY AND DIRECTIONS

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Abstract

In this paper, we examine research directions in manufacturing logistics based on recommendations from an NSF sponsored workshop, and subsequent efforts by the authors to synthesize, extract and revitalize the vision formed in the workshop. To convey this vision we suggest a taxonomy that characterizes research problems in manufacturing logistics by the physical entities (*systems*) involved, the level-of-abstraction, the focus, and the type of decision (*decision scope*) intended, and the broader business context (*business environment*) of which the research can be justified. A main goal of the paper is to envision a broader and richer research base in manufacturing logistics through the explicit consideration of business contexts and technological trends. We argue that these renewed directions for manufacturing logistics research offer opportunities for the OR/MS professionals to exert influence on corporate decision making, and to make direct impact on software innovation.

1. Introduction

Manufacturing Logistics refers to all planning, coordination and service functions required to carry out manufacturing activities. The temporal scope of manufacturing logistics begins from the point where end-item customer demands are determined, and extends to the point where the demands are fulfilled. In this process, the flow of material, information, and service may move across enterprise, industry and national boundaries. Coordinating the complex variety of activities in this environment poses significant challenges to manufacturing enterprises. While manufacturing logistics can be viewed as an academic research area encompassing many aspects of operations management and developments in supply chain logistics, it can be also viewed as a domain of ever evolving industry problems that are driven by technological innovations and the global economy. It is this latter view that we set out to explore in this paper. We believe this area of research represents unique opportunities for OR/MS professionals to make significant impact and to exert influence on software innovation and corporate decision making.

Even though manufacturing productivity has been a subject of extensive study, most existing research is still encased within the context of domestic, single facility scenarios assuming information technologies and data collection capabilities of the past. While these efforts have contributed significantly to the methodological base in manufacturing decision making, they seldom consider the multi-facility, multi-national context of current business environments, nor do they address the information, software and organizational structures that form the implementation context of these methodologies. A major goal of this paper is to envision a broader and richer research base in manufacturing logistics through the explicit consideration of business contexts and next-generation information technology.

In 1997, a workshop sponsored by NSF on Manufacturing Logistics was held at Lehigh University in Bethlehem, Pennsylvania. Over 100 researchers from universities and industry attended the workshop. After lively discussion and many debates, a research agenda for Manufacturing Logistics evolved. The research results are summarized in a report (Wu et al, 1997) to NSF, along with poster sessions and conference presentations made at various professional meetings. The recommendations from the workshop form the basis for new research initiatives sponsored by NSF. This paper documents an attempt subsequent to the meeting to synthesize, extract and revitalize the vision formed during the workshop. A main outcome is an informal taxonomy of manufacturing logistics research, which offers a vision that helps to discern the roots as well as future directions for this vast area. Unique to this taxonomy is its industry view of topics and dimensions that are perceived as vital in the coming decades. Segments of this taxonomy were offered to us by active researchers and practitioners from industry. Using the taxonomy as a guide, we try to fuse industry and academic while attempting to define a continuum that bridges past and future research efforts.

The motivations for an organized effort to identify research directions are three folds. First, as Bill Maxwell (recently retired from Cornell) commented during the workshop, this is a critical time for the OR/MS profession to get involved in an area that is at the brink of fundamental changes and innovations. The advances in computing and information technology exacerbate the pace and scale of these changes. Second, the National Science Foundation has recognized the critical importance of this area, and major research funding has been committed to support efforts in this and related areas. Third, in order for the OR/MS community to gather momentum and leverage its influence, some shared vision of future directions is of critical importance. Nevertheless, we recognize the existence of differing opinion on what manufacturing logistics is, or should be. We do not argue that our point of view is more compelling, rather, we seek to a forward step in defining a domain of research problems that we believe to have broad based support among researchers and strong relevance to industry.

2. *Manufacturing Logistics: Definitions, Scope and Key Elements*

We offer two perspectives of manufacturing logistics – the *primary domain* and the *essential context*. We focus on research opportunities in the primary domain that address issues within the essential context. These application contexts must be better understood and carefully considered when undertaking substantial research within the primary domain.

The Primary Domain of Manufacturing Logistics: Manufacturing Logistics addresses opportunities and problems whose primary focus falls within a given scope. These opportunities either involve a set of key logistic activities or support the deployment of a set of key resources that support manufacturing activities. The scope of manufacturing logistics begins at the point where end-item customer demands are determined, and extends to the point where they are fulfilled. A narrow and more traditional view of manufacturing logistics includes the planning, scheduling and control of all activities resulting in the acquisition, processing, movement and storage of inventory. These activities include order acceptance, production planning and scheduling, inventory control, inventory distribution, and the design of the corresponding decision processes and decision support systems. A broader view of manufacturing logistics considers the flow of material, information, and services across enterprise, industry and national boundaries. Coordinating these complex activities may require integration of multiple facilities and firms, integration of manufacturing and service functions including sales, marketing, and information technology, and integration with traditional logistics functions such as transportation, warehousing and distribution. While research topics falling into the narrower view of manufacturing logistics have been studied intensively, many issues involved in the broader view are still not well understood.

The Essential Context of Manufacturing Logistics: Substantial contributions to manufacturing logistics must address, or at a minimum be compatible with, important aspects of the business environment. These aspects include, for instance, various sources of uncertainty, ambiguity, and inaccurate information in the application domains, restrictions imposed by legacy systems and organizational structures, issues raised by new business paradigms such as electronic commerce, the effects of product and technology life-cycles, outsourcing opportunities and strategic alliances, and the firm's long term strategic directions. The essential business context of manufacturing logistics is a dimension that is ever evolving over time. Technological innovations, business alliances, and global competitive positioning can all have significant influence on the essential context of manufacturing logistics.

3. Current Issues and Problems in Manufacturing Logistics

The first step toward defining future research directions in manufacturing logistics is to assess the current state of the art and to identify underpinning issues of current problems. Not surprisingly, this subject triggered heated discussion during and after the workshop. Nonetheless, after some effort to decipher and combine different points of view, a few general themes emerged. In the following, we summarize these general themes, as we believe they capture the essence of general concerns in the research community.

Uncertainty and Variability

The need to better deal with uncertainty in manufacturing logistics problems is a theme widely accepted by researchers. Failure to account for the effects of uncertainty is seen as a significant inhibitor in the use of research results in practice. While notable progress has been made to include uncertainty in modeling and analysis, much work remain to be done. Not only do the current models impose serious computational challenges for practical problems, the notion of uncertainly tends to be narrowly defined. The need to generalize uncertainty beyond *variability* should be recognized. Sources of uncertainty present in practice may include missing, incorrect, and superfluous data, vague or incomplete definitions, and ambiguity caused by human behavior. The importance of uncertainty as an issue in manufacturing logistics should continue to grow as a result of shorter product life cycles, reductions in inventory, and shortening market response time.

