MANUFACTURING LOGISTICS RESEARCH: TAXONOMY AND DIRECTIONS

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Abstract

This paper examines research directions and opportunities 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 that these expanded directions for manufacturing logistics research offer opportunities for OR/MS professionals to not only generate new knowledge in this rapidly growing research area but to also exert influence on corporate decision-making and software innovation.

Even though manufacturing productivity has been a subject of extensive study (c.f., Graves et. al., 1993), 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, the National Science Foundation (NSF) sponsored a two-day workshop on Research Directions and Opportunities in Manufacturing Logistics at Lehigh University in Bethlehem, Pennsylvania. Over 100 academics and industrial participants 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) submitted to NSF. These results have also been disseminated at poster sessions and conference presentations made at various professional meetings. The recommendations from this workshop have direct impact to the direction of existing NSF programs and have contributed to the development of new NSF initiatives. Most notable among these has been the 1999 NSF initiative entitled “Exploratory Research on Scalable Enterprise Systems” which includes among its objectives the development of a fundamental research base in many of the extended enterprise-level and supply chain design issues that emerged from the workshop discussions. In addition, a special two-issue series of *IIE Transactions* dedicated to research problems in manufacturing logistics has been published (Wu, et al. 1999).

This paper documents the efforts subsequent to the workshop that attempted to further synthesize, extract and revitalize the vision formed during the meeting. A main outcome of these subsequent discussions has been the development of an informal taxonomy of manufacturing logistics research in accordance with this vision. The taxonomy is presented as a mechanism that helps discern the roots as well as future directions for this growing 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 have tried to fuse industrial and academic perspectives 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 fold. 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 take a step forward 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 on 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. The application context must be fully 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 more appropriate, 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. This subject triggered heated discussion during and after the workshop. Nonetheless, after some effort a few general themes emerged. We now summarize these general themes, as we believe they capture the essence of general concerns in the research community.

3.1 Uncertainty and Variability

Most researchers believe that our inability to effectively address uncertainty in manufacturing logistics is an increasingly critical limitation, and is a significant inhibitor in the use of research results in practice. While notable progress has been made, much work remains to be done. Stochastic models often pose serious computational challenges for practical problems. Incorporating uncertainty in planning is a philosophical one as well as a technical one. Many corporate decision makers just begin to understand the implications of uncertainty, to buy into the notion of uncertainty modeling, and to incorporate it in their data collection practices (c.f., Coy, 1999; Smith and McCardle, 1999). We also need to generalize the notion of uncertainty beyond *variability*. Sources of uncertainty present in practice may include missing, incorrect, and superfluous data, vague or incomplete definitions, and ambiguity caused by human behavior. As it stands, there are substantial computational, cultural, conceptual, and educational obstacles to the proper incorporation of uncertainty within enterprise planning.

As a visible example in the business context, Enterprise Resource Planning (ERP) and other corporate information and planning systems seldom incorporate mechanisms to consider variance or other information on randomness. While uncertainty is universally recognized as a complicating factor for planners and schedulers, planning and scheduling systems seldom 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 (Wu and Meixell, 1998), planning stability, and the "bullwhip" effect (Lee et al. 1997) 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 implications 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.

3.2 Human Behavior

Most participants agreed that capturing human behavior in models of design and decision-making is, and will continue to be, a key research need. Unfortunately there is very limited literature in manufacturing logistics addressing these issues. 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. Planning or decision models that capture the dynamics of a system run primarily by human beings will require the consideration of multiple aspects of human behavior. Game theoretic models addresses aspects of human behavior assuming perfectly rational decision makers. The integration of these models with OR/MS decision models is a crucial and challenging task (c.f., Cachon and Lariviere, 1999; Kutanoglu and Wu, 1999).

3.3 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 presents new opportunities to logistics operations, but it also poses serious threats and increases scope, instability and complexity (Cohen and Huchzermeier, 1999). Multi-national logistics considerations include currency valuation, labor force capabilities, tax laws, international treaties and trade agreements, engineering practices and business conventions, environmental and union regulations, etc. Because globalization is fast emerging as the norm for all major corporations, related issues must incorporated into OR/MS logistics models.

3.4 Limitations of Current Information Systems

Both academic and industrial researchers expressed deep dissatisfaction with current information and software systems. With regard to manufacturing logistics software, a “tail wagging the dog” scenario was recognized. Often fundamental organizational changes are required to accommodate the information system. Installing enterprise resource planning (ERP) software is painful and costly. One participant referred to it as a "corporate root cannel." However 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.

