Int J Adv Manuf Technol (2002) 20:515–525
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The International Journal of
Advanced Manufacturing Technology

Integrated Production Model in Agile Manufacturing Systems

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To reach the goals of quick response to customers' needs and increasing the flexibility of producing goods, we integrate "push" and "pull" production models, which are the most popular production systems nowadays, for controlling automated manufacturing systems. This integrated production model can best be applied in an agile manufacturing environment. Push systems, involving MRP calculations, are the basis of distributing materials to the plant. Pull systems the so-called just-in-time (JIT) systems, produce products that exactly meet customers requirements. By introducing the concept of the theory of constraints (TOC) and optimised production technology (OPT), the integrated production model is made possible. Optimised production technology, based on the theory of constraints is the most important theory for manipulating constraint resources in a production line employing both the push and pull concepts. By merging these two fundamental principles, an integrated push and pull production paradigm is developed.

This work aims at finding a production model for manufacturers to apply in continuously and unanticipated changing competitive environments.

Keywords: Agile manufacturing systems; Automated manufacturing systems; Optimised production technology; Theory of constraints

1. Introduction

The characteristics of flexibility and fast organisation of manufacturers and suppliers reveal the applicability and strength of agility in agile manufacturing systems. Agile system characteristics can be achieved only in automated manufacturing systems (AMSs) (a thorough discussion can be found in Huang [1]). Automated manufacturing systems are the manufacturing systems that consist of resources including machines, robots, and automated guided vehicles (AGVs). With the abilities of automation and computerisation, quick response to customers' and suppliers' requests can be fulfilled. However, the numerous concurrent operations and actions involved in these systems make their control and analysis difficult and complex. This paper focuses on the study of modelling issues related to agile manufacturing systems (AGMSs) under the integration of push and pull paradigms.

For today's manufacturing systems, the material requirements planning (MRP) technique which is involved in the push production systems and the just-in-time (JIT) technique which is involved in pull systems using the Kanban technique are the two major production control systems. Each of them results in different system performances, especially in both production and inventory control. The push systems using the MRP technique are simply schedule-based systems starting from forecasting and can be implemented using a master production schedule. The resulting system performance can be easily identified as increasing the throughput and enhancing machine utilisation. This is simply because a system using the master production schedule, which is based upon forecasts, tends to send parts and materials to a plant regardless of what is required for next operation. On the other hand, pull systems using the Kanban technique manufacture or replenish parts only after being requested by the succeeding operations or machines. This indicates that machines only produce the goods that the customer required and so the systems will produce a low work-in-process (WIP).

Although we can achieve improved system performance either by maximising utilisation and throughput or minimising the WIP inventory by selecting either push or pull systems, the disadvantages, which are produced by those two production paradigms, cannot be neglected. Selecting a push system may increase WIP and create capacity and flow disorder. Choosing a pull paradigm, the system performance may result in low facility use. Therefore, trying to integrate both push and pull production paradigms for modelling a new production paradigm is the major concern of this paper.

2. Existing Production Models and Agile Manufacturing Systems

Owing to the fast changes of technology and manufacturing environments, manufacturing methods have altered from mass

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production, through low volume–high mixed production, to today's high volume–high mixed world class manufacturing (WCM). It is well known that the existing production control systems which are mostly used by industry can be divided into push and pull production systems. Both production models lay the foundation of agile manufacturing systems.

In this paper, the entire production paradigm can be seen as forward and backward manufacturing structures and the operational paradigms may trigger material-issuing control, which can resolve the bottleneck problem. The construction of an integrated model can fulfil the requirements of an agile manufacturing systems.

2.1 Existing Production Models

Push and pull systems are defined from different perspectives [2–5]. From this, we realise that manufacturing systems can be partitioned roughly into three portions namely distribution control, material control, and production. For both the push and pull systems, different process aspects are assigned to those three portions. *Distribution control*, for a push system, refers to a system for replenishing field warehouse inventories in which replenishment decision-making is centralised, usually at the manufacturing site or central facility; whereas for a pull system, the replenishment decisions are made at the field warehouse itself, not at the central warehouse or plant. *Material control*, for a push system, refers to the issuing of material according to a given schedule and/or issued to a job order at its start time; but on the other hand for a pull system, it refers to the withdrawal of inventory as demanded by the using operations, i.e. material will not be issued until a signal or a request card (the so called Kanban) comes from the user. *Production*, for a push system refers to the manufacturing of items at times required by a given schedule planned in advance; whereas for a pull system, items are manufactured only as demanded for use, or to replace those taken for use. For operational perspective, a "push" system produces parts or items without waiting for a request from the succeeding machine; whereas a "pull" system manufactures parts or items only after it receives a request from the succeeding machine [2,4,5].