As a visible example in the business context, ERP and other corporate information and planning systems seldom incorporate mechanism to consider variance or other information on randomness. While uncertainty is universally recognized as a complicating factor for planners and schedulers, seldom do planning and scheduling systems support non-deterministic views of data. Current ERP systems often boast how frequently and quickly they can update the deterministic view of the enterprise system. Nevertheless, frequent updates often create more problems then they solve. Issues related to multiple production releases, planning stability, and the "bullwhip" effect are just a few examples. Incorporating uncertainty in planning is not only a technical challenge, but also a philosophical one. Until corporate decision makers start to understand the implication of uncertainty, buy into the notion of uncertainty modeling, and incorporate it in their data collection practice, research in this area is unlikely to have much impact. As it stands, there are substantial cultural, conceptual, educational and computational obstacles to the incorporation of uncertainty within enterprise planning.

Human Behavior

The role of human behavior within manufacturing logistics systems is another significant issue. While both industry practitioners and academic researchers recognize the importance of people within a system, there is virtually no literature in manufacturing logistics addressing these issues. Most participants agreed that humans will remain key factors, and that research in system design, and decision making must recognize this important dimension. It has been cited repeatedly that middle management often spends a significant fraction of its time dealing with people issues ranging from variability and inconsistency rooted in human behavior, to issues related to incentives, union regulations, and team dynamics. Typical OR/MS models do not address issues of human behavior. Game theoretic models attempt to capture a certain essence of human behavior under various rationality assumptions. However, in order for planning or decision models to capture the dynamics of a system primarily run by human beings, consideration of different aspects of human behavior is a crucial and challenging task.

Globalization

The emergence of the European Union and Asian Pacific economic alliance has brought the issue of global logistics to the forefront of development in all major corporations. Globalization plays a significant role in manufacturing logistics since it presents new opportunities and at the same time poses serious threats and instability to logistics operations. Multi-national logistics considerations involve such issues as currency valuation, labor force capabilities, tax laws, international treaties and trade agreements, engineering practices and business conventions, environmental and union regulations, etc. Due to scale and complexity, global logistics considerations have not been broadly incorporated in OR/MS models. However, it is recognized that globalization is fast emerging as the norm of all major corporations thus related issues must be addressed and incorporated.

Limitations of Current Information Systems

Dissatisfaction with current information and software systems was a general theme expressed during the workshop. It is worth noting that both academic and industrial researchers shared this view. With regard to manufacturing logistics software, a "tail wagging the dog" scenario was recognized. In many cases fundamental organizational changes must take place in order to fit the scheme of the information system. Oftentimes the effort involved in installing enterprise resource planning (ERP) software is referred to by one participant as a "corporate root cannel." Not only is this a painful and costly endeavor, it has been difficult to document quantitative evidence of productivity or profitability improvement from new IT implementations. Worse yet, without widely adopted standards and built in scalability and flexibility, these systems pose major problems when asked to inter-operate with peer systems. IT incompatibility often becomes the roadblock for business alliances, organizational integration, and in some cases, long-term expansion. While IT issues pose significant problems in the business world, they also presents a significant opportunity for manufacturing logistics research. As will be discussed in further depth later in the paper, the committed resources and built-in structure of IT in corporations provides an opportunity for manufacturing logistics researchers to make impacts at a level and scale that was previously unimaginable.

Data Overload and Bad Data

A problem related to current information systems is that they generate an overwhelming volume of data that is immensely complex. Along with the large volume is the inevitable problem of inconsistent, erroneous and misinterpreted data. Companies are often awash in data and yet out of control with respect to data integrity. Most current production information systems operate on ERP concepts. In such environments, a large amount of data must be kept track of, maintained and manipulated. Bad data (out-of-date, or erroneous data) can trickle-down and cause significant discrepancies in decision making. The ultimate effect is that the information system loses credibility among users and becomes the scapegoat for inefficiency and waste. It is often heard in corporate environments that the information provided by the information system is "20% off 80% of the time." Decision-makers are forced to *compensate* for such perceived inaccuracy. By doing so these systems create instability problems as exemplified by the beer game or the bullwhip effects. The majority of research in manufacturing logistics not only relies on, but thrives on data, thus issues of data management and model robustness are both of significant importance.

Product Proliferation and Shortening Life Cycles

As companies continue developing new products to penetrate new markets, shortening product development cycles aimed at maximizing market advantages, product proliferation and shortening product life cycles result. Compounding this effect are the accelerated technological advances and the rate of innovations. Electronics, computer and semiconductor products, for instance, have an average product life cycle shorter than 18 months. With a relatively long production lead-time for these products (most semiconductor products have an average production lead-time of 16 weeks), there is little margin for error. The shortening product life-cycle complicates manufacturing operations significantly. Since most products never reach "steady-state" production, facilities must accommodate new products and processes while phasing out old products. This phenomenon makes operational efficiency a constant challenge. Product proliferation is another significant change in the market place. As product variety increases while volume decreases, setup time and setup cost both become a more significant issues, and producing efficient production schedules become more difficult. Process consolidation, design alternation, flexible layout configurations, and other approaches are among the steps taken to address these problems.

Misaligned Decisions and Performance Measures

In the industrial environment, it is common to observe a poor alignment of decisions made at different levels and/or locations. Similarly, the measures of performance used at different levels and locations can be misaligned, causing significant disconnects and inefficiency. For example, an MRP system may generate stacks of schedules daily only to find that the shop floor doesn't implement them. The corporate planning team may spend major resources conducting market analysis and demand forecasting, only to find that the operations managers trust only their own gut instincts. While the problem is partially due to the design and the data accuracy of the information system, these misaligned decisions may have deeper roots in corporate decision structure, incentive schemes and system legacy. System wide metrics and better-coordinated decisions will no doubt improve performance. However, this is a problem of significant difficulty especially when the structure and size of enterprises reach a certain level of complexity.

4. Dimensions of Research in Manufacturing Logistics- An Informal Taxonomy

In this section, we propose an informal taxonomy of manufacturing logistics research. This taxonomy provides a basis that helps us to understand the roots of this vast research area and offers a vision for new research directions motivated by long-term industry needs. In the section that follows, we describe specific research topics brought forward during the workshop in the context defined by the taxonomy. Figure 1 summarizes the main aspects of manufacturing logistics research in a three-dimensional space. The three main dimensions are *systems, decision scopes*, and *business environments*. Given the three main dimensions, we may categorize manufacturing logistics research using the nomenclature:

System | Decision Scope | Business Environment

In the following, each of the three dimensions is defined.