3.5 Data Overload and Bad Data

Current information systems generate an overwhelming volume of immensely complex data. Along with the large volume is the inevitable problem of. Companies are often awash in data, but plagued by data that is inaccurate, inconsistent, misinterpreted or out-of-date. Most current production information systems operate on ERP concepts. In such environments bad data can trickle down and cause significant discrepancies in decision making. Ultimately the information system loses credibility and becomes a scapegoat for inefficiency and waste. It is often heard in corporate environments that the information system is "20% off 80% of the time." Because a majority of the research in manufacturing logistics relies on accurate data, issues of data management and model robustness are of significant importance.

3.6 Product Proliferation and Shortening Life Cycles

Now companies are maximizing market leverage and penetrating new markets by developing new products in larger numbers, compressing product development times, and shortening product life cycles. The accelerating pace of technological advances exacerbates this trend (Lancaster, 1990). For example, electronics, computer and semiconductor products now have an average product life cycle shorter than 18 months. With a relatively long production lead-time (usually over 16 weeks for semiconductor products), there is little margin for error. These trends complicate manufacturing operations. Most manufacturing systems never reach "steady state". New products are introduced and old products are phased out continually, so operational efficiency is a constant challenge. Product proliferation increases, volume decreases, setups become more significant, and scheduling becomes more difficult. Process consolidation, design alternation, flexible layout configurations, and other approaches are among the steps taken to address these problems. But the time available for analysis and evaluation is being compressed, and the margin for error is getting smaller.

Product proliferation represents a significant change in the market place. As product variety increases while volume decreases, setup time and setup cost both become a more significant issue, and planning efficient production become more difficult. Process consolidation, design alternation, flexible layout configurations are among the steps currently being taken to address these problems.

3.7 Misaligned Decisions and Performance Measures

In industrial environments, poor alignment of decisions made at different levels and/or locations is common. 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. Performance measures used at different levels and locations are often misaligned, causing disconnects and inefficiency. Problems of decision alignment are partially due to the design and data accuracy of corporate information systems. Often they have deeper roots in incentive schemes, management practices, the decision structure and culture of the corporation. These problems become especially difficult when the structure and size of an enterprise reaches 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.

Production Facility (PF): A production facility is a manufacturing system that consists of a collection of production units. This definition 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 production facility 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:

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 cannot 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 (c.f., Huchzermeier and Cohen, 1996)..

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 1998 NSF workshop (Bai, 1999), 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.

Human Factors: Human behaviors have a substantial impact on virtually all manufacturing and logistical enterprises. This category includes efforts to predict and optimize the impact of human behavior on systems, to reap the potential benefits of human expertise, and to align the goals of individuals with those of the corporation. Personality and its implications, performance metrics, incentive systems and cultural differences are all relevant.

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 ***(PF|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|_), (PF|PN|_)*** dominate much of the research in operations management, while ***(SC|PN|_), (SC|OD|_),*** and ***(E|DS|_)*** has attracted more attention in the past decade (c.f., Tayur, et al., 1998). 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. decentralized) 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 (NSF 1999).

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 Managing Uncertainties (_ | _ | Uncertainty)

Random behavior, lack of essential information, incorrect data, and vague or incomplete definitions exemplify the general theme of uncertainty in manufacturing logistics. It was universally accepted that failure to adequately address issues of uncertainty can render otherwise insightful research unusable, and that a great deal of further research is needed. This opinion was firmly held in spite of the large literature addressing uncertainty in manufacturing logistics, including forecasting, queuing, inventory and simulation. We believe that the importance of modeling randomness in logistics systems is growing for a number of reasons. In the current competitive environment, innovative new approaches to manage uncertainty and to respond rapidly and reliably to changing market conditions is crucial (c.f., Aviv and Federgruen, 1999; Smith and McCardle, 1999; Meixell and Wu, 2000). As product life cycles contract, the relevance of historical data is diminishing, leading to ambiguity. In addition to the topics listed below, see subsection 5.4 on Planning and Scheduling Systems.

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

The differences between randomness and other types of ambiguity have modeling implications. When the traditional "random variable" approach to modeling uncertainty is appropriate, the information necessary to build probability models may be unavailable. Beyond this, there are important types of uncertainty that have not yet been addressed effectively and may not be amenable to probability theory. These include the lack of essential information, incorrect data, vague or incomplete definitions, and the uncertainty involving human behavior.

