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Invited Review

Manufacturing planning and control: The evolution of MRP and JIT integration

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Abstract

Material Requirements Planning (MRP) and Just-in-Time (JIT) system are directed toward planning and controlling the important characteristics of material flow: how much of what materials flow and when. Since the material flow is at the heart of the manufacturing firm, MRP and JIT are the powerful management tools that could determine the success or failure of an entire manufacturing system. One of the strongest debates in manufacturing has been centered on the performance comparison and compatibility of JIT production system to the existing MRP. The primary intent of this research is to provide an overview of the manufacturing planning and control environment associated with MRP and JIT. Classifying the existing MRP/JIT comparison and integration literature, two different perspectives on MRP/JIT are discussed, and future research area is proposed based on the taxonomy.

Keywords: Manufacturing planning and control; MRP; JIT; Shop floor management

1. Introduction

In its simplest form, 'the manufacturing process' is a composition of the material flows. Both Material Requirements Planning (MRP) and Just-in-Time (JIT) are designed to manage the flow of materials, components, tools, and associated information. The entire manufacturing systems from purchasing to shop floor management can be controlled based on either MRP or JIT systems. Therefore, MRP and JIT systems are powerful management tools that could easily determine the success or failure of the manufacturing system.

For decades, MRP and JIT production systems have followed two independent research streams. As the popularity of JIT motivated by the success of Japanese manufacturing firms has grown, numerous western practitioners have initiated complete changeovers from the traditional methods to JIT methods. For instance, Harley–Davison and Hewlett–Packard are two of the more popular examples of JIT success stories. In addition, the

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Big Three automobile manufacturers have attempted partial implementation of JIT production system.

However, the performance comparison and compatibility of JIT to the existing MRP systems have led to a strong controversy among the practitioners as well as researchers. Although, there are numerous unsuccessful implementations of the JIT system, the literature in this area is piecemeal. MRP and JIT as surrogates for push and pull methods have created even more controversy. For example, some researchers have approached MRP as a push system and JIT as a pull system. On the other hand, another group of researchers regards push/pull as characteristics of the underlying manufacturing and distribution control systems. In reality, both manufacturing and distribution systems will contain elements of push or pull to varying degrees regardless of the identity of system (Pyke and Cohen, 1990).

There are many similar characteristics between JIT and MRP systems. Rice and Yoshikawa (1982) show the similarities between the two systems. According to Rice and Yoshikawa, *Kanban* (the operation control system of JIT production) may be considered a different type of MRP system in which the time buckets are short. In addition, MRP is a pull-through approach where the master production schedule is converted into material requirements and the requirements are time phased to provide just in time production. The importance of 'on time delivery', one of the operational principles of JIT, was also emphasized by Orlicky (1975) since the MRP system assumes the stock-outs of dependent demand items before the production (Orlicky, 1975).

Moreover, there rarely exists a pure MRP or JIT production system in practice. Even at Toyota, the inventor of the JIT system, production smoothing is planned by the master production schedule (MPS), and the material requirement plan is followed based on the MPS, using bill of materials (BOM). This type of manufacturing planning has been adopted by automobile manufacturers (Monden, 1993). The recent emergence of the integration between MRP and JIT in literature reflects the trend toward a more realistic hybrid-manufacturing environment.

The current shift toward the hybrid manufacturing environment is one of the major motivations for this research. Although there have been numerous MRP/JIT comparison or integration studies, there is no research that addresses the dynamics between the MRP and JIT systems. There is also a strong need to organize the previous MRP/JIT studies and provide directions of implementation and research.

This review proceeds in the following order. First, the identities of MRP and JIT in the literature are defined in their historical context. Second, the relationship between MRP/JIT and push/pull strategies, an MRP/JIT related controversy, will be analyzed. Third, the MRP/JIT literature will be classified. Finally, areas and direction for the future research will be suggested.

There exist three major controversies in the MRP/JIT literature. The first controversy is whether MRP and JIT production systems are equivalent to push and pull systems, respectively. The second controversy is the compatibility issue of whether JIT systems require an MRP based MPS structure. The final controversy is the system flexibility issue associated with the 'MRP nervousness' and inability of JIT to cope with demand variation. In this review, we attempt to resolve each of the above controversies and uncover the essential elements of MRP/JIT integration.

2. MRP vs. JIT

The acronym 'MRP' in this article is used interchangeably for either Material Requirements Planning (MRP) or Manufacturing Resource Planning (MRP II). Although there are additional features such as costing procedure and simulation possibilities in the MRP II, the basic mechanism of the MRP and MRP II systems, the time-phased closed-loop material or resource preparation process, remains the same. However, if necessary, 'the original MRP' and 'MRP II' will be used to denote the Material Requirements Planning and the Manufacturing Resource Planning respectively for the sake of clarification.

An attempt will be made not to use 'JIT' alone because the term, JIT, can be easily misinterpreted.

Rather, the conventional definition of JIT by Ohno (1988) and Monden (1983) will be used. 'JIT' is defined as 'the basis of Toyota production system on which the right parts are needed in assembly line at the time they are needed and only in the amount needed' to achieve 'the absolute elimination of waste (Ohno, 1988).' 'JIT' will be treated exclusively as a management philosophy rather than a physical system. The entire system including subordinated activities which is governed by the JIT philosophy is defined as 'JIT system'. [1] The scope of JIT system reaches every function such as product and process design, human resource management, MPC, and physical distribution. In this review, 'JIT production system' and 'Kanban controlled manufacturing system' are used interchangeably to represent the shop floor oriented production system of Toyota. However, unlike Monden (1983), we will limit the meaning of 'Kanban system' to the shop floor mechanism controlled by pull logic since most of the researchers have used the term, 'Kanban system', in this manner.

'JIT purchasing', 'JIT delivery', and 'JIT delivery system' have different meanings. 'JIT purchasing' is a popular term that emphasizes the Japanese conventional buyer-seller linkage based on a small-supplier base and a long-term relationship. Hahn et al. (1983) suggest that the concept of JIT purchasing is very similar to that of Kanban controlled production system in which smaller production lot sizes and frequent setups are required. 'JIT delivery' is another popular term especially in the purchasing area. From time to time, JIT delivery simply implies 'on time delivery (of the right product in the right amount).' However, JIT delivery and JIT purchasing are not used by Ohno and Monden. Rather, Monden (1993) uses 'JIT delivery system,' or 'JIT physical distribution system' in order to describe the JIT delivery system as an inbound freight consolidation of small lots to achieve full loading efficiency for each truck. Based on the differences of meanings, more specified terms such as 'JIT production system' will be used depending on the context.

[1] Monden uses 'total JIT system' to describe the entire Toyota production system.

MRP/JIT comparison or integration will not be treated the same as *push/pull* comparison or integration. In fact, there is a stream of research that focuses exclusively on the push/pull manufacturing processes or strategies (Lee, 1989; Sarker and Fitzsimmons, 1989; Pyke and Cohen, 1990; Olhager and Östlund, 1990; Spearman and Zazanis, 1992, etc.). In addition, some of the researchers stipulate that the push and pull systems are not equivalent to MRP and JIT.

Nevertheless, it is reasonable to accept that the push/pull debate must be raised to help clarify the controversy related to the MRP and JIT systems. In addition, several MRP/JIT studies associate push and pull principles as surrogates for the MRP and JIT systems. Hopefully, this review will flesh out some of the similarities and differences between MRP/JIT systems vs. push/pull principles.

2.1. MRP and MRP II

The original focus of MRP was to manage the inventory waste for dependent demand items (Orlicky, 1975). The primary objective of an MRP system is to generate accurate inventory information in order to determine the right order quantities at the right time. The idea behind the MRP system is quite similar to that of JIT. However, the critical disparity is while the JIT system requires the right execution, on time delivery, the MRP's focus is the right signal, on time ordering. The MRP system also serves as a central organizer that translates the overall production plans into a series of specific steps in order to accomplish the planned production.

The perspectives among the researchers on MRP vary in the literature. The opponents of MRP argue that MRP is just an information software package, which only determines the prospective material flow and has nothing to do with running production systems. In contrast, the proponents accept MRP as an overruling manufacturing planning and control device, which involves the entire manufacturing functions. For MRP supporters, adopting the MRP system implies that management has devoted itself to operating the entire manufacturing process by the MRP system as can be seen in Fig. 1.

The cited operational failures of the MRP controlled production system are significant. First, there is a conflict between the MRP's deterministic nature and uncertainty of operations. A critical MRP problem is in its inherent assumption that the actual production parameters such as lot size and delivery lead-time can be determined or fixed. Accurate lead-time estimation and lot size optimization are the essential components to sustain efficient operation of the MRP system. However, in reality, especially in the job-shop environment, actual lead times and optimal lot sizes are neither known nor fixed (Karmarkar, 1989; Huq and Huq, 1994). Small parameter changes at the final assembly level often results in drastic changes at earlier production levels. It is difficult for rigid MRP systems to cope with the uncertain nature of production and operations. 'MRP nervousness' is the product of this interaction (Krupp, 1984, Benton (1983, 1985)). In some cases, MRP nervousness forces companies to accept the worst-case scenarios in determining the total production lead-time in order to minimize the impact of operational uncertainty and failures (Huq and Huq, 1994).