4.1 System

This dimension specifies different levels of physical entities in a manufacturing environment. We identity four levels of manufacturing logistics systems as follows:

Production Unit (PU): A basic production unit may be a production line, a job shop, a flexible manufacturing cell, or other operational unit that is considered the basic production entity of the manufacturing system. Primary logistics issues of consideration at this level may include *labor, product* and *physical processes*. This is an area of concentration for much existing research. Much finer categorization is clearly possible.

Plant (P): A plant is a manufacturing system that consists of a collection of production units. The definition of a plant assumes a certain means of integration that defines the dependencies across production units. This integration could be vertical by corporate organization, or horizontal by products, or a combination of both. From the viewpoint of manufacturing logistics research, issues at the plant level focus on *inter* production unit problems concerning *people, products*, and *information.*

Enterprise (E): An enterprise is a business entity that consists of multiple manufacturing plants as well as other aspects of the business such as design, engineering, marketing, and sales. Manufacturing logistics at the enterprise level concerns *inter* plant issues corresponding to *products, capacity* and *information*. A significant issue at this level is the interface between manufacturing and other functional areas of the business. Modern Enterprise Resource Planning (ERP) systems capture the most significant essence of practical logistics problems at this level.

Supply Chain (SC): From the viewpoint of manufacturing logistics, a supply chain is a dynamic collection of manufacturing, service and distribution enterprises organized loosely within different industries. The composition and key players in a supply chain are typically alliances formed over time while changing over time. For manufacturing logistics research, the supply chain perspective brings into focus significant and fruitful topics related to *products, information* and *transportation/distribution*.

4.2 Decision Scope

A significant part of manufacturing logistics research is about making sound decisions. We use decision scope as a dimension in the taxonomy that distinguishes different levels of abstraction and focus for decision making. We propose four levels of decision scope with ascending degree of specificity as follows:

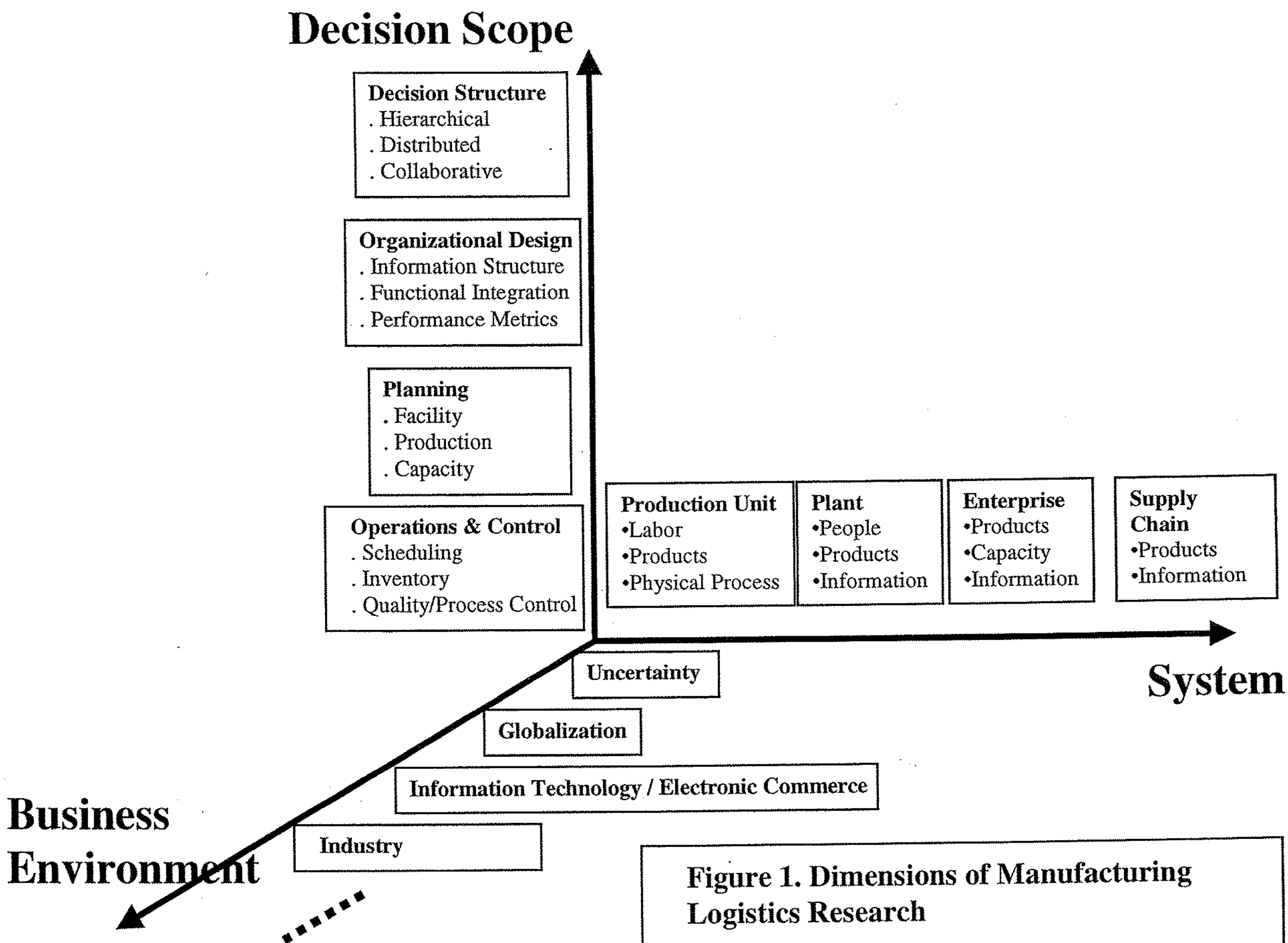

Figure 1. Dimensions of Manufacturing Logistics Research

Operations and Control (OC): This corresponds to short to medium term decisions that have direct impact to various aspects of production operations. Primary decisions at this level include *scheduling, inventory* and *quality and process control* decisions.

Planning (PN): This corresponds to medium to long term decisions that affect the overall prospect or the design of the operations. Primary decisions at this level include *facility planning, production planning* and *capacity management.*

Organizational Design (OD): This corresponds to the fundamental business processes that dictate the mode of integration, evaluation, and information sharing across different organizational entities. Primary decisions at this level include *information structure, functional integration*, and *performance metrics*. The principal-agent theory, for instance, had a profound impact on the design of business processes and organizational structures.

Decision Structure (DS): This corresponds to the fundamental structure that drives decisions and business processes. In addition to the widely used *hierarchical* decision structure, *decentralized, distributed, and collaborative* decision structures may be subjects of research and discovery. A decision structure makes explicit assumptions on the nature of information sharing, incentive structure, and systems goals or equilibrium conditions.