Some of these uncertainty issues may offer research opportunities. We need approaches that mitigate the effects of ambiguity rather then simply understanding their impact, and that capture and manage the resolution of ambiguity. In practice, sensitivity analysis is the most common approach to ambiguity. One alternative might be an approach akin to "model reconciliation", whereby one builds a model of physical reality (e.g. constraints, event sequences, etc. that *must* logically be obeyed), reconciles current information with the model.

Transient Behavior (_|PN;OC|Uncertainty)

Probabilistic models usually analyze systems in steady state. For several reasons, the transient behavior of logistics systems is gaining in importance. Large-scale systems such as automotive supply chains and semiconductor manufacturing systems take months to reach steady state. Simultaneously, the time scales on which companies act and innovate are getting shorter, so systems are re-configured more frequently. The periods of time in which new products are being brought to market and new markets are being opened up are usually the times of greatest risk.

Risks associated with Globalization (_|_|Globalization; Uncertainty)

Risk has taken on many new dimensions with the advent of global markets (Kouvelis et al., 1997;Cohen and Huchzermeier, 1999)**.**. A company runs new and unfamiliar risks when it enters a new and emerging market or opens a plant in an unfamiliar environment. After a company gets past these issues they face ongoing risks stemming from politics, unrest, currencies, local and global economies, and legal remedies. Little is known about how to quantify and manage these risks, or how to use the global structure of the company to ameliorate them.

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

Information systems and their data management subsystems are not just an important element of the business environment - to a certain extent they *define* the business environment (Mukhopadhyay et al. 1995). Viewed from the research taxonomy, on the one hand *information* connects logistics systems at all levels, and on the other it presents a critical element of organizational design. The recent emergence of electronic commerce adds yet another dimension - it will change business processes and operational paradigms in fundamental ways. While the technological aspects of information systems are beyond the scope of manufacturing logistics research, the implications of and opportunities presented by IT are part of the research core. Because modern information infrastructures offer vast amounts of data, data management is an integral part of this research theme. We offer two specific, related research themes.

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 2005, 90 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 will be one of the most critical 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 with strong interdependencies. For a more extensive discussion of this research theme, see (Bai, 1999) and (NSF, 1999).

Data Management (_,Information | _ | _)

Modern information systems create an unprecedented volume of data. A decade ago data availability was a major obstacles in modeling manufacturing logistic systems. Today the issue is how to extract useful information from massive amounts 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. Seemingly minor changes in the formulation can have drastic impacts on information requirements, so data availability and accuracy must be considered. Issues concerning sensing, gathering, storing, transmitting, and interpreting of data are crucial in implementations, and should have a higher profile in research. Advances in *data mining* hold promise, but there are not many models of manufacturing logistics that take advantage of data mining capabilities.

5.3 Supply Chain Design and Coordination (SC|_|_)

Supply chain integration 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, the *supply chain* system level encompasses all the others in manufacturing logistics research.

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. However 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 innovations, to the design and prototyping of logistics and control systems, etc.. 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, that model material flow and shared resources, and that have flexible data requirements.

Adding to the complexity of decision structure is that of timing. A compelling reason why supply chain research has received the attention it has in the 1990's is that of shortening decision lead-time. 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. The increasing impact of this element on supply chain design has more recently led to the coining of the phrase "clockspeed" to describe the multiple dimensions and impacts of timing on product and process development (Fine, 1998). 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.

Other aspects of organizational design are addressed in sub-section 5.2, "Information Technology and Data Management."

Modeling Supply Chain Decision Structures

This research theme centers on the fundamental decision structure, therefore, the modeling paradigms for supply chain management. We offer two research areas.

Decentralized Decision Structures *(SC | 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.

Enterprise –Level Software Integration *(_|DS|Information Technology)*

For a brief discussion of the critical research issues in this area, we refer the reader to Subsection 3.4, Limitations of Current Information Systems.

5.4 Planning and Control Systems (_|PN,OC|_)

We now consider the planning, operations and control in different levels of the enterprise and the supply chain. For the most part these topics are important continuations of existing research streams.

Algorithms for Planning and Scheduling (_|PN;OC|Uncertainty)

Traditional production planning models are commonly used for modern supply chain operations, but they are inadequate for the task. 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. Quickly generating and updating high-quality schedules for problems of industrial size and complexity is critical for supply chain coordination. Finally, all of these systems need to accommodate randomness and uncertainty. For example, due to shortened product life cycles and rapid-response manufacturing, time buckets are getting shorter. Consequently the coefficients of variation of the demand that occurs in a time bucket have grown very rapidly, and are now much less than one in many systems.