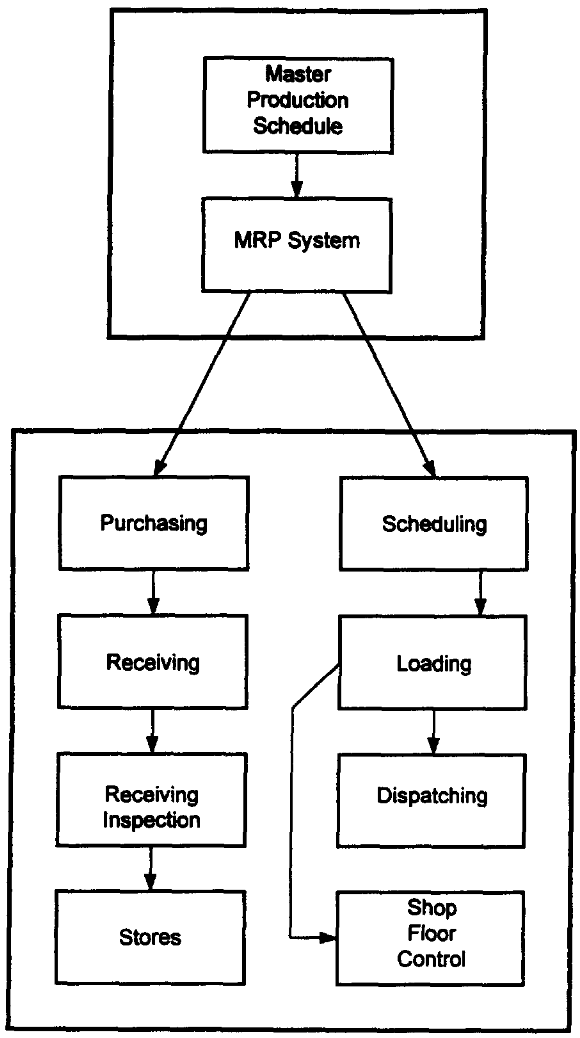

Fig. 1. MRP planning and execution system (* source: Material Requirements Planning (Orlicky, 1975)).

Second, the original MRP environment often neglected capacity constraints. The analysis of material flow separated from capacity and routing is another major pitfall of the MRP system (Lambrecht and Decaluwe, 1988). Even today, MRP production schedules are usually adjusted by a bottoms-up replanning procedure in which the production capacity limit is incorporated and compromised. This two-step procedure of determining the capacitated lot sizes is much more complex than the rate-based capacity control associated with the JIT production system (Huq and Huq, 1994).

Third, some of the researchers (Huq and Huq, 1994) point out the stockpiling of work-in-process inventory as a major drawback of the MRP system. Nevertheless, the work-in-process inventory problem may be caused by associated batch sizes, not by the MRP system itself. Lot sizing for the dependent demand items below the master production level is also a complex task. To date, a significant volume of MRP research has been aimed at optimizing lot sizes to resolve the shop floor problems (Buzacott and Shanthikumar, 1994).

In addition to these three major pitfalls, there are several minor MRP system problems such as the interface between the MRP system and other software packages. The popularity of the JIT production system has been partially enhanced by the operational failures of the existing MRP systems. Moreover, since the focus of the JIT system is on control and execution, the JIT system's capability to control process has been contrasted to the operational failures under the MRP production control.

2.2. Just-in-Time production

The JIT production system is relatively new to western manufacturing firms. As mentioned earlier, JIT is Toyota's manufacturing philosophy to minimize waste, and the JIT production system is a subsystem controlled by Kanban. The Kanban controlled JIT production system has been erected based on the premise of minimizing work-in-process inventories (waste) by reducing or eliminating discrete batches. The reduced lot sizes not only contribute to production efficiency and product quality, but also reduce the overall costs associated with production in the JIT manufacturing environment. This proposition holds true only when certain conditions are sustained. According to Monden (1983), the success of Toyota's Kanban controlled production system is supported by smoothing of production, standardization of jobs, reduction of setup times, improvement of activities, design of machine lay out, and automation of processes (automation with human touch). In fact, the JIT production system appears most suitable for the repetitive manufacturing environment.

Improvements in the Kanban controlled production systems have followed a pragmatic approach, 'Continuous Improvement'. Therefore, success of the JIT production system must be explained in conjunction with Continuous Improvement and Total Quality Management. Experience and commitment of the workers on the shop floor to continue to improve performance and methods are the major drivers of the JIT production system. A host of cases and evidence from the literature indicates that the JIT success has been achieved not by the predetermined scheduling technique, but by the continuous improvement effort.

The JIT production system is not a panacea. As with the MRP system, the operational problems with the JIT system are discussed in the literature. In fact, there is a list of reasons why the Toyota manufacturing system does not work in western firms. The reasons include cultural differences, geographical dispersion of suppliers, and different management styles, etc. These operational problems with the JIT production system will be evaluated and discussed in detail.

The Toyota's manufacturing system has been viewed in different ways by a variety of researchers. The JIT production system is often called 'lean production system' because it uses less of every resource compared with the conventional mass production system (Womack et al., 1990). On the other hand, the JIT system is viewed as a conventional 'Reorder Point' system with extremely small lot sizes (Zipkin, 1991). The most common standpoint in understanding the JIT production system is that the JIT production is a 'pull' system as opposed to the conventional push system. In the MRP/JIT comparison or integration literature, the pull nature of JIT production system has been discussed extensively. Thus, it is only natural to portrait the push/pull debates in conjunction with the MRP/JIT studies.

3. JIT pull and MRP push?

There are two principles that initiate material flow in the MPC system, push and pull logic. The terms 'push' and 'pull' have been used for decades without clear definitions. Recently, Pyke and Cohen (1990) raised the push/pull issue. Clarification of the push and pull systems is not the major purpose of this literature review. But, it is necessary to summarize some important propositions because the push/pull principles have been treated as dominant factors underlying each of the production control systems, MRP and Kanban.

In general, there is a common agreement among the researchers that the Kanban controlled manufacturing system functions as a pull system and MRP as push. Yet, this proposition does not always hold true. For example, Rice and Yoshikawa (1982) suggest that there are many practical similarities between the Kanban system and MRP and both are "pull-through" approaches. Also, Karmarkar (1989) addresses that JIT can be either a pull system or a push system because it is an integral philosophy rather than a timing based manufacturing technique. Summarizing the existing viewpoints on push/pull principles, Pyke and Cohen (1990) conclude that an entire manufacturing system cannot be labeled as a push or pull system. They also suggest that the push/pull principles are an attribute of the underlying manufacturing and distribution control systems that may contain a certain degree of push or pull components.

There are three ways to define or distinguish the nature of push and pull systems in general. The most common way is characterizing the differences in terms of the order release (De Toni et al., 1988; Karmarkar, 1989; Ding and Yuen, 1991, etc.). According to this viewpoint, in a pull system, removing an end item (or a fixed lot of end items) triggers the order release, by which the flow of materials or components is initiated. In contrast, push systems allow for the production or material flow in anticipation of future demand.

The second way is to examine the structure of the information flow (Olhager and Östlund, 1990; Hodgson and Wang (1991a, b) etc.). In a pull system, the physical flow of materials is triggered by the local demand from the next server. The local demand in this system is signified by the local information, empty Kanbans. In this context, the pure pull system is a decentralized control strategy in which the ultimate goal of meeting demand (orders) is disregarded in the local servers (individual stations). However, a push system uses global and centralized information. Global information of customer orders and demand forecasts is released and processed to control all the levels of production in the push system.

If one understands push/pull systems based on this notion, Pyke and Cohen's argument that a particular MPC system has the push/pull elements simultaneously appears valid. According to Pyke and Cohen (1990), (centralized) planning systems always have push element. Therefore, even in the pull-manufacturing environment, outcomes of the central planning decisions may limit certain operating variables of the production control systems. For example, the JIT production system has a push element in setting capacity limit of a batch, the container (bin) sizes.

Finally, the third way to interpret push/pull systems is a practical approach associated with WIP level on the shop floor. In a simulation study comparing push, pull and *constant work-in-process* (CONWIP) systems, Spearman and Zazanis (1992) found that the merits of the pull system are generated by the bounded WIP, not by the characteristics of pull logic. They show that a hybrid approach, CONWIP, functions in a very similar manner to the pull approach due to its bounded WIP level. Simply, a push system is considered an open queuing network with infinite queue space, and a pull system is a closed queuing network. Therefore, the MRP controlled shop floor system without WIP blocking mechanism would create more WIP inventory than a pull system, unless the production strictly follows the original planned schedule. One of the critical implications of this result is that comparison based on WIP level between MRP and Kanban system at the shop floor level may not be fair since WIP level of the Kanban system is inhibited by the size and number of containers.

Based on three viewpoints mentioned above, it can be concluded that if materials flow is initiated by the central planning system without controlling WIP level, this system is close to the pure push system. In a pure push system the parts or component will proceed based on the predetermined schedule regardless of whether the next server is busy or idle. In a pure pull system the subsequent process will withdraw (i.e., pull) the parts from the preceding process using local information and controlling WIP inventory level.