4.3 Business Environment

This dimension identifies the broader business context of manufacturing logistics research. Unique to this dimension is the fact that its essential components can not be enumerated (they evolve and change over time) but they set the stage for all problems described in the first two dimensions. In the following, we list a few important components that drive the business environment. However, it should be made clear that this list is never complete.

Uncertainty: Real systems contain various sources of uncertainty, most of which significantly affect our ability to model, compute and make decisions. The view of uncertainty needs to be generalized beyond the traditional notion of variability. Sources of uncertainty may include missing, incorrect, and superfluous data, vague or incomplete definitions, and human behavior. Uncertainty is among the most critical elements of the business environment, and requires significant attention by manufacturing logistics research. Its importance grows with the need for modeling complex systems with increased product proliferation, shorter product life cycle, and reduction in inventory.

Globalization: Globalization is another significant element of the business environment that deserves attention in manufacturing logistics research. As discussed earlier, globalization presents new opportunities and at the same time poses serious threats and instability to logistics operations. As a research dimension, globalization sets the stage for such issues as currency valuation, labor force capabilities, tax laws, engineering practices and business conventions, environmental and union regulations, etc. Globalization also provides incentives to integrate diverse information and supply chain logistics systems.

Information Technology and Electronic Commerce: Next generation information technology in the context of electronic commerce presents one of the most profound changes in business environment. Electronic commerce redefines business paradigms and potentially changes the very nature of business processes. As suggested in a recent NSF workshop, electronic commerce presents significant issues for supply chain logistics due to the tight electronic integration of supply chain subsystems. This results in issues such as interdependency and complexity, data overload and information starvation, legacy systems and interoperability, among others.

Industry Convention: Every industry develops over time its own unique conventions and business paradigms. For instance, the automotive industry and the electronics industry operate under significantly different conventions and therefore present different logistics issues in their corresponding business environments. The logistics issues become even more complicated when these industries need to coordinate in different tiers of a supply chain.

Environmental Considerations: Varying by industry, environmental issues could play a dominant role in manufacturing logistics research. Issues related to environmentally conscious manufacturing, recycling, demanufacturing, and environmental regulations present issues and topics that have been greatly ignored in the manufacturing logistics literature.

4.4 Characterizing Manufacturing Logistics Research

With the three basic dimensions of system, decision scope and business environment, we may characterize manufacturing logistics research using the familiar notation $\alpha|\beta|\gamma$, respectively. In the following, we provide examples on how the notation is used to describe the main essence of a research effort.

Example 1.
(Enterprise, Information: production releases in multi-tier ERP systems |
Planning, Production: multi-period, multi-item scheduling |
Uncertainty: demand, capacity; Industry Convention: automotive)
describes a research project that investigates the effect of multiple order-releases in automotive firms when demands and plant capacity are uncertain. In a broader scale, this research project belongs to the category ***(E|PN|Uncertainty,_).***

Example 2.
(Plant, Products: resource allocation over product lines | Decision Structure, Distributed: auction and bidding | Electronic Commerce, Industry Convention: just-in-time delivery)
may describe the study of a distributed resource allocation structure for production lines where customer orders are processed through EDI under the restrictions of just-in-time delivery. This line of research is under the broader category of ***(P|DS|Electronic Commerce,_).***

Example 3.
(Supply Chain, Products: IC | Operations & Control, Scheduling: production scheduling, inter-continent transportation | Globalization: currency exchange rates; Uncertainty: demand, travel time)

may be used to describe the study of a supply chain operations problems in semiconductor manufacturing, where the front-end wafer production and back-end packaging are performed in different parts of the world. Here the problem of production scheduling is coupled with inter-continental transportation and exchange rate fluctuations. Sources of uncertainty may include end-item demand and travel time. This line of research is under the broad category of ***(SC|OC|Globalization,_)***

It is important to recognize that the structure introduced in this taxonomy provides a problem-, rather than methodology-, oriented characterization of manufacturing logistics research. We argue that the particular way researchers choose to view their domain of research has direct impact on how research progresses over time. While a methodological view of manufacturing logistics research may paint a very different picture, a problem-oriented view shows that past research in this area is highly concentrated on the lower left quadrant of the three-dimensional space. Using the established taxonomy, we may find that ***(PU|OC|_)***, ***(PU|P|_)*** dominate much of the research in operations management, while ***(P|OC|_)***, ***(P|P|_)*** has attracted more attention in the past decade. It is interesting to note that most emerging research topics in manufacturing logistics lie along the 45° line extrapolated from the lower left quadrant. This suggests an emerging trend for research larger in scale while broader in scope. Note also that broader scope research topics in organizational design and decision structure can be (or should be) examined across systems of different scales. For instance, a new operational control structure for manufacturing cells may be categorized as ***(PU|OC|_)***, so long as it can be implemented within the existing organizational and decision structures. However, more typically, a fundamental change in operational control is the result of business process reengineering or organizational changes. In this case, the research must be put into the broader context of ***(PU|OD|_)*** or ***(PU|DS|_)***, since the information structure, performance metrics, and basic mode of decisions (e.g., hierarchical vs. flat) may require fundamental changes as well. Ignoring these broader implications in problem context may lead to many undesirable outcomes: the research results never get used, or the entire research domain is refined to the role defined in existing practices. In the latter case, the research area becomes stagnant, innovation stifled, and the area regresses into a pattern of repetition.

The addition of the third, business environment dimension is a critical one, which provides the focus needed to address problems of real concern and added complexity. Since the business dimension is defined in a discrete, topical manner along the third axis, it can be viewed as a list of critical elements used to define the particular research perspective. Uncertainty, for instance, is an aspect of the business environment that has attracted a great deal of attention in the modeling community. The recognition of various sources of uncertainty such as demand and capacity enrich manufacturing logistics research beyond adding a few random variables in the mathematical model. It provides a generalized view of the problem context and therefore motivates more accurate and better-justified decision models. Following along this dimension, it is not difficult to see that various aspects of the business environment, such as the ones listed above, provide fruitful and rich research opportunities. For instance, research in the areas defined by ***(E|_|Globalization)*** or ***(SC|_|Electronic Commerce)*** present tremendous opportunities for research in manufacturing logistics.

It is also important to recognize that a problem-oriented categorization does not necessarily promote an application-oriented research agenda. On the contrary, defining the research domain in a broader setting introduces richer grounds for theoretical exploration. Instead of making minor technical extensions from a one-dimensional methodological track, one may choose to define new niches and points of interests using one's own unique perspectives in the research domain.

5. Research Directions

In this section, we summarize a particular set of research subareas identified during the Manufacturing Logistics Workshop. These research directions are put into the perspective of previous work and future trends using the taxonomy established above.