From the preliminary study, push and pull systems each have their own advantages and disadvantages. When running in the push paradigm, the system issues and produces materials and parts based on the given schedule without considering the entire production capacities. This may result in high resources utilisation and output rate, however, it is accompanied by the higher work-in-process (WIP). Running in pull production paradigm, on the other hand, the system issues and produces materials and parts only as demanded by the required operations or customer orders. It is well known that a low WIP can be achieved by implementing just-in-time (JIT), which is based on a pull paradigm. Unfortunately, systems implementing JIT may result in low resource utilisation and throughput.

2.1.1 MRP Technique – the Push Model

Material requirements planning (MRP), is a computational technique used for the push paradigm that converts the master production schedule (MPS) into a detailed schedule for raw materials and components used in the end products. Parts are loaded into the AMSs based on minimising the difference between the actual products produced and the scheduled orders released. This control concept is also used to dispatch parts to machines within the plant whenever necessary.

The well-known MRP algorithm is given as follows (see, for example, [6,7]). The formulas give the schedule of material required at each level of the bill of materials (BOM) and incorporate the backtracking used in MRP.

Define the planning horizon as $t = 1, 2, \ldots, T$; i is the part type or product.
Let $P_{i,t} = x_{i,t-1} + Q_{i,t} - G_{i,t}$,

where:

1. $x_{i,t}$ is the *final inventory* of parts type i at period t,
2. $Q_{i,t}$ is the *scheduled order receipt* of period t,
3. $G_{i,t}$ is the *gross requirement* of period t,

therefore,

$$x_{i,t} = (P_{i,t})^+$$

where $(\cdot)^+$ denotes positive inventory,

$$y_{i,t} = -(P_{i,t})^-$$

where $y_{i,t}$ = net requirement and $(\cdot)^-$ denotes negative inventory,

$$Q_{i,t} = y_{i,t}$$

$$O_{i,t-Li} = y_{i,t}$$

where:

1. L_i is the *lead time* of part i,
2. $O_{i,t}$ is the *schedule order release* of parts type i at period t,

$$G_{i,t} = \sum_{\substack{all\ predecessors \\ k}} O_{k,t} \times e_{i,k} + d_{i,t}$$

where:

1. $e_{i,k}$ is the (i,k) element of the BOM matrix,
2. $d_{i,t}$ is the independent demand (if any).

Based upon the above calculation and all the production information required, including the estimation of production defect rate, safety stock, etc., we can dispatch materials and parts so calculated, to machines in the factory.

2.1.2 JIT System – the Pull Model

The just-in-time (JIT) system is based on the pull production paradigm using Kanban techniques when implementing the pull system. JIT is actually a philosophy in which materials and components required in the production process are available at exactly the time required. When implementing the JIT system, several considerations are important:

1. The plant should have their suppliers as close as possible and suppliers have to maintain excellent schedules themselves otherwise the whole system falters.

2. The transportation between plant and suppliers should be close or efficient enough to keep deliveries on time.
3. All the materials must have zero defects because of the zero inventory concept.
4. Communications between the manufacturer and supplier should be optimised and no delay can be tolerated.
5. The in-house schedule has to be maintained. This requires short set-ups, high quality, and realistic schedules.

2.2 Agile Manufacturing Systems' Environment

The concepts of agile manufacturing systems (AGMS) were first expressed in 1991 [8]. Various definitions were provided from different perspectives (Table 1). All of them agree that the major aspect of AGMS is to respond quickly enough and correctly to the unanticipated changes of the manufacturing environment. We have tried to provide an overall definition of AGMS which is stated as follows: AGMS is a new production management concept and philosophy. It integrates and employs an enterprises' inner resources, including manpower, information and organisation abilities, and outside virtual organisations expertise in order to response quickly, efficiently, and economically to the changes and uncertainties of the outside environment, to satisfy market requirements which are increasingly for high quality and customisation.

Some believe that agile manufacturing is similar to lean production, flexible manufacturing, or computer-integrated manufacturing, or the extension of these systems. In fact, AGMS is more than that. AGMS not only contains the characteristics of the above systems, but also integrates the changes of customer, supplier, and market requirements. It employs a large amount of information technology and enhances flexibility by using a dynamic approach to respond to requests rapidly. The basic differences between traditional manufacturing systems and agile manufacturing systems are shown in Table 2.

Hence, we have aimed at finding an applicable production model for manufacturers to run and to survive in a continuously and unpredictably changing competitive environment.