At the shop floor level, Kanban system functions as a pull system, and MRP works as a push system. At other levels, 'MRP = push' and 'JIT = pull' are not always true as mentioned by Pyke and Cohen (1990). In practice, for example, JIT production system also uses global information for the long term production planning. The push/pull and MRP/JIT studies are related in a way of deliberating issues associated with material flow. But, MRP or JIT production system plays a role as a structure of an MPC system whereas push or pull logic is a principle only for material flow in the MPC system. Thus, it is possible for an MPC system to operate under the push and pull principles simultaneously depending on the stage of production. Notice that the combination of push/pull principles has been adopted and tested in the push/pull integration literature (refer to Appendix B, Table B.2). In this push/pull hybrid-manufacturing environment the distinction between push and pull becomes more ambiguous.

4. Taxonomy of the literature

The literature discussing MRP/JIT systems simultaneously can be classified as comparison studies and integration approaches (See Fig. 2). In general, for the researchers who conducted comparison studies, MRP and JIT are mutually exclusive. On the other hand, the integration researchers consider the complementary nature of JIT and MRP systems.

The first subcategories of classification are conceptual approach and analytical approach. In the former, general aspects of the MRP and JIT or push and pull systems are compared, and conceptual framework is constructed to examine the possibility of the MRP/JIT integration. In the latter, the scope of discussion is narrower and more organized to provide the clear distinction between MRP and JIT production systems or among the hybrid, MRP and JIT production systems, providing a set of performance measures. In the analytical comparison or integration studies, analytical methodologies such as simulation and mathematical analysis are the most commonly used.

The second subcategories of this taxonomy are MRP/JIT and push/pull studies. Although, there is no strict hierarchical order between the first and second subcategories, MRP/JIT vs. push/pull criterion is considered relatively minor to the categories of research methodology. The reason for this is because clear distinction between MRP/JIT and push/pull has not been detected in some studies, especially in the analytical comparison studies.

The final level of the taxonomy is the directions of discussion. Therefore, the literature is classified based on the categories of shop floor management, manufacturing planning and control (scheduling approach), production and inventory control, and inventory management including distribution system. Because there are many overlaps among the studies at this level, we do not attempt to over-classify the literature. Instead, a summary of the scope of articles is provided in Appendix A Tables A.1 and A.2 and Appendix B Tables B.1 and B.2.

4.1. Comparison studies

4.1.1. Conceptual MRP/JIT and push/pull comparison studies

The conceptual comparison studies describe the general aspects of the MRP and JIT system or push and pull system with regard to the basic structure and essential principles (see Appendix A Table A.1). Unlike the analytical comparison studies, conceptual comparison studies do not limit their focus to one area. The pioneers of this type of MRP/JIT comparison studies are Rice and Yoshikawa (1982). In their research, overall differences and similarities of the MRP and JIT production systems are discussed.

In Japan, MRP is understood as a systematic top-down MPC system (Matsuura et al., 1995). Nevertheless, implementing an MRP system is not a top priority among the Japanese companies because pure MRP systems lack workers' involvement, continuous improvement concepts, and a formal shop floor control *methodology*. The Japanese practitioners' viewpoint of MRP implies why MRP (a system) cannot be directly compared with JIT (a philosophy). MRP is an MPC tool that requires the right execution principles and activities. Thus, implementing MRP at the operational level is a different matter. In a JIT production system, successful implementation is achieved by executing the core philosophy, JIT. Therefore, comparison between JIT and traditional manufacturing philosophies or between MRP and Kanban controlled production system is a more appropriate approach. Two excellent comparisons are outlined in Tables 1 and 2.

One of the interesting appearances in the conceptual comparison studies is that some of the researchers have realized the possibility of cohesion between MRP and JIT or between push and pull principles. (Gelders and Van Wassenhove, 1985;

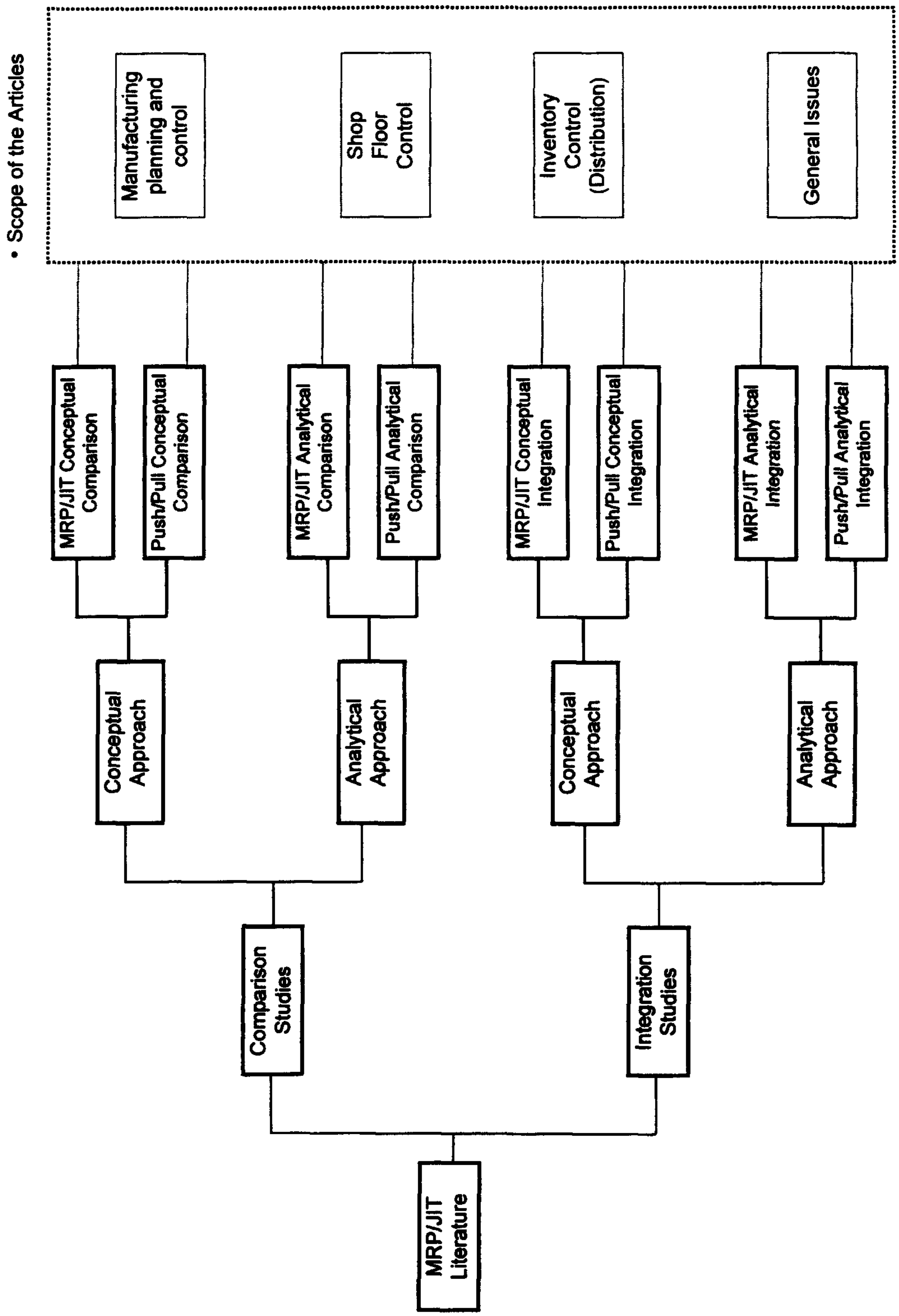

Fig. 2. Taxonomy of the MRP/JIT literature.

Table 1
Comparison of JIT and tradition manufacturing philosophies

Factor	JIT	Traditional philosophy
Inventory	A liability. Every effort must be expended to do away with it	An asset. It protects against forecast errors, late deliveries and machine problems
Lot size	Immediate needs only, minimum replenishment	Formulas
Setups	Make them insignificant. This requires rapid changeover to minimize the impact on production	Low priority issues. Maximum output is the usual goal. No thought given to quick changeovers
Queues	Eliminate them. When problem occurs, identify the causes and correct them	Necessary investment. Queries permit following operations to continue in the event of a problem with the feeding operation
Vendors	Co-worker; part of team. Multiple deliveries for all active items are expected daily	Adversaries. Multiple sources are the rule
Quality	Zero defects	Tolerate some scrap
Equipment maintenance	Constant and effective. Machine breakdown must be minimized	As required. Not critical because of queues
Lead times	Keep short – simplifies operation	The longer the better. Most foreman and purchasing agents want more time
Workers	Management by consensus. Changes are not made until consensus is reached – teamwork	Management by edict. New systems are installed in spite of workers. Their measurement is used to determine workers production

Adapted from modern materials handling, June 1982.