5.1 Supply Chain Research (SC | _ | _)

Supply Chain Management has been one of the most vibrant areas of research and industrial innovation in manufacturing logistics in recent years. Viewed broadly, it encompasses a significant part of manufacturing logistics. From the viewpoint of the taxonomy, supply chain corresponds to a system level encompassing all others in manufacturing logistics research.

Recent and Future Innovation in Supply Chain Management

Many of the most commonly used models in supply chain management pre-date the advent of the "supply chain management" campaign. These include production planning models, stochastic inventory models and inventory distribution models, discrete event simulation, IP models for capacity management and facility location, forecasting models, and heuristic algorithms for job shop sequencing. In most cases, there is no significant innovation in the mathematical formulation of the models, but there have been remarkable advances the design of the software and in the manner in which it is being used.

In many ways it seems that innovation in supply chain management by the private sector has bypassed the academic research community. For example, the state of published research in production scheduling is inadequate for the size and complexity of industrial scheduling problems. Nonetheless, a myriad of finite-capacity scheduling packages are available in the market place, and solution optimality is of little concern. Similar statements can be made about models for optimizing supply chain design: global configurations of factories and warehouses, global stocking decisions, vehicle loading and vehicle routing problems, and production planning problems that incorporate integer variables. There is a clear need for software that has these and other vital capabilities, and research is needed to determine the best modeling and computational approaches to them. In order for academic research to have an impact in this innovation, researcher must pay close attention to the issues of concern.

There are other vital problems in supply chain management that have not been modeled and are not currently supported by models or by software, and are still unusual in corporate practice. For example, very early on in the product design process, decisions are made which have a dramatic impact on manufacturing logistics. Models are used to manage product variety and to evaluate design for manufacturability. In "best practice": company's manufacturing experts are an integral part of the design team from the start, and they bring manufacturing considerations to the table. However models that predict the impact of early product design decisions on the configuration and performance of the supply chain, that predict material flow and evaluate the impact of shared resources, are not available.

In the following, we offer three research themes related to supply chain management within the framework of manufacturing logistics research.

Modeling Supply Chain Decision Structures *(SC|DS|_)*

This research theme centers around the fundamental decision structure, therefore, the modeling paradigms for supply chain management. A unique aspect of supply chain decision making is the diverse decision entities involved in the process. With multiple companies and fiscal entities in the system, no longer can one assume that some centralized decision authority can impose a decision on all involved using some monolithic model. This phenomenon changes the basic premise of most existing decision models. The issues of centralized and hierarchical decision structures vs. decentralized or distributed decision making and control, are as important as ever. However, within the post-information-revolution context of supply chain management they are taking on new dimensions (strategic alliances, the virtual corporation, etc.). See the subsection titled "The Design of Decision Structures" below for further discussion.

Adding to the complexity of decision structure is that of timing. A compelling reason why supply chain research received the attention it has is that of shortening decision lead-time in the 1990's. One of the common phrases of the decade was "rapid response". Indeed, it is difficult to over-emphasize the strategic importance of time. Product design cycles, product life cycles, and inventory replenishment cycles are becoming markedly shorter with every passing year. Consequently the time available for analysis and evaluation is being compressed, and the margin for error is getting smaller. Most existing models that incorporate randomness view systems in their steady state, but it is becoming more and more important to model the transient behavior in a much more dynamic setting. The time element of decision making motivates the need for real time and dynamic decision structures. See the subsection titled "Real-Time Decision Making" for further details.

An important trend in the commercial software industry is that of functional expansion and integration. We have recently seen dramatic changes in the need and the ability to create seamless, rapid-response channels for the flow of information and materials between different corporate entities. Increasingly, under the umbrella of Enterprise

Resource Planning systems, this integration is taken farther to integrate planning and scheduling, maintenance, and quality management across different corporate entities. The globalization of the economy has created many new challenges and opportunities for decision modeling. Among them is the challenge of entering new and emerging markets efficiently and the elements of risk involved. Risk has taken on many new dimensions with the advent of global markets, including politics, unrest, currencies, local and global economies, legal remedies, and customer preferences. Along with these risks come opportunities to use the global structure of the company to ameliorate risk. In summary, the supply chain decision structure adopted by manufacturing enterprises has long lasting impact that warrant significant research effort.

Design of Supply Chain Logistics Networks *(SC|OD|_)*

This area concerns the selection, location and characterization of assets and services throughout the supply network. One of the most fundamental questions in supply chain design is the selection of performance metrics. There is both a large literature and a wealth of anecdotes on the fact that poorly selected performance metrics for individuals can have negative consequences for the system as a whole. The same is true of subsystems in a large supply chain. In spite of the attention devoted to these issues in both the past and the present, the real impact and long term implications of system performance metrics are not well understood. Throughout the design process there is a need to quickly evaluate the logistical impact of design decisions. This applies to product and process design, and to the design and prototyping of logistics and control systems. Usually much of the information needed to completely characterize the system is not available. The practical impact of supply chain evaluation tools is often driven more by the amount of effort required to set them up and use them, than by their accuracy. There is a need for easy-to-use modeling tools that capture the entire scope of the supply chain, that capture the effects of randomness, and that model material flow and shared resources.

Other aspects of organizational design such as information structure and functional integration define important aspects of supply chain design as well. We will leave this discussion to the section on "information technology and data management."

Planning and Control in a Supply Chain *(SC|P|_), (SC|OC|_)*

We now consider the planning, operations and control of supply chains. These topics represent continuations of existing research streams that we deem to be critically important. Traditional production planning models are not adequate to model supply chain operations that require coordination among multiple production facilities and transportation logistics services. For instance, the limitations of long-time-bucket LP and MRP models become increasingly apparent as lead-times within the supply chain continue to be compressed. The practical optimization of batching, setups and level scheduling in planning models still elude us even at a modest level of complexity. The advent of finite capacity scheduling systems has drawn attention to the importance of detailed scheduling, sequencing and batching in job shops and flow lines. Unfortunately, most of the published literature on these topics is limited to single-processor systems, or very small systems, and to static problems. High quality schedules to problems of industrial size and complexity is critical for supply chain coordination.

Demand management is a field of growing importance that has not received much attention in the published literature. Due-date quotation and order acceptance are increasingly being integrated into scheduling and planning functions. Customer orders are often aggregated for planning purposes and disaggregated later on. As the margin for error continues to get smaller, the aggregation and disaggregation techniques that have been used in the past are becoming an impediment to effective decision making.