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. Since these systems are inherently dynamic, they are often effective in dealing with uncertainty. As an 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 often more important than having efficient routing and scheduling algorithms.

Real-time decision making usually requires real-time information and communications capabilities. Notable examples in logistics are on-board (the truck) personal data terminals and global-positioning satellite systems. With real-time systems there is a danger of myopic decision making. To avoid this, continuous (as opposed to periodic) planning is required. The important research issues include the problem of *when* to make a decision, in addition to what the decision should be.

At lower levels of the *decision scope* dimension, automated real-time decision making is a reality. As real-time operation and control systems proliferate, there will be increasing pressure to push the concept higher up in the decision scope. This will create research opportunities in real-time planning and in new approaches to temporal decomposition in manufacturing logistics.

Demand Management (_|PN,OC|_)

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. When customer orders are aggregated information that can be used for planning scheduling, and contingency planning is often lost.

5.5 People Issues in Manufacturing Logistics Systems (_ | _ | Human Factors; Industry Conventions)

Human behavior plays a pivotal role in the performance of most manufacturing and logistics systems. The following research opportunities stand out. First, we need models that predict and optimize the impact of human behavior in the performance of systems. Second, the impact of performance metrics and recognition, of incentives and sources of motivation need to be better integrated into manufacturing logistics research. Third, many control systems, information systems and decision-making processes are implemented in cross-cultural and multi-cultural settings, and need to be viable in those environments. Finally, there is a critical need to simultaneously reap the potential benefits of human experience and expertise, and large-scale, data-driven decision support systems. It is seldom clear how that can be accomplished.

5.6 Logistics Implications in Product Development and Design *(_, Products|_|Uncertainty, Environmental Considerations, _)*

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.

The introduction of new products can have a major impact on a supply chain, and the transition periods are especially critical. The research issues mentioned in subsection *Design of Supply Chain Logistics Networks*, and under the *Transient Behavior* caption in Managing Uncertainties, are relevant.

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.

6. University-Industry Research Collaboration

The development of new methods of university-industry collaboration also constituted part of the workshop discussion. The objective was to discuss mechanisms that would facilitate and/or enhance 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 and how it relates to the practice of manufacturing logistics.

6.1 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. Most of the workshop participants agreed that the gap between theory and practice has narrowed in the past decade. However, 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 discussed in the workshop are now summarized.

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1. **The role of academia should be to study 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 logistics research is that many models and solution methods are built without basic operational principles of manufacturing being well understood. Trying to study, extract and communicate these basic principles should be an important role for the academics.
2. **The role of academia should be to provide intuition and document best practices.** Many believe that academic groups should not operate like consulting companies. The 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. **Academia should place 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 theory 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. **Academia should 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 production facility 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.

It is important to observe that these discussion points do not necessarily represent mutually exclusive views of the role of academics in manufacturing logistics research. It should be possible to generate new, fundamental knowledge in this area that would incorporate many of the characteristics of the expanded and broad vision of manufacturing logistics that is implied by the taxonomy that we are presenting in this paper. What is required, however, is an understanding of those mechanisms that have proven successful for those academics that have established research programs in this area with industrial relevance. This was also part of the workshop discussion and is summarized in the next section.

6.2 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. One suggestion was that academics seeking industrial support for their work in manufacturing logistics should consider developing an "impact statement" 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 at the workshop, 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.

Any approach for enhancing collaboration among those in universities, industry and software firms must start with a basic understanding of the priorities and performance measures that motivate each of these sectors. New and effective collaborative research efforts among these communities exist in the intersection of their common interests and the identification of this intersection will assure relevance of any joint effort to all the parties involved. The NSF programs identified previously are a good starting point for researchers that desire to learn both from the successes and mistakes of industry-university efforts in many manufacturing related fields. Given the significant impact of the "business environment" as defined in the taxonomy for manufacturing logistics research, it is even more imperative that university researchers in this area seek to develop and nurture the industrial relationships that will eventually serve as the foundation for collaborative efforts. As one of the workshop participants pointed out, "we should not shy away from the field study component of our scientific inquiry, for it is from this endeavor where the overwhelming majority of the new discovery in manufacturing logistics will arise". Since it will also be where the empirical base that will validate our new theories will come from, we owe it both to ourselves and to our students to engage in efforts that will make university-industry collaboration in manufacturing logistics the norm rather than the exception.