Table 2
Comparison of Kanban and MRP

Function	Categories	Kanban	MRP II
Rates of output	Families of products	Leveling	Production plan
Products to be built	Finished goods for make to stock, customer orders for make to order	Master production schedule	Master production schedule
Materials required	Components – manufactured and purchased	Kanban card	MRP
Capacity required	Output for key work center and vendors	Visual	Capacity requirements planning
Executing capacity plans	Producing on high priorities in factory	Visual	Input/output context
Executing material plans – manufactured items	Working on high priorities in factory	Kanban cards	Dispatching reports
Feedback information	What cannot be executed due to problems	Andon	Anticipated delay reports

Adapted from modern materials handling, June 1982.

De Toni et al., 1988; Buxey, 1989 and Ptak, 1991). Matsuura et al. (1995) also address that some Japanese companies have attempted the integration of MRP and JIT production system to exploit the strength of MRP and that of Kanban.

The study by De Toni et al. (1988) of application conditions for each of the production control systems shows a consistent result with the simulation work by Krajewski et al. (1987). The logic behind this study is that there exist certain conditions that help a particular controlling technique perform better. For instance, in the repetitive manufacturing and distribution system the Kanban technique is appropriate to level the physical flow of materials. Also, De Toni et al., strongly address that the marriage between Kanban and MRP systems is desirable as the MRP system lies within the philosophy of JIT production system.

Evaluating the production scheduling mechanism of MRP and JIT, Buxey (1989) provides an empirical example of Australian automotive plants that have used the MRP and JIT simultaneously. In those plants, Kanban system is used as the production control mechanism, and MRP is used for purchasing and capacity requirements planning. As a result, actual batch sizes in those plants are dramatically reduced to a fraction of the required lot-for-lot order quantity. Even though Buxey's focus is on production scheduling, he does not depict the scheduling technique of the JIT production system. Indeed, as can be seen in the JIT literature reviews by (Golhar and Stamm, 1991; Singh and Brar, 1992; Berkley, 1992), JIT production scheduling technique presents a major research gap in the literature. This is still true.

4.1.2. *Analytical MRP/JIT and push/pull comparison studies*

A series of analytical MRP/JIT and push/pull comparison studies was published in the late 1980s and early 1990s (refer to Appendix A Table A.2). In comparing the performance of the JIT and that of MRP (or push and pull), the most appropriate research methodologies are simulation and mathematical analysis. In Table 3 the experimental factor setting clearly suggest the complexities of comparing MRP and Kanban systems.

Most of the analytical comparison studies focus on the shop floor level, where attaining a set of operational performance measures is comparatively uncomplicated. As discussed earlier, MRP functions as a push system and JIT production system as a pull system at this level. Therefore, it is difficult to detect clear distinction between MRP/JIT and push/pull arguments in this category. In fact, some of the analytical studies adopted push/pull principles as dominant factors that make each system unique.

It is meaningful to categorize the analytical comparison studies with regard to the final results. The results are as diverse as the model settings in each of the studies, but a majority of the studies indicate better performances of the pull system or JIT production system (Lambrecht and Decaluwe, 1988; Lee, 1989; Pyke and Cohen, 1990; Spearman and Zazanis, 1992). Other researchers indicate neutral results (Krajewski et al., 1987; Sarker and Fitzsimmons, 1989; Steele et al., 1995). Only the simulation by Rees et al. (1989) which assumes the changeovers from MRP to Kanban favors the existing MRP based lot-for-lot system.

Krajewski et al. (1987) performed an extensive simulation comparison of MRP and JIT systems. In this study, seven major categories that affect manufacturing effectiveness are constructed as the representative factors of the US manufacturing environment. Then, the performance of Kanban and MRP is measured based on labor requirements, inventory, and past due demand. One of the critical findings of this research is that the manufacturing environment factor settings greatly affect the performance of each system, i.e., environmental factors are the keys to manufacturing effectiveness. For example, reducing lot size is the most effective way of decreasing inventory investment, yet reducing lot sizes is only affordable when setup times are small.

Steele et al. (1995) conducted a similar simulation study for the cellular manufacturing environment with experimental settings similar to that of Krajewski et al. (1987). In their study, setup time, lot size, and MPS variation are identified as critical factors in selecting an MPC system. Steele et al., suggest that if the lot size is large, MRP is the most appropriate approach.

In the studies in favor of the JIT production system, superiority of Kanban controlled production system in shop floor control is highlighted. Low work-in-process inventory level, less congestion, higher controllability, and reduced production lead time are the prevailing features that contribute to the success of the JIT production. Spearman and Zazanis (1992) provide meaningful insight into why the pull system shows prominent performance on the shop floor. According to them, strength of the pull system is not attributed to the pull principle itself, but to the ability of pull system to limit the level and variability of WIP inventory. Within this context, they predict the future success of the hybrid controlling principle, CONWIP.

One of the common findings in the performance comparison studies is that the JIT production system is sensitive and susceptible to variation in MPS volume or demand because JIT production system operates without buffers (Sarker and Fitzsimmons, 1989; Steele et al., 1995, etc.). Therefore, the problem with the JIT system appears more destructive and severe than that of the traditional sequential push system such as MRP. In an ideal JIT production system, all of the materials and components flow as smooth as a single stream of water. This 'status quo' can easily be broken down unless such important conditions such as smoothing of production, standardization of jobs, and reduction of setup times are sustained.

Sarker and Fitzsimmons (1989) found the possibility of low utilization rate as a potential problem with the pull system. In JIT production, low work-in-process inventory level may create low utilization rate of each server unless perfect balance between workstations exists. However, this problem can be resolved by increasing number of Kanbans, increasing mobility of in-process parts, or reducing physical distance between servers.

In almost every analytical comparison study, a critical concern is to organize a reasonable experimental setting on which the result of the experiments are not biased or distorted. Unlike other comparison studies such as comparison of lot size algorithms in inventory management, MRP/JIT or push/pull comparisons contain some inherent problems in establishing the fair experimental surroundings. First of all, the bases of operation in the push and pull systems are quite contrary. Spearman and Zazanis (1992) indicate that "push systems control throughput (input/output) by establishing a Master Production Schedule and measure WIP to detect problems in meeting a schedule". In contrast, "pull systems control WIP and must measure throughput against required demand". This argument implies that controlling variables related to input, output, and WIP level could have a critical impact on the results of the push/pull comparison studies.

Second, determining performance measures and the scope of comparison is a critical challenge. Even in the MRP/JIT comparison studies, researchers designed the same physical settings for both MRP and JIT system to sustain the impartiality of comparison and employ a group of decision variables to emphasize the differences between MRP and JIT production systems. Therefore, if the research experiment is limited to comparing performances of the shop floor management measuring WIP level, there is a higher chance that the Kanban system shows exceptional performance. Likewise, the Kanban controlled system cannot respond effectively to lumpy demand without the buffer mechanism, MPS, because controlling WIP level and throughput rate regulates the capacity the JIT production system can cope with.

Third, the performance comparison studies do not incorporate a set of managerial aspects of the JIT and MRP. Spearman and Zazanis (1992) address that comparing the JIT production systems and push systems may not be fair because the JIT system includes other managerial features such as short setup times, excellent quality, and increased worker involvement. For example, the material flow in the conventional Kanban controlled shop floor is initiated by the operators' physical record of Kanban card. Therefore, the Kanban system provides visual information of material flow that helps the field managers find bottlenecks on the shop floor.

In conclusion, the difficulties in comparing the MRP and JIT production system originate from the fact that MRP was developed as a planning tool and Kanban as a controlling device. In practice, the MRP only sets the production plan and

Table 3
Experimental settings of the analytical comparison studies

Refs.	Experimental setting (or factors)	Performance criteria	Measures	Methodology in detail
Krajewski et al., 1987	• Customer influence • Vendor influence • Buffer mechanism • Product structure • Facility design • Process • Inventory	• Workforce productivity • Inventory investment • Customer service	• Average weekly labor hours • Weeks of supply • Average past-due demand expressed as weeks of supply	• Discrete event simulation (MASS)
Fallon and Browne, 1988	• A five station synchronous assembly line • Multiple products • Batch size with variation • Set-up time	• Inventory costs	• Inventory holding cost • Ordering cost and set-up cost	• Discrete event simulation (SLAM)
Buzacott, 1989	• Single or multistage production • Maximum inventory level • Kanban size • Number of Kanbans • Lead time	• Production capacity • Delivery performance • Inventory • Kanban related measures	* Performance comparison is not provided with specified measurements	• Linked queuing network model
Grünwald et al., 1989	• Market (specificity, uncertainty, irregularity, life cycle, commercial lead time, and heterogeneity) • Product/Process characteristics (final product structure, production allocation, capacity)	• Inventory level • Service level	• Performance indicators	* No solution provided
Lee, 1989	• Multistage production • Choice of queue discipline	• System effectiveness	• Mean daily job completion rate • Process utilization • Job queue time • Job lead time • WIP and total inventory level	
Luss, 1989	• Single feeder shop and final assembly shop • Lot size • Manufacturing time		• Component WIP inventory • Finished component inventory	• Mathematical cost model

Table 3 (Continued)