5.2 Information Technology and Data Management (_,Information | _|_) (_|OD,Information Structure|_) (_|_|Electronic Commerce)

The advent of modern information systems and their data management subsystems have perhaps the most profound influence on manufacturing logistics research. Viewed from the research taxonomy, on the one hand *information* connects logistics system of all levels, and on the other it presents a critical element of organizational design. The recent emergence of electronic commerce adds yet another dimension to the significance of information technology, which could change in fundamental ways the business processes and operational paradigms. While the technological aspects of information systems are beyond the scope of manufacturing logistics research, studying the implications and opportunities presented by IT is close to the research core. IT is not only an important element of the business environment, but to a certain extent it *defines* the business environment. Of particular relevance and critical importance to manufacturing logistics research is the intensive data offered by the information infrastructure. The issue of data management is therefore an integral part of this research theme.

In the following, we offer two research themes related to information technology and data management within the framework of manufacturing logistics research.

Transition of Manufacturing Logistics Functions to Electronic Commerce
(_|OD,Information Structure|Electronic Commerce)

Electronic commerce refers to the use of electronic means to conduct business transactions within or across business entities. It has been predicted that, by the year 2000, nearly 80 percent of all Fortune 500 companies will be doing their core business using some form of electronic commerce. This research theme centers on the conceptual, theoretical, and methodological issues associated with this massive transition in the business world. The transition of manufacturing logistic activities to the realm of electronic commerce is unavoidable, and is among the most critical element of economic activities in the decades to come. To facilitate this transition, companies recognize the need to integrate their manufacturing and logistics functions to a much higher degree. While such integration potentially enhances coordination, without proper management it may create systems of immense complexity and interdependencies. Managing system complexity forms one core of this research theme. For a more extensive discussion of this research theme, see (Bai, 1999).

Data Management *(_,Information | _|_)*

Modern information systems create an unprecedented volume of data. A decade ago the obstacles in modeling manufacturing logistic systems were that of insufficient input data. The issues today are how to decipher massive amount of data, reconcile inconsistencies from different data sources, and provide correct interpretations. Before developing specific models of a system, there is a need to think through the role that data should play in the decision process that the model supports. When and what data is available with which level of accuracy could affect the mathematical formulation of a problem significantly. On the other hand, seemingly minor changes in the formulation can have drastic impacts on information requirements. Although this is an observation well known to OR/MS researchers, little research addresses these problems formally. Advances in information technology will push data management to the forefront of manufacturing logistics research. Issues concerning sensing, gathering, storing, transmitting, and interpreting of data should be an integral part of modeling and the development of solution methodologies. Many of the above issues are addressed by research in *data mining,* which is a relatively new and booming field. The applications of data mining to existing manufacturing logistics models seem to be growing much faster than research on new models that take advantage of new data management capabilities. More work in this area will be very fruitful.

5.3 Managing Uncertainties (_ | _ | Uncertainty)

We now turn to the another vast research area that is defined from the perspective of business environments. Random behavior, lack of essential information, incorrect data, and vague or incomplete definitions exemplify the general theme of uncertainty in manufacturing logistics. Uncertainty was cited as an undeniably crucial component of, and challenge to research in manufacturing logistics systems. It is likely universally accepted that uncertainty must be dealt with effectively in decision making. Failure to adequately address issues of uncertainty can render otherwise insightful research unusable. Indeed, methods for modeling and addressing uncertainty have been central to research in manufacturing logistics for decades. Examples are readily found in forecasting, queuing and inventory models, and simulation. Despite progress to date, it was generally conceded that the need remains for a great deal of further research in this area. In the following, we suggest three research themes related to managing uncertainty.

Uncertainty Modeling in Planning and Control (_|PN;OC|Uncertainty)

Uncertainty plays a crucial role in modeling planning and operations control problems in manufacturing logistics. Uncertainty can be classified as either randomness or ambiguity. For example, consider a new product whose manufacturing process will inherently create a certain percentage of defective parts. Initially we face both ambiguity and randomness – the random yield, and ambiguity about what will be the percentage of bad parts. The importance of modeling randomness in logistics systems is growing for a number of different reasons. In the current competitive environment, the ability to respond rapidly and reliably to changing market conditions is crucial. Tremendous efforts have been made to design products and systems in ways that reduce the role of randomness. At the same time changes are taking place that increase the impact of both randomness and ambiguity. For example, as product life cycles contract, the relevance of historical data is diminishing. This leads to ambiguity. Many models of logistics systems use discrete time buckets, and the coefficients of variation of the demand that occur in these time buckets are growing. Consequently, randomness has a greater impact in these models. One reason for this change is that shortened product life cycles create greater market volatility. Another reason is that rapid-response manufacturing systems tend to have shorter time buckets.

The differences between randomness and ambiguity have modeling implications. The literature contains many models that estimate and explicitly model randomness. In practice, sensitivity analysis is the most common approach to ambiguity. Approaches that mitigate the effects of ambiguity rather then simply understanding their impact are needed.

Designing Systems Robust to Uncertainty (_|DS;OD|Uncertainty)

Distinctively different from the modeling of planning and control uncertainty is the issue of robust system design. In large-scale application environments, it may be more effective to design systems that are robust to uncertainty than to build complex planning and control policies on poorly designed systems. However, few models attempt to understand the impact of randomness on large-scale system design, such as the case in supply chain design. Models of subsystems are much more common. Existing models that incorporate randomness usually use demand distributions with coefficients of variation that are much less than one. However, many logistics systems experience highly volatile behavior attributed to a complex mix of uncertainties much beyond that of end-item demand fluctuation. The well known bullwhip effect, for instance, describes an aspect of demand uncertainty primarily triggered by the *interpretation* of demand information within the supply chain.

The design of robust decision and organizational structures that addresses (or mitigates) the issue of uncertainty is a research problem of critical importance. Existing modeling paradigms need to be examined carefully against the true nature of real-world systems. For instance, probabilistic models usually analyze systems in steady state. This is often appropriate, but the transient behavior of logistics systems is gaining in importance. Several considerations are driving this trend. The time scales on which companies act and innovate are getting shorter, so systems are re-configured more frequently. Second, large-scale systems such as an automotive supply chain and or a semiconductor manufacturing system can take months to reach steady state. But the transient period is where risk is most prevalent and modeling is most needed. Finally, the periods of time in which new products are being brought to market and new markets are being opened up are crucially important in their own right, and they need to be studied directly.

Innovative Tools and Methodologies (_,_,Uncertainty)

Many models have been developed and used to support strategic, tactical and operational decisions. However, there is a shortage of *flexible tools* that are useful for design and analysis as well as planning and operation. To this end, the need to expand on the traditional "random variable" view of uncertainty must be recognized. While many phenomena certainly are appropriately modeled as random variables, the information necessary to build these probability models is often unavailable. Beyond this, there are important uncertainty phenomena which are either not amenable to probability theory, or which have not yet been well addressed. Included are the lack of essential information, incorrect data, vague or incomplete definitions, and the uncertainty inherent in systems involving human behavior. There may be significant research opportunities in the information and data management area for dealing with some of these latter uncertainty issues.