7. Conclusions

In this paper, we provide an overview of research directions and opportunities in manufacturing logistics motivated by an NSF sponsored workshop in Manufacturing Logistics at Lehigh University. An informal taxonomy for this area using *system*, *decision structure* and *business environments* is developed which is used to propose an agenda for manufacturing logistics research building on the foundations of industry needs and economic trends. A summary of workshop discussions and perspectives on industry-university collaboration is also included. Together with the NSF workshop, this paper is a step toward forging a common vision among OR/MS researchers and providing an outlook of this exciting area with the tremendous opportunities that it offers.

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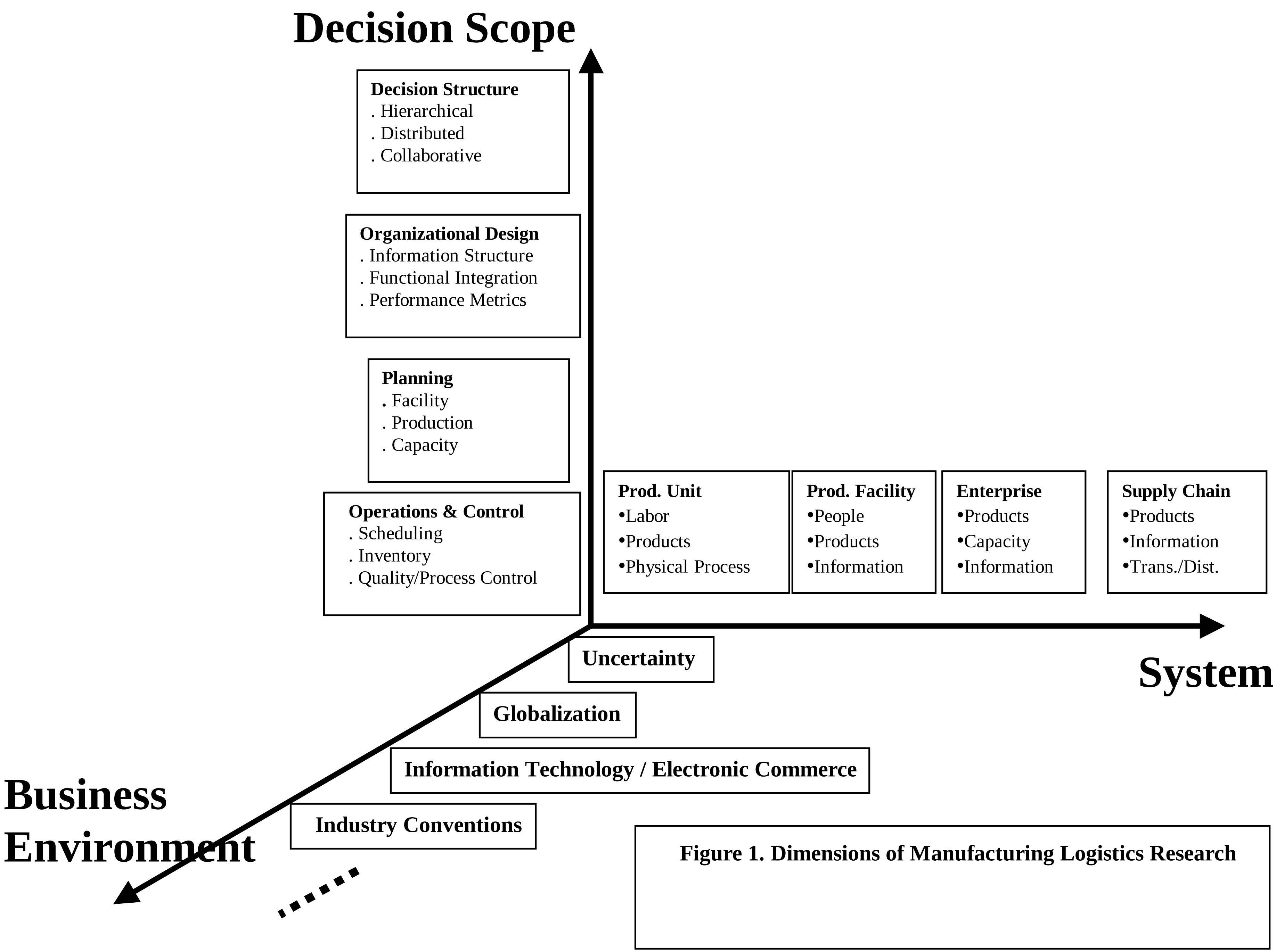

Figure 1. Dimensions of Manufacturing Logistics Research