Refs.	Experimental setting (or factors)	Performance criteria	Measures	Methodology in detail
Rees et al., 1989	• Multiple work centers • Serial assembly operation • Product structure		• Inventory holding cost • Setup cost • Backorder cost	• Q-GRET (FORTRAN) simulation
Sarker and Fitzsimmons, 1989	• Multistage sequential production • Coefficient variation of service times • Machine breakdowns • Buffer storage	• Line efficiency -	• Out-put rate • Time-average queue length of the kanban • WIP and total inventory level • Machine utilization	• Slam simulation
Sipper and Shapira, 1989	• Financial cost • Penalty for late delivery • Process reliability (time interval between machine failures, repair duration) • Ration between WIP and the maximum possible shortage	• Total cost	• Inventory holding cost • Shortage cost	• Mathematical cost model
Pyke and Cohen, 1990	• Single line production and single channel distribution • Batch Size • Timing (of a production or shipment request) • Priorities (for production and shipment) • Interference		• Retail inventory • Retail shortage • Finished good inventory • WIP • Total cost • Service level	• Simulation (no detailed information provided)
Spearman and Zazanis, 1992	• Frequency of order release • Order size (lot size) • WIP level • Lost production costs • WIP costs	• Congestion - • Controllability - (Robustness)	• Mean cycle time • Sensitivity of the optimal solution	• Comparison between open queuing network and closed queuing network • Static optimization
Steele et al., 1995	• Multicell manufacturing • MPS volume variation • MPS mix variation (product mix proportion) • Setup time • Parts commonality • Rate similarity (mean coefficient variation of machine rates) • Part range	• Tardiness • Inventory level • Lead time	• Mean of the order lateness in days • Average WIP, subassembly, and finished good inventory in days • Accumulative planned lead times	• Simple_1 (a language) simulation

detailed schedule and does not concern with operational performance on the shop floor. Nevertheless, in analytical comparison studies researchers must assume the perfect execution of MRP ignoring the throughput rate and failures in operational activities. Indeed, unrealistic capacity limit and failures in executing the original plans are the common problems with MRP systems. In this situation, organizing a set of realistic experimental settings for the MRP/JIT comparison is a critical challenge.

4.2. Integration of MRP and JIT

A relatively new research trend associated with the MRP and JIT is to explore the possibility of a hybrid system and to develop a model for the integrated system. The rationale behind these approaches is that both the MRP and JIT system has its own unique advantages and disadvantages, and the advantages of both systems can be exploited to achieve better performance. In addition, the MRP and JIT systems are compatible, and MRP must be considered a framework that can upgrade the JIT production more efficiently.

Superficially, the JIT implementation and MRP/JIT integration result in very similar outcomes although some researchers postulate peculiarity of the MRP/JIT integration approaches. For the majority of western firms, JIT implementation is equivalent to embedding the JIT production system into the predecessor MPC tool, MRP. Because complete JIT implementation requires a substantial investment, a partial or pilot implementation has been inevitable. Implementing a JIT production system is not simply a shift from the pure MRP system to the pure Kanban system. The implementation of JIT systems is usually a reconciliation between the existing MRP and JIT production system.

In this context, MRP/JIT hybrid manufacturing environment is a result of the natural evolution of the production planning system derived from the JIT implementation in the US (or, conversely, implementing MRP in Japan) (see Table 4). Recently, some of the MRP/JIT and push/pull integration studies have adopted a more proactive approach to identify the optimal control systems given the existing production settings. This phenomenon can also be considered natural evolutionary progress toward an idealistic hybrid-manufacturing environment.

There are three important factors that have contributed to the evolution of the hybrid manufacturing environment: (1) accumulated operating problems in implementing JIT manufacturing techniques, (2) researchers and companies' understanding of compatibility between the MRP as a planning system and the JIT production system as a shop floor control device. (3) MRP flexibility in the long term capacity planning and JIT agility in daily production control.

Since the JIT production technique became popular, some researchers have focused on the performance of JIT and operating problems at various stages of JIT implementation. Interestingly enough, the problem of interfacing JIT with the existing MRP system was cited by only a few companies (Crossword et al., 1988). This result also implies the intrinsic possibilities associated with the integration between MRP and JIT.

4.2.1. Operating problems in implementing just-in-time

Although many of the JIT success stories are overemphasized by the practitioners and JIT proponents, there is empirical evidence that indicates some of the achievements of western manufacturing firms. Companies usually report inventory cost reduction, lead time reduction, production-site/warehouse space reduction, and quality improvement as their major JIT accomplishments (Celley et al., 1986 and Crawford et al., 1988). The impact of adopting the JIT system on various accounting performance measures (e.g., Earnings Per Share) has also been tested by Huson and Nanda (1995). According to Huson and Nanda, implementation of the JIT production system also increases earnings and enhances firm value. Moreover, JIT production systems increase a company's unit cost after adoption, however the increase in unit cost is mitigated by a long-term reduction in inventory and manufacturing costs.

Despite the success testimonials of JIT systems, numerous problems have been also cited in the lit-

Table 4
Summary of the implementation or operating problems with JIT production system in the US firms

Refs.	Celley et al., 1986	Crawford et al., 1988	Im et al., 1989
Title	Implementation of JIT in the US	A study of JIT implementation and operating problems	How does Kanban work in American companies?
Sample	Automotive industry action group	Companies in the process of implementing JIT	Companies in the process of implementing JIT
Number of responses	131	38	33
Problems identified	Implementation problems [a] • Customer scheduling changes • Poor supplier quality • Poor production quality (Internal) • Inability to change Paperwork systems • Shortage of critical parts • Lack of employment commitment • Inability to reduce setup time • Inadequate equipment & tooling • Surplus of non-critical parts • Lack of top management commitment • Labor contract problem	Implementation problems [a] • Cultural resistance to change • Lack of resources • Lack of top management understanding or commitment • Performance measurement • Miscellaneous problems Operating problems [a] • Inability to meet the schedule • Poor quality • Lack of vendor support • Poor forecasting • Data accuracy • Machinery breakdown • Performance measurement • Miscellaneous problems	Major problems in Kanban implementation [a] • Lack of knowledge • Lack of top management commitment • Lack of worker participation • Long setup time • Unstable demand • Various product • Imbalance between production • Stages • Inflexible work force • Variable processing time

[a] Arranged by descending order of ratings.

erature. The major implementation problems center on cultural, human, and geographical factors. Young (1992) found that the JIT production system aggravates workers because they are expected to work continuously. There is no work in process to protect them. In addition, longer physical distance between a manufacturer and suppliers has caused a set of operational problems with JIT delivery system.

The implementation and operating problems with JIT production system among western firms are summarized in Table 2. Some of the major operating and implementation problems with JIT production systems include the following:

- Cultural resistance to change including employees and suppliers.
- Lack of infrastructure and resources for training and education for the JIT system.
- Lack of performance measurement.
- Inability to meet the production schedules.
- Lack of vendor support.
- Difficulties in reducing lot sizes and setup times.

Western firms have been reluctant to adopt the original form of JIT manufacturing system for these reasons. An empirical study by Ahmed et al. (1991) shows that 131 out of 177 sample companies were in the learning, pilot program, or partial implementation stage. Most of the firms are more comfortable implementing a trial JIT system that can be easily integrated into their existing MRP system. This new system has evolved into a hybrid manufacturing system.

4.2.2. Compatibility between planning driven MRP and control driven Kanban

MRP and JIT production systems are not mutually exclusive. According to a study by Im (1989) 13 out of 33 firms indicated that they use MRP & JIT simultaneously. In general, MRP does not conflict with JIT, but MRP must assume that production environment has fixed lead times (Karmarkar, 1989).

As mentioned earlier, Pyke and Cohen (1990) provide a useful insight in defining the nature of MRP and JIT. Distinguishing the concepts between planning systems and control systems, Pyke and Cohen argue that planning systems use global information in setting requirements, lead times, etc., whereas control systems only use local information to control materials flow between servers. In fact, MRP is a popular example of the planning system, and Kanban is a one-of-a-kind control system.

The strength of MRP is in long range planning, scheduling, materials planning and coordination. The MRP system functions same as a central coordinator for the inter-functional communication. In contrast, JIT production systems are effective systems for the shop floor scheduling and to control. JIT is an excellent release mechanism for the product system. Thus, the integration of MRP and Kanban would allow firms to improve manufacturing efficiency and customer service level. (Golhar and Stamm, 1991; Karmarkar, 1989). Lee (1993) also points out while MRP is basically a planning system, having little association with the actual manufacturing processes. On the other hand, the Kanban system is an execution system for the shop floor.

This inherent nature of MRP as a planning system and the JIT production system as a shop floor control system is not well understood by the researchers. Indeed, conducting MRP/JIT integration studies, the majority of researchers adopt the approach of using the MRP as an integrated planning tool, and JIT production system as the production control device. Fig. 3 shows materials and information flow under the MRP system and JIT production system. At a glance, there is no reason why centralized planning information should not be used at the earlier stages of JIT production system. By the same token, Kanban control mechanism can be used to execute the production plan in the MRP based manufacturing environment by adjusting daily or weekly (time bucket) throughput rate.