To deal with lack of information, incorrect data, and similar problems, an approach akin to "model reconciliation" has been suggested. The general theme involves building a model of physical reality (e.g. constraints, event sequences, etc. that *must* logically be obeyed), then reconciling current information with the model.

5.4 *Design of Decision Structures* (_ | **DS**| _)

There is a large literature on centralized vs. decentralized decision-making and control, and on hierarchical decision structures. In the manufacturing community, this debate continues to take on new dimensions as technology progresses. Although the current practice in material management is towards centralized control, the emergence of electronic commerce and global logistics points to an important future trend that constitutes decentralized, distributed multi-agent and collaborative decision making. A primary driving force is that of system complexity. As a manufacturing entity seeks coordination with their internal or external customers and suppliers, it is quickly confronted with difficulties associated with different operational conventions, locally specific constraints, conflicting objectives, and misaligned incentives. If some form of centralized coordination is to be formed, significant time and resources must be first devoted to reconcile these differences. However, as the level and the scope of coordination increase, the notion of centralized coordination breaks down at a point where the system complexity reaches its limit, and some form of decentralized coordination with local autonomy becomes inevitable. Hierarchical decision making has been suggested to cope with the system complexity through decomposition, aggregation and feedback mechanisms. However, most decision entities in manufacturing have their own unique perspectives and economic incentives. Rather than forcing all decision entities into some unified decision structure, it may be helpful to view them as autonomous agents acting on their own behalf. This is a fruitful direction of research that may lead to fundamental shifts of paradigm in manufacturing logistics.

5.5 *Design and Analysis of Real-Time Systems (_|OC, Real-Time Decisions|_)*

Real-time systems are decision support systems that continually collect data and make decisions in real time and at the last minute, based on the most up-to-date information available. For example, the routing and scheduling of delivery in a supply network can be pre-planned, or the decisions can be made at the last minute by a dynamic, on-line system, as a function of the current state of demand and of supply. Having access to the most up-to-date information is at least as important as having efficient routing and scheduling algorithms.

At lower levels of the *decision scope* dimension, automatic, real-time decision making is a reality. At the level of truck loading, vehicle routing and last minute re-routing, decisions are typically localized and simple, and information on the (local) system state is readily available. Real-time systems make decisions based on up-to-the-minute information on current system status, and thus are inherently advantageous in uncertain environments. Indeed real-time decision-making may be among the most powerful tools for dealing with uncertainty. To accomplish real-time decision making, it is necessary to have in place the necessary information and communications technologies that support a real-time system. Notable examples in logistics are on-board (the truck) personal data terminals and global position satellite systems which provide the information and communication infrastructure necessary to support real-time decision-making.

With real-time systems comes the danger of myopic decision making. To avoid this, continuous (as opposed to periodic) planning is required. Therefore, research issues surrounding the problem of *when* to make decisions arises, in addition to what the decisions should be.

As real-time operation and control systems proliferate, there will be pressure to push the concept higher yet in the decision scope dimension. As an example, periodic sourcing and capacity planning decisions may well become obsolete before the next decision time. However, the existence of real-time operation and control systems may make it *patently obvious* that these decisions are no longer valid, creating upward pressure in scope. This in turn may provide research challenges to new temporal decomposition approaches in manufacturing logistics.

The continued upward pressure for real-time decision-making at higher levels of decision scope presents many interesting research opportunities. We would be remiss not to point out the existence of real or near real-time decision systems at higher levels of decision scope. Examples exist in the retail sector where point of purchase data collection drives decisions along a supply chain. It is reasonable to assume that research aimed at pushing real-time decision-making upward in the *decision scope* dimension will provide significant research opportunities in the near future.

5.6 Additional Research Themes Motivated by the Business Environments

The above discussion presents exciting research opportunities that form the core of research themes in manufacturing logistics. In the following, we point to two additional research themes that address different aspects of the business environments.

Logistics Implications in Product Development and Design

Many of the most crucial elements of a research agenda on product development and design lie outside of the primary domain of manufacturing logistics, as we have defined it. However many important aspects of this research area lie within the specified domain.

Companies use models to decide what products they should manufacture, and many of those models incorporate a cost of product variety. However, these models do not accurately capture the logistical implications of the decisions being made on the flow of products, or on the ease and efficiency with which the supply chain will be managed.

As we have mentioned earlier, the introduction of new products can have a major impact on a supply chain. During the transition period resources need to be deployed in different ways, pipelines need to be filled, and inventory of older products needs to be phased out. More research on the management of these activities seems warranted.

Finally, we mention that the logistics involving the entire product life-cycle, including recycling, re-manufacturing, and re-use will grow in importance. There is a substantial literature on the design and manufacturing portion of the life-cycle, but this latter aspect has been greatly ignored.

People Issues in Manufacturing Logistics Systems

Human behavior plays a pivotal role in the performance of most manufacturing and logistics systems. The impact of performance metrics and recognition, of incentives and sources of motivation, and of cultural deviations present challenging research issues that need to be better integrated into manufacturing logistics research. In addition, there is a critical need to simultaneously reap the potential benefits of human experience and expertise, and of models that predict and optimize human behavior in the system. In most situations it is not at all clear how that should be accomplished. What is the most effective role of the human decision-maker now that the world has been changed by modern database systems, forecasting systems, ATP, ERP, DRP, and is moving toward the realm of electronic commerce. Adding to the difficult question are cultural issues that are becoming increasingly important. Many control systems, information systems decision-making processes, and models that support them need to be implemented in cross-cultural settings. The design of the systems and processes need to be viable for human decision makers in that environment.

6. *University-Industry Research Collaboration*

In order for manufacturing logistics research to have an impact on industry practices, there is a need for greater synergy and collaboration among academia, industry and software developers. The development of new methods of collaboration also constituted part of the workshop discussion. The objective is toward the creation and/or enhancement of long-term industry-university relationships that would result in research and educational efforts of greater relevance to both academic and industrial partners. In the following, we first examine the status of academic research in this practice motivated area.

The Role of Academia in Manufacturing Logistics Research

While the areas of production, manufacturing and logistics represent an active area of research in OR/MS, the influence of this research on industry practice has been limited. While most would agree that the gap between theory and practice has been narrowed significantly in the past decade, as major software providers continue to implement the concepts and principles of production and operations management for industry use, a majority of the academic knowledge base remains unused. The role that academia should play in industry practice is a topic deserving of long debates, and ultimately better understanding and resolution. Several different points of views are summarized here.