3. Theory of Constraints and Optimised Production Technology

The optimised production technology (OPT) is a philosophy for scheduling and working and is a tool for developing optimised production schedules. The fundamental theory of OPT is the theory of constraints (TOC), or constraint management [15]. By managing and controlling the constraint resources in production lines, the production schedules are able to achieve the so-called schedule optimisation.

For manufacturing systems, TOC attempts to identify the constraint resources, which are those operations in a production line with the least relative capacity and tries to smooth critical situations. These constraint resources are categorised as "physical constraints" which include machines, facilities, and useable resources; and "policy constraints", which include organisation at the system, management style, and attitude. In production lines, the resources with the smallest relative capacity constrain a plant's production level to their own capacity, that is, the excess capacity of non-constraining resources cannot be used.

By identifying those work centres where WIP inventory accumulates and which consistently produce late orders, the constraint resources can be found. Once the constraint resources are identified, the backward pull Kanban paradigm is applied from the constraint resources to initial operations and the push forward paradigm is employed from the constraint resources to the finished product packing and shipping. Figure 1 shows the basic structure of combining push and pull control concepts.

Table 1. Definitions of agile manufacturing systems.

Researcher	Definition of AGMS
Kidd [9]	AGMS integrates the entire organisation. In AGMS, workers have high skill knowledge and advanced technology for innovation and quick response to customers' needs, and provide high-quality and customised products.
Gunasekaran [10]	In a continuously and unpredictably changeing competitive environment, an enterprise can be successful and survive only through providing customised designed products and services, and quick and efficient response to the changing market. Agile manufacturing is required not only to reach the goal of correct response and flexibility for products, but also requires the abilities of adaptation and fast response for future changes.
Monker [11]	AGMS aims to make a quick response to the sudden and unexpected changes of the competitive environment and to manufacture the products or provide services that the customer requires.
Hormozi and Amir [12]	AGMS means employing resources having efficient, flexible, automated equipment, and re-assembly systems to respond quickly to customers and to manufacture highly customised products.
Steven, Goldman and Nagel [13]	AGMS combines the skills and characteristics of flexible manufacturing technology, total quality management, just-in-time production, and lean production to form a brand new production system.
Cheng, Harrison and Pan [14]	AGMS is a new developed technology. It means that enterprises have the abilities of flexible and quick response to customers' needs and the required design ability. With those abilities, companies are able to satisfy the changes of markets and customers' needs.

Table 2. Differences between traditional manufacturing system and AGMS.

Characteristics/System	Traditional manufacturing systems	AGMSs
Product character	Consistency/standardisation	Diversity/customisation
Source of information	Comes from the system itself	An upgraded, information, and service oriented opening system
Information system	Seldom employed	Large amounts of it are used
Life span of product market	Longer life span	Shorter life span
Manufacturing method	Production by forecasting	Production by order
Price strategy	Price = Cost of manufacturing + Profit	Value can be accepted by customers
Market position	Set in a special market	Existing in diverse market

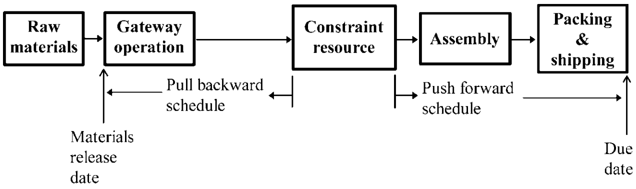

Fig. 1. Basic concept of TOC.

3.1 Studying the Nine Principles of TOC

The elementary concepts and logical way of thinking of the theory of constraints can help us in understanding the basis of this theory. The followings are nine principles of TOC, which are useful for implementing the theory in systems.

Principle 1. Balance flow, not capacity. Balancing the production flow can help to make sure the bottleneck resource is identified. Once the bottleneck resource is identified, schedule planning is based on the capacity of the constrained resource, instead of the capacities of all resources.

Principle 2. Constraints determine non-bottleneck utilisation. System throughput is controlled by the bottleneck resource; therefore, the utilisation of non-bottleneck resources is decided by the bottleneck resource. Hence, increasing the non-bottleneck resource utilisation will not increase the entire system performance. This, however, will produce more work-in-process (WIP) and inventory.

Principle 3. Utilization and activation of a resource are not synonymous. Utilization is related to the entire system's effective outputs; however, resource activation is trying to maximise its own capacity. Therefore, resource activation has no relation with effective output.

Principle 4. An hour lost at bottleneck is an hour lost for forever. The entire system throughput is determined by the bottleneck resource; if the bottleneck resource is idle or being set-up, then the production loss caused is not only for that bottleneck resource but also for the entire system.

Principle 5. An hour saved at non-bottleneck is just a mirage. The saving of set-up time or operation time for non-bottleneck resources can only increase a system's cost and increase WIP. This will not add to the system's output.

Principle 6. Bottlenecks govern both throughput and inventory. It must be understood that the influence of throughput and inventory by a bottleneck resource is not temporary.

Principle 7. Transfer batch should not always equal a process batch. Separating a process batch from a transfer batch can minimize the total production time.

Principle 8. The process batch should be variable, not fixed.

Principle 9. Schedules should be established by looking at all of the constraints simultaneously. Bottlenecks or constraint resources will change and move within the system. Therefore, schedules should consider all the constraints in the entire system simultaneously. For example, the MRP system set production batch and lead-time to a fixed value previously; the system will check the limitation of capacity only after actually operating.

3.2 Five Basic Steps for Executing TOC

There are five basic steps for implementing the theory of constraints. Based upon these five steps, different businesses or systems can perform their procedures or operations effectively and efficiently. Here we show those steps as follows:

Step 1. Identify the system constraints. System constraints represent those constraints which affect the global goal most. After the constraints are identified. The major concern is focusing on those items having insufficient supplies. The level of insufficiency restricts the system's outputs.

Step 2. Decide how to exploit the system constraints. After identifying the constraints, we must manage and control constraint items. Constraint items should have no waste. This is because once waste occurs in a system; it will damage the entire system performance.

Step 3. Subordinate everything else to the above decision. System performance is decided by constraints. Hence, the non-constraints should be responsible for supplying sufficient resources needed by constraints.

Step 4. Elevate the system constraints. Enhancing effectiveness of a system helps to improve the entire system performance. By continuous improvement, the previous constraint may no longer exist, but may be substituted by a new constraint.

Step 5. Warning! If in the previous steps a constraint has been broken, go back to step 1, but do not allow INERTIA to cause a system's constraints. If the previous constraint is relieved, then we must return to step 1 to start a new cycle. However, we must not allow inertia to cause system constraints.

In these five basic steps, the major focus of TOC is the bottleneck processes or operations. The fundamental of TOC is that the best way of scheduling is to identify constraint resources and attempt to acquire the best use of those constraints. Constraint resource can usually be detected from the process or operation that has the least relative capacity. This implies that the remaining capacities of the non-constraint resources cannot be used for the entire system.

4. Integrated Paradiasm in Agile Manufacturing Systems

4.1 Analysis Among MRP, JIT, and TOC

Different studies show that MRP, JIT, and TOC are the methods applied most in production systems nowadays. These three system models have their own advantages and disadvantages. Table 3 gives a comparison of the three production control models.

4.2 Push–Pull Integrated Model Under the Concept of TOC

The theory of constraints that is used as the fundamental theory of optimised production technology involves the constraint resources within production lines. In this paper, the proposed integration model and controlling structure are to integrate push and pull systems, not only considering the controlling concept for the constraint resources (which we usually consider as critical resources where a bottleneck may occur), but also controlling the entire automated manufacturing system by distributing or loading parts and materials to the production system from the very beginning according to the master production schedule (see Fig. 2). Thus, the desired-entire system performance will be enhanced because of loading the exact materials to a plant to meet the varied schedules and providing the materials that the constraint resources request using the backward pull paradigm. The operations after the constraint resources and those non-constraint resources will operate according to the forward push production paradigm to increase the production rate and machine usage as much as possible.

The numbers shown in Fig. 2 indicate the steps, which are based on the steps shown in Section 3.2 that we can perform in the push and pull integrated model. The details are shown in Table 4 for further explanation and implementation details.

Table 3. Comparison results among MRP, JIT, and TOC production control models.

Index/Model	MRP	JIT	TOC/OPT
Production load	Model presumes there exist infinite effective facilities and resources and scheduling system will work continuously.	Model presumes there exist only finite resources and controls capacity by using Kanban technique.	Model presumes there exist finite resources. Considers limitations of bottleneck and those of MRPs. It merges functions of MRP and CRP to be a production-planning tool.
Balanced capacity	Needed	Needed	Not needed
Buffer	Built in front of every machine or work station.	None	Built in front of the bottleneck.
WIP	High	None	Low
Batch size	Batch size is fixed. When batch size is increased, lead-time for production is also increased.	Very small. The set-up time is down to minimum.	Can be separated to achieve stack production status. Under such an approach, the set-up time of a bottleneck can be shortened to the minimum and maximises the output.
Production disorder	Using safety stock to balance the production fluctuations.	Using Kanban and a series of red lights or yellow lights to manage production disorders.	Using a tighter schedule and buffers to prevent production fluctuations.
Production flexibility	Compared to TOC/OPT, the production has less flexibility.	Having the maximum flexibility; this is because of having the smallest batch size and low inventory level.	Intending to schedule a lower inventory level and more flexible batch size.
Cost	Because it requires a high certainty and accuracy of data, the cost is the highest.	Since the data requirement can be neglected, the cost is the cheapest.	The cost is between the cost of MRP and JIT.
Central idea	To maintain an accurate schedule.	To eliminate waste.	To maximize effective output of bottleneck resources.

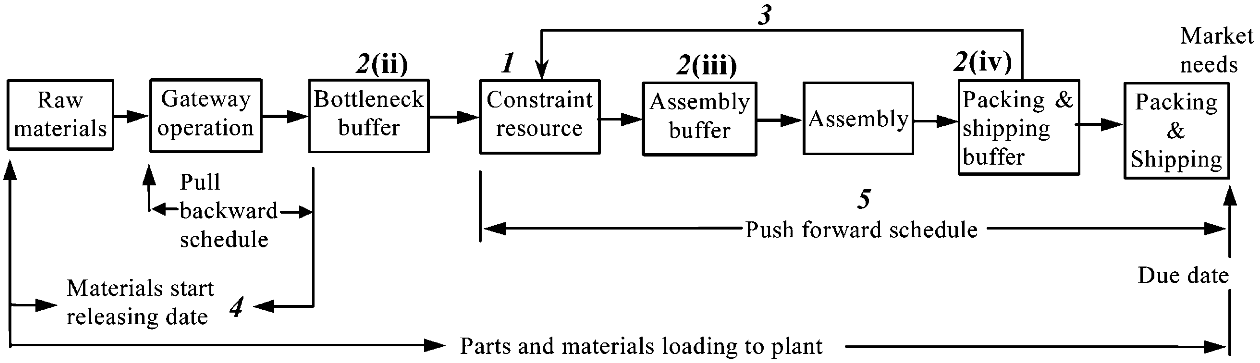

Fig. 2. Integrated concepts of push–pull systems with materials loading.

Table 4. Summary of implementing procedures for the push and pull integrated production model.

Implement steps	Implementation details	Method applied	Related reference
Step 1: Finding for constraint resources	(i) Finding first the workstation which easily accumulates jobs. (ii) Carefully observe the sources where parts are lost or delayed. (iii) Finding out those orders which have been delayed.	Capacity analysis Cause–effect diagrams; Result–Cause–Result analysis –	[16] [17,18] –
Step 2: To set up a buffer in front of a critical resource to protect system outputs	(i) Deciding the categories of buffers. (ii) Set up bottleneck buffer to avoid constraint resource running out of materials needed. (iii) Set up assembly buffer to avoid constraint resource waiting for parts to process. (iv) Set up packing and shipping buffer to ensure due date is kept.	V-A-T analysis DBR implementing principle DBR implementing principle DBR implementing principle	[19,20] [19,21] [19,21] [19,21]
Step 3: To decide the constraint resources' schedule	(i) Based on market needs and constraint resources. (ii) Considering the available set-up time and process time of constraint resource to decide the batch size and the possibility of mixed production.	Considering priority of orders. Batch size-two goals model; Tabu search	[22]
Step 4: Controlling the material release time in the plant to provide the needs for constraint resources	(i) For the processes from bottleneck resource to the initial operation (i.e. materials releasing place), proceed according to the pull backward schedule. (ii) To schedule by applying the rule of priority. This policy is used for the operations which will be processed on the same resource (i.e. shared resource).	DBR; JIT *Bottleneck*: Marginal profit analysis. *Non-bottleneck*: SPT, EDD, CR, FCFS, etc.	[16,19,21]
Step 5: Increasing the flow speed of constraint resources to smooth the operations of non-constraint resources	(i) Applying the push forward schedule where workstations have to follow the pace of bottleneck operations. (ii) Allow variable transfer batch and process batch to ensure material flows more smoothly.	DBR, MRP, Finite push forward Batch size-two goals model; Tabu search	[16,18,23] [2]

The proposed approach will incorporate the MRP system technique to load parts and materials to manufacturing systems. The approach comprises of two portions, which are referred to part loading, i.e. sending the desired materials to the manufacturing system and part dispatching that resolves problems when shared resources conflicts occur.

4.2.1 *Part Loading*

A part-loading rule can be developed to attempt to minimize the difference between the scheduled order releases and the quantities actually released to the AMS machine cells. For such a purpose we define the discrete function of time P^{In}_{ijt}, where

P^{In}_{ijt} = final total number of parts type i loaded in