4.2.3. Long term flexibility of MRP and short-term agility of Kanban

The ability to respond to new or unforeseen circumstances is one of the major components of system flexibility (Slack and Correa, 1992). In that manner, production control based on either MRP or JIT can be considered *inflexible* depend-

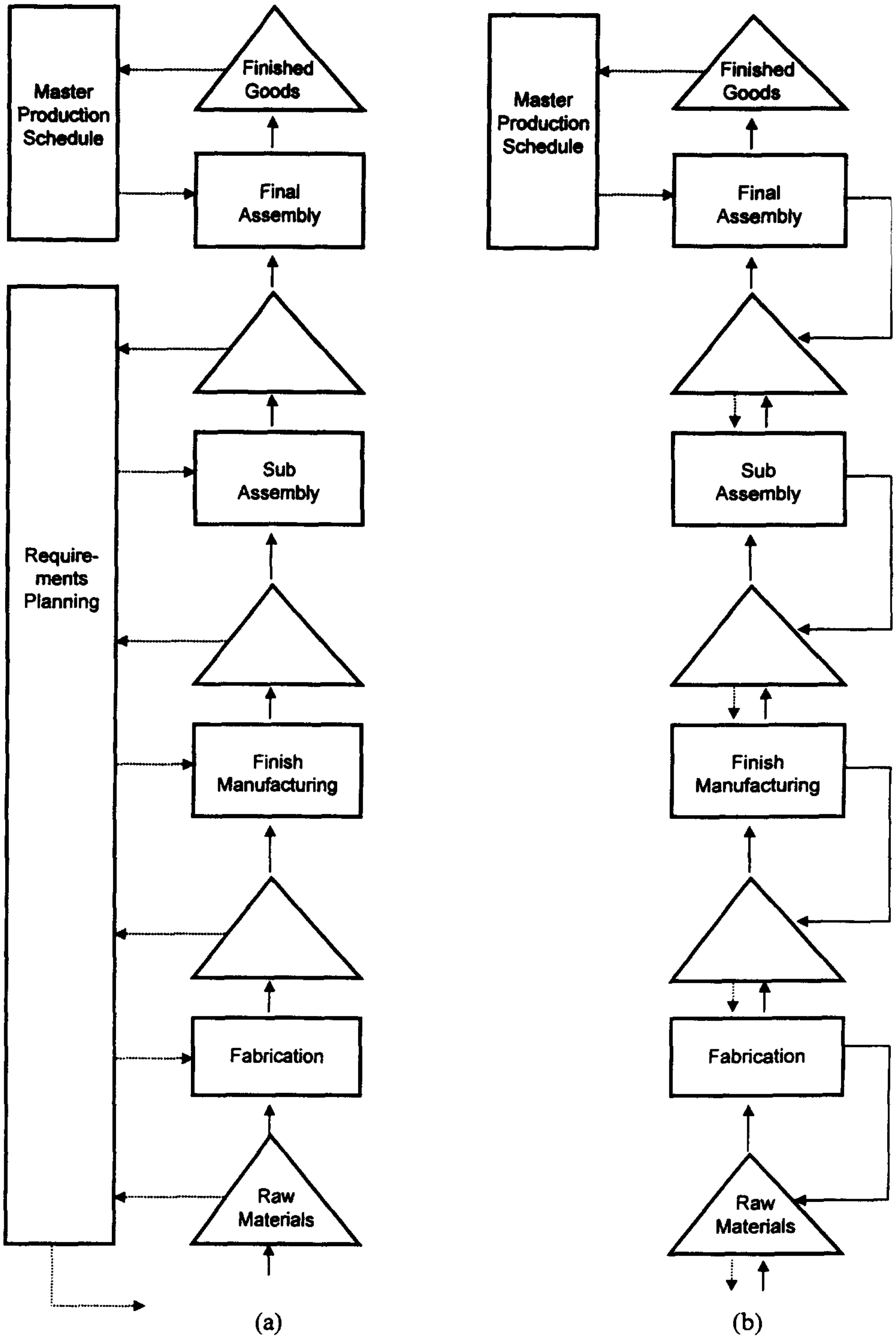

Fig. 3. Controlling production processes with MRP (a) and JIT (b): source "Embedding JIT into MRP" (Flapper et al., 1991).

ing on the manufacturing environment. In the literature, 'MRP nervousness' and 'susceptibility' of Kanban to lumpy and various demands are the very causes of inflexibility. [2]

MRP rigidity is a systematic problem that will remain permanently unless the pure MRP system is modified. MRP nervousness can be easily alleviated by reducing day to day operational failures. Adopting JIT philosophy is a way to tighten control over the production system. It is important to notice that the superiority of JIT production system in controlling production is achieved not by the Kanban itself, but by the management emphasis on the shop floor operation. In conjunction with JIT philosophy, Kanban system must be considered *"a convenient way to implement small lot strategy and a way to expose environmental problem* (Krajewski et al., 1987)". In addition, the purpose of Kanban is to provide agility in daily production. According to Monden (1984), a Kanban system is able to adjust production to daily oscillation of demand *within* ±*10%* deviations from the monthly production schedule.

It is quite predictable that JIT production systems cannot respond effectively to lumpy demand without the buffer mechanism. Therefore, in reality, implementing a JIT production system also requires main features of conventional MPC system such as aggregate production planning, MPS, and material requirements planning in order to be effective (Vollmann et al., 1992). The role of the MPS is twofold. First, limited by capacity of the plant, the MPS provides the basis to meet various customer demands. Second, it plays a role as a balancing mechanism to sustain smooth production throughout the planning horizon.

Steele et al. (1995) shows that higher variations in the MPS volume and product mix reduces the performance of JIT production systems. What's more, intuition tells us that constant part usage rate and production rate are essential in scheduling of rate based production system. In the JIT production system, the production rate predetermines the capacity and volume of MPS, and this rate based MPS is the major ground to meet demand and achieve stability in the future production.

The material requirement planning process is also a critical function of JIT production system in which smaller production lot sizes and frequent setups and deliveries are required. JIT also requires suppliers to respond quickly. The MRP explosion process would help suppliers estimate part usage of the manufacturer, and the responsiveness of supplier as well as system flexibility can be enhanced as a result. After all, flexibility of a production system can be much improved by combining MRP/JIT planning and controlling techniques, yet this proposition has not been empirically tested or proved so far.

4.3. MRP and JIT integration literature

4.3.1. Conceptual MRP/JIT and push/pull integration studies

Just as the conceptual MRP/JIT conceptual studies, research on the conceptual and structural integration between the MRP and JIT production system discusses the general issues and possibilities of the integration. In the conceptual integration studies, MRP and Kanban are understood as tools that help companies achieve just-in-time production. Thus, conflict between them can be altered through coordination (Belt, 1987; Karmarkar, 1989).

In his conceptual framework for the MRP/JIT hybrid manufacturing system, Karmarkar (1989) states that an MPC system can be tailored in terms of the process characteristics: continuous flow, batch repetitive, batch dynamic, and custom engineering. Depending on the process nature, the choice of push/pull at the various stages of production must be determined for optimal performance. Karmarkar also provides several examples of the modified MRP systems in which the MRP/JIT components coexist. Those examples are 'syncro MRP', 'rate-based MRP', and 'JIT-MRP'.

The possibility of integration of MRP and JIT was also predicted by Bullinger et al. (1986) in their article, "Toward the Factory of the Future", that discusses the future of the manufacturing in-

[2] The meaning of flexibility varies in the literature. Since defining flexibility of MPC system is out of scope of this review, the authors did not attempt to analyze in detail. For further information, refer to Slack and Correa (1992).

dustry. Bullinger et al. predicted that the future development of MPC systems would focus on combining the advantages of MRP (integrated planning, control, and ability to respond to customers' requests) and those of JIT production system (reduced work in process inventory and cycle time). Bose and Rao (1988) also argue that implementing the JIT system, into the MRP system could rationalize and simplify the existing production processes, resulting in an operating environment containing both repetitive and discrete processes, i.e., an MRP/JIT hybrid environment. They suggest that MRP be used as a general guideline to achieve smooth production in the long run, and Kanbans be used in determining the capacity constraints of daily production.

Discenza and McFadden (1988) and Belt (1987) focused on the information flows. They identify Bills of Materials and MRP explosions as the major opportunity for change. In particular, Belt suggests the use of JIT systems on the shop floor since Kanban provides visual information flow, and this capability of Kanban can cover the information gap between the production planning and the finished goods inventory control.

Unlike the researchers who suggest the decision criteria in determining the coverage by the MRP/JIT strategies, Flapper et al. (1991) provide a framework for embedding JIT into an MRP system. The primary motivation of Flapper et al.'s study is to prevent JIT implementation failures. To combine MRP and JIT production systems, Flapper et al., suggest two MRP techniques, 'Backflushing' and 'Phantom Bills of Materials'. Backflushing is an automatic registration process of resources in standardized units for a particular order. Backflushing helps all of the operations functions prepare for the upcoming production. Phantoms are the fake items on BOM that cannot trigger order release for production or purchasing. The use of Phantoms is to allow the JIT production system to control materials flow within the MRP hierarchy. Using these MRP techniques three steps can be taken to embed JIT production system as the following: (1) creating a logical line flow through rapid material handling, (2) using a pull production control system on the logical line, (3) creating a physical line flow.

Olhager and Östlund (1990) studied various integration techniques under a set of different environmental settings. Classifying the manufacturing continuum into make-to-stock, assemble to stock, make to order, and engineer to order, they indicate that the bottleneck in the production network is the critical decision point where the pull and push techniques can be divided.

In general, most of the researchers realize that the MRP system is an ideal mechanism for planning production activities, but is less successful as a controlling mechanism for reducing costs and lead-times and improving quality in production processes. Therefore, the MRP planning based Kanban controlled production system is the hybrid system described in the literature.

4.3.2. Analytical MRP/JIT and push/pull integration studies

Numerous conceptual studies contribute to the performance measurement of hybrid systems, however they have built analytical frameworks on which each of the different production control techniques can be compared. Nine articles are classified into this category, and the experimental settings and performance measures are categorized in Table 5.

In this category, the primary focus of MRP/JIT integration studies is different from that of push/pull integration approaches. In the push/pull comparison studies, researchers designed the same physical settings for a push, pull, and hybrid system and employed a set of decision variables to compare the shop floor performance of each system (Hodgson and Wang (1991a, b); Hirakawa et al., 1992; Deleersnyder et al., 1992). Since this push/pull integration studies assume the same production environment for both push/pull and hybrid system, the problem of how to organize reasonable experimental settings and how to determine performance measures for the impartial comparison still remains critical.

Unlike the push/pull integration approach, the MRP/JIT integration studies start with a premise that the MRP/JIT integrated system would perform better than a pure MRP or pure JIT production system. Therefore, these integration studies try to find an optimal MRP/JIT hybrid system among the possible alternatives (Ding and Yuen,

Table 5
Experimental settings of the analytical integration studies

Refs.	Experimental setting (or factors)	Performance criteria	Measures	Methodology in detail
Chaudhury and Whinston, 1990	• Multiwork station production • Adaptive learning algorithm with reward-penalty reinforcement • Ability of the adaptive agent to recognize the loading situations (state space)	• Response times for tasks	• Average queue length	• Stochastic automata methods and simulation
Ding and Yuen, 1991	• Multiple level production • Modified MRP systems • Cycle times • Lead time		• Total inventory level • Shortage level	• Simulation by GPSS-H
Hodgson and Wang, 1991a	• Parallel multistage production inventory system • Probabilistic production rate • Conditions for the production trigger • Conditions for the production objective	• Based on strategy evaluation function	• Total cost including inventory carrying cost and shortage cost • Optimal gain of solution (g)	• Markov decision process model with a probability mass function of production • Test simulation by FORTRAN 77 programming
Hodgson and Wang, 1991b	• Parallel multistage production inventory system • Various push/pull hybrid policies • Conditions for the production trigger	• Based on strategy evaluation function	• Total cost including inventory carrying cost and shortage cost • Optimal gain of solution (g)	• Control and information structure analysis • Markov decision process model • Test simulation by FORTRAN 77 programming
Deleersnyder et al., 1992	• N-stage serial flow line model • Machine reliability as a probability mass function • Conditions for the production trigger • Conditions for the production objective • Number of Kanbans • Variability of demand and production	• Sensitivity of the system (service level) • Inventory	• Average backlog • Total inventory level	• Discrete time Markov process

Table 5 (Continued)

Refs.	Experimental setting (or factors)	Performance criteria	Measures	Methodology in detail
Hirakawa et al., 1992	• Multistage production • Fluctuation of Demand quantity • Demand forecast errors • Inventory (ending and target)	• Behavior of production • Behavior of inventory	• Variance in production quantity • Variance in inventory level	• Mathematical production order quantity model • Demand model • Forecasting model
Huq and Huq, 1994	• Hypothetical job shop environment • Multiple work stations with multiple machines • Setup and processing time variations • Load levels • Machine breakdowns	• Inventory • Service	• System and WIP inventory value • Due date performance based on the percent of jobs tardy and average tardiness in days	• Discrete event simulation of a hypothetical job shop (SIMSCRIPT II.5)
Hirakawa, 1996	• Multistage production • Fluctuation of demand quantity • Demand forecast errors • Length of push horizons Production lead time	• Behavior of production • Behavior of inventory	• Variance in production quantity • Variance in inventory level	• Mathematical production order quantity model • Demand model • Forecasting model

1991) or application conditions where a particular model functions appropriately (Chaudhury and Whinston, 1990, and Hug and Hug, 1994).

Chaudhury and Whinston (1990) present a hybrid control methodology for a flow shop that is decentralized and adaptive in nature. In scheduling jobs for their model, both Kanban type pull and push mechanism are used simultaneously. The flow shop model is similar to Kanban controlled production system in terms of low data handling processes and decentralized nature. However, Chaudhury and Whinston argue that their model comprises more flexibility than the Kanban system since it incorporates self-adaptability to a changing environment. According to them, this flow shop environment is related to the computer aided or computer integrated manufacturing process (CAM, CIM).

The simulation study by Ding and Yuen (1991) presents a model of a modified MRP production system with the coexistence of MRP and Kanbans. The main proposition of this study is that the MRP system itself has a capability of adopting the Kanban production control scheme. The primary focus of this study is to evaluate how the modified MRP systems can deal with the coexistence of MRP and Kanban, effectively.

Modeling a hypothetical job shop, Huq and Huq attempted to identify the best application conditions on which JIT production techniques can be embedded in an MRP based job shop system. As discussed earlier, Huq and Huq (1994) argue that the unrealistic capacity constraints of MRP system and the gap between MRP's deterministic nature and uncertainty of operations are the major reasons why MRP alone does not work effectively in a job shop environment. In order to find optimal conditions, they simulate the effect of setup and process time variations, load levels, and machine breakdowns on a JIT (pull) job shop production system. The results show that in a job shop environment variations in setup and process time do not significantly affect the performance, and leveling workload is a key factor to sustain better performance of JIT based job shop production.

A series of studies by Hodgson and Wang (1991a, b) opened a new area of the integration studies by formulating a more complex production environment, multiproduction stage with parallel production lines. The objective of their study was to measure the realistic performance of the optimal push/pull hybrid system. The performance of the pure pull system, pure push system, and push/pull-combined system was compared based on the inventory carrying cost and shortage cost. After testing their mathematical model using simulation, Hodgson and Wang demonstrate better performance of the hybrid system. Deleersnyder et al. (1992) also conducted the same type of study comparing the performance of the pure pull, hybrid, and pure push in the multistage serial flow line production environment. The result of this study also indicates that the hybrid approach combines the benefits of both pull and push systems, that is, the hybrid system is able to respond to demand variations and retain the simplicity of control at the same time.

Hirakawa et al. (1992) focused on the behaviors of production and inventory by measuring the variance in production and inventory level rather than measuring total production quantity and average inventory. This experimental setting was constructed under the reasoning that the variability of production and final inventory would determine the safety stock level. In addition, two critical assumptions were made as the type of production control would affect the length of forecasting horizon and as the real demand triggers pull production and forecast initiates push production. According to Hirakawa et al., the performance of each production control system can vary depending on the variability of forecast and actual demand. However, in general, the push/pull hybrid system with a limited push horizon is effective in reducing the inventory variance.

It is important to note that while the conceptual studies only concentrate on discussing the static strength of hybrid systems, analytical integration studies have examined the dynamic nature of the MRP, JIT, and hybrid production systems using various experimental tools. Yet, the scope of most MRP/JIT studies is still limited to shop floor. Moreover, some of the researchers do not successfully extract the managerial implications of their studies. As a matter of fact, this analytical integration area shows a great deal of potential for future research.

5. Summary and future research directions

Since JIT was introduced by Toyota, the strongest debate in the Operations Management has centered on the performance comparison and compatibility with MRP system. Moreover, defining the nature of MRP and JIT as push and pull has created even more controversy. To clarify the current research focus in this area, the true identities of MRP and JIT were defined in conjunction within their historical context. The relationship between MRP/JIT and push/pull strategies was also reviewed. A taxonomy of MRP/JIT and push/pull studies was also provided. Following the taxonomy, two major categories of the literature, comparison studies and integration approaches, were examined.

After an extensive review, we identified three major controversies associated with push/pull principles, compatibility between MRP and JIT system, and flexibility of systems. There appears to be no conclusive answer to these issues. However, in this literature review, we uncovered the potential of MRP/JIT integration that may provide approximation solutions for the controversies. In a hybrid system, MRP and JIT work together, combined push/pull principles are used, and JIT inflexibility and MRP nervousness may be reduced. Therefore, the above mentioned controversies are reconciled to achieve an acceptable level of performance.

One of the important findings of this study is that a complete changeover from the conventional manufacturing system to a pure JIT production system is not popular and may not be successful. Rather, a partial implementation of JIT philosophy and JIT production system might be more reasonable, economical, and effective. In practice, there rarely exists a pure MRP or JIT controlled manufacturing system. Hewlett–Packard, one of the distinguished JIT users in the US, uses a modified MRP system, 'Selective MRP-JIT', in order to link the JIT production technique to the previous MRP system (Vollmann et al., 1992). Under these circumstances, a direct comparison of a pure Kanban or JIT production system with a pure MRP system may no longer reflect the current business practices. In this context, the future research direction should be related to developing theories and models for the hybrid manufacturing system.

Several future research extensions are suggested in this evaluation.

1. How to view or how to structure this hybrid environment in practice remains controversial and can be studied further. Some researchers believe that adopting JIT production techniques to the MRP system has simply created the hybrid manufacturing system (Bose et al., 1988; Chin and Rafuse, 1993, etc.). For other researchers, combining the MRP and JIT systems should follow a more systematic route based on understanding the process characteristics and production environment (Lee, 1993; Karmarkar, 1989, etc.). If the future of MPC systems is to be built following the latter argument, practical problems with the MRP/JIT integration must be recognized and solved beforehand to provide a set of managerial implications. MRP/JIT integration is easy in theory, but challenging in practice. For instance, the JIT production system requires reduced lot size and setup time and unique facility layout. Indeed, how to adjust those requirements to the MRP controlling mechanism and ultimately how to structure an optimum hybrid environment in practice remains incomplete and can be studied further.

2. One possible extension is to study the push/pull integration without using the Kanban type of shop floor control system. The possibility of substituting CONWIP for the traditional Kanban has been discussed (Spearman and Zazanis, 1992; Gstettner and Kuhn, 1996). The CONWIP is a bounded work-in-process system but allows "pushing" items between servers to a certain degree. When the process time in a production station is extremely diminutive, sending the pull signal by Kanban may not be valid and the push system is a natural shop floor control technique (Spearman and Zazanis, 1992). The rationale of this research is that Kanban is not a representative or universal language for the pull system. By this research, further improvement of the push/pull hybrid system would be expected.

3. The flexibility of a push/pull hybrid system must be tested. Despite growing concern with

flexibility of manufacturing system, there is no research that analyzes and compares flexibility of the different MPC systems is available in this area. It has been believed that 'MRP nervousness' and 'susceptibility' of Kanban to lumpy and various demands would be reduced, yet this proposition has never been hypothesized.

As mentioned earlier, there is no clear distinction between the JIT implementation and MRP/JIT integration. JIT implementation implies embedding the JIT system into the predecessor MPC system for western firms. In this context, the MRP/JIT hybrid-manufacturing environment is to be understood as a natural evolution. In a hybrid manufacturing system, the strength of the MRP in materials planning and coordination and that of JIT production system at the shop floor level would be exploited in a harmonized way. Recently, some of the MRP/JIT and push/pull integration studies have adopted a more proactive approach to identify the optimal control systems given the existing production setting. This phenomenon can also be considered a natural progress in academia to develop the idealistic hybrid manufacturing environment.

Appendix A

Table A.1
MRP/JIT conceptual comparison literature

Category	Refs.	Title	Discussion	Methodology
MRP-JIT	Rice and Yoshikawa, 1982	A comparison of Kanban and MRP concepts for the control of repetitive manufacturing systems	Shop floor control Inventory control	Text
	Schonberger, 1983	Selecting the right manufacturing Inventory system: Western and Japanese approaches	Inventory control	Conceptual framework
	Gelders and Van Wassenhove, 1985	Capacity planning in MRP, JIT and OPT: A critique	Manufacturing planning and control	Text
	Aggarwal, 1985	MRP, JIT, OPT, FMS	General issues	Text
	Plenert and Best, 1986	MRP, JIT, And OPT: What's "Best"?	Manufacturing planning and control	Text
	Buxey, 1989	Production scheduling: practice and theory	Manufacturing planning and control	Text
	Ptak, 1991	MRP, MRP II, OPT, JIT, and CIM – succession, evolution, or necessary combination	General issues	Text
	Brown and Mitchell, 1991	A comparison of JIT and batch manufacturing: The role of performance obstacles	General issues	Survey
	Matsuura et al., 1995	Concepts, practices and expectations of MRP, JIT and OPT in Finland and Japan	General issues	Survey
Push–pull	De Toni et al., 1988	Production management techniques: push–pull Classification and application conditions	Inventory control manufacturing planning and control	Conceptual framework

Table A.2
MRP/JIT analytical comparison literature

Category	Refs.	Title	Discussion	Methodology
MRP-JIT	Krajewski et al., 1987	Kanban, MRP, and shaping the manufacturing environment	Manufacturing planning and control	Simulation
	Fallon and Browne, 1988	Simulating JIT systems	Shop floor control inventory control	Simulation
	Lambrecht and Decaluwe, 1988	JIT and constraint theory: The Issue of bottleneck management	Shop floor control	Simulation
	Buzacott, 1989 [a]	Queueing models of Kanban and MRP controlled production systems	Manufacturing planning and control shop floor control	Mathematical modeling
	Rees et al., 1989	A comparative analysis of an MRP lot-for-lot system and a Kanban System for a multistage production operation	Shop floor control manufacturing planning and control	Simulation
	Grünwald et al., 1989	A framework for quantitative comparison of production control concepts	Manufacturing planning and control	Mathematical analysis
	Sipper and Shapira, 1989	JIT vs. WIP- a trade-off analysis	Inventory control	Mathematical analysis
	Steele et al., 1995	Planning and control in multicell manufacturing	Manufacturing planning and control shop floor control	Simulation
Push–pull	Lee, 1989	A comparative study of the push and pull production systems	Shop floor control	Simulation
	Sarker and Fitzsimmons, 1989	The performance of push and pull systems: A simulation and comparative study	Shop floor control	Simulation
	Luss, 1989	Synchronized manufacturing at final assembly and feeder shops	Shop floor control	Mathematical analysis
	Baker et al., 1990	The performance of push and pull systems: A corrected analysis	Shop floor control	Simulation
	Pyke and Cohen, 1990	Push and pull in manufacturing and distribution systems	Manufacturing planning and control inventory control	Simulation
	Slack and Correa, 1992	The flexibility of push and pull	Flexibility (Product, mix, volume, delivery)	Field study
	Spearman and Zazanis, 1992	Push and pull production systems: Issues and comparisons	Manufacturing planning and control shop floor control	Mathematical modeling

[a] MRP/JIT integration model is included.

Appendix B

Table B.1
MRP/JIT conceptual integration literature

Category	Refs.	Title	Discussion	Methodology
MRP-JIT	Bullinger et al., 1986	Towards the factory of the future	Manufacturing planning and control	Text
	Belt, 1987	MRP and Kanban – A possible synergy	Manufacturing planning and control	Conceptual framework
	Discenza and McFadden, 1988	The integration of MRP II and JIT through software unification	Manufacturing planning and control	Conceptual framework
	Bose and Rao, 1988	Implementing JIT with MRP II creates hybrid manufacturing environment	Manufacturing planning and control shop floor control	Conceptual framework
	Rao and Scheraga, 1988	Moving from manufacturing resource planning to JIT manufacturing	Manufacturing planning and control	Conceptual framework
	Summers et al., 1989	MRP and JIT, can they be complementary?	General issues	Case study
	Karmarkar, 1989	Getting control of JIT	Manufacturing planning and control shop floor control	Conceptual framework
	Rajput and Bennett, 1989	Modular system design and control for flexible assembly	Manufacturing planning and control shop floor control	Conceptual framework
	Flapper et al., 1991	Embedding JIT into MRP	Manufacturing planning and control	Conceptual framework
	Lee, 1993	A recent development of the integrated manufacturing system: A hybrid of MRP and JIT	Manufacturing planning and control shop floor control inventory control	Conceptual framework
	Sillince and Sykes, 1983	Integrating MRP II and JIT: A management rather than a technical challenge	Manufacturing planning and control	Conceptual framework
	Chin and Rafuse, 1993	A small manufacturer adds JIT techniques to MRP	General issues	Case study
Push–pull	Olhager and Östlund, 1990	An integrated push–pull manufacturing strategy	Manufacturing planning and control	Case study

Table B.2
MRP/JIT analytical integration literature

Category	Refs.	Title	Discussion	Methodology
MRP-JIT	Chaudhury and Whinston, 1990	Towards an adaptive Kanban system	Manufacturing planning and control shop floor control	Mathematical analysis and simulation
	Ding and Yuen, 1991	A modified MRP for a production system with the coexistence of MRP and Kanban	Manufacturing planning and control	Simulation
	Huq and Huq, 1994	Embedding JIT in MRP: The case of job shops	Shop floor control	Simulation
	Betz, 1996	Common sense manufacturing, a method of production control	Manufacturing planning and control	Field study
Push–pull	Hodgson and Wang, 1991a	Optimal Hybrid push/pull control strategies for a parallel multistage system: Part I	Shop floor control	Optimization
	Hodgson and Wang, 1991b	Optimal hybrid push/pull control strategies for a parallel multistage system: Part II	Shop floor control	Optimization
	Hirakawa et al., 1992	A hybrid push/pull production control system for multistage manufacturing processes	Manufacturing planning and control shop floor control	Mathematical analysis
	Deleersnyder et al., 1992	Integrating Kanban type pull systems and MRP type push systems: Insights from a Markovian model	Shop floor control	Mathematical analysis
	Hirakawa, 1996	Performance of a multistage hybrid push/pull production control system	Manufacturing planning and control shop floor control	Mathematical analysis

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