1. Studying fundamental principles. Some researchers feel strongly that the primary role of the academic community should be that of education and providing insights. A problem in manufacturing systems is that many models and solution methods are built but basic operational principles of manufacturing are not well understood. Trying to study, extract and communicate these basic principles should be an important role for the academics.
2. Providing intuition and documenting best practices. Many believe that academic groups should not operate like consulting companies. Focus should be put on intuition-providing research (i.e. exact solutions to simplified problems), research that provides sound solutions to specific, real problems (i.e., approximated solution to real problems), and research that studies, analyzes and documents industry practices of specific interest.
3. More emphasis on empirical work. While it is true that an important role for academics is to "stand back and seeing how things work," or develop new theories. Currently much of the theories in manufacturing logistics is not backed by sound empirical work. Unfortunately, it is currently difficult to publish empirical work in OR/MS journals. The paradigms of research in social science can be followed here.
4. Articulate the roles of models and research efforts in industrial settings. The goals of academic involvement in industry projects can be broadly categorized as understanding, control, planning and design. These goals are often mutually reinforcing. For example, a queuing network model can be used to understand the flow of product through a manufacturing facility. Kanbans or an intelligent dispatching system can be used to dynamically control the flow of product. Finite-capacity scheduling systems plan and attempt to optimize the flow of materials through the facility in advance. All of this works much better if the products, the manufacturing processes and the factory are designed to make the flow of materials through the facility smooth and efficient, and to simplify the tasks of load planning and load control.

Mechanisms for Industry-Academia Collaboration

Collaborative efforts do not have to be broad in scope to be successful. In fact, an underlying characteristic of many current success stories is that they started as small, one-on-one interactions between academia and industry counterparts. Another characteristic of successful collaborations was their ability to provide real value to both parties, this being a necessary condition for any continued support from the industrial partner. Academics seeking industrial support for their work in manufacturing logistics should consider building an "impact statements" from an industry perspective that would incorporate arguments that would justify to a company CFO the potential business implications of the research.

Some of the more important issues that arise and need to be considered in the development of mechanisms for collaboration include the following: the difficulty of growing the intersection between academic and industrial research, the need to include incentives from an industrial perspective and the current academic reward system. Other related issues may include company specific versus generic research, the handling of proprietary information, the acknowledgment and understanding of major differences in the rate of change in industry, software development, and academia.

An example of an existing mechanism that contains many of the attributes needed for the development of successful industry-university collaborations is the Grant Opportunities for Academic Liaison with Industry (GOALI) program developed and sponsored by the National Science Foundation (NSF) in Arlington, Virginia. Initiated in 1990, the program was started in response to a need to provide academic faculty in manufacturing the opportunity to obtain relevant experience in industrial settings. From its small start as essentially a "short-stay faculty internship program" the program has grown to include both faculty and student internships, extended visits for industry participants at university sites, and long-term (two to three year) sponsored research programs at university sites with industrial collaboration and matching resources.

The key to the success of this program was that its design included elements that were consistent and complimentary to both academic and industrial reward structures. From the academic side, the participant was the recipient of a NSF grant, an accomplishment that contributes very positively to academic career enhancement. From the industrial side, the original program was focused on small grants that were within the signature authority of many middle managers that would be the primary beneficiaries of the short-term stay. The fact that NSF would be matching the industrial commitment provided the industrial partner with a leveraging argument that was well understood and appreciated by company CFO's. Expectations for the "faculty in industry" portion were also realistic and explicit with the understanding that this step was the precursor to a longer-term research relationship if the value of such a relationship were established for both parties during the internship stay. Documentation of the longer term research and development agreements that ensued revealed that while some efforts had clear research versus development components, (corresponding to the NSF versus industrial part of the funding base), many of the relationships had been able to define research and development "intersections" that had not been part of the programs of either the academic or industrial participants prior to the development of the new relationship.

While a host of possible mechanisms for long term collaboration were discussed and promoted by various workshops and conferences, many of these suggestions focused on the need for the academic participants to identify and work closely with one or more industrial "internal champions" in the development of his or her proposal. What this implies is that academics aspiring to develop these collaborations need to recognize that promotion of their research interests in manufacturing logistics to the industrial sector need to be "context driven" rather than "generic". While the search for industrial partners in many cases is an outgrowth of personal ties or university alumni, academics may find it helpful to contact the industrial liaisons of many of the industry-university consortia that currently exist throughout the U.S. in related areas such as material handling and distribution, manufacturing systems and related areas. One source that could be particularly rewarding in this regard is the registry of member organizations associated with the NSF Engineering Research Centers (ERC) program as well as those companies currently participating in manufacturing related NSF Industry/University Cooperative Research (I/URC) consortium. In addition to serving as a sounding board for the development of new consortiums in manufacturing logistics, the industry liaisons would also be a source of answers for issues related to the handling of proprietary information. Detailed information on the many existing NSF sponsored industry/university consortia can be accessed through *www.nsf.gov* and searching through the programs under the *engineering directorate.*

In addition to the creation of formal collaboration mechanisms the growth of the intersection between academic and industrial research and education in manufacturing logistics will depend on many individual interactions between university faculty, their students, industrial managers and software developers. Faculty members with common interests in manufacturing logistics either within or across university boundaries need to "bond together" and form "research and education groups or institutes" to create the kind of team-based research and education environments that would facilitate the involvement of students in industry-university research projects and the development of graduate thesis and dissertation projects with real world impact and dissemination. These groups would also serve as catalysts for fostering an appreciation for research among undergraduates by bringing research projects into the classroom and by impacting the undergraduate curriculum through the development of industrially-based case studies in manufacturing logistics. Once these groups are established, various NSF, DOE and DOD programs could serve as the funding base for supporting industrial participation in research and curriculum development and for facilitating faculty and student stays in industrial settings.

Another issue of frequent debate is under the general mantra of technology transfer and the issue of software prototyping and software development in manufacturing logistics. The role of university researchers versus that of software vendors was not one where an intersection was discerned. The university environment would more than likely continue to focus on software prototyping and it would be the vendors who would develop the production codes. Relevant research issues in this domain were considered to be field research efforts that would provide feedback, modification and reiteration of code in either prototype or pre-production status. Since university research groups in manufacturing logistics would by their very nature produce students educated in software development, this was seen as a potential source of human resources for internal technical staff positions for software developers and vendors in this area.

7. Conclusions

In this paper, we provide a comprehensive overview of research directions in manufacturing logistics. With an informal taxonomy using system, decision structure and business environments, we propose an agenda for manufacturing logistics research building on the foundations of industry needs and economic trends. Some discussion on the practicality of industry-university collaboration is also included. Together with the NSF workshop, this effort is a step toward forging a common vision among OR/MS researchers, and a outlook of this exciting area with tremendous opportunities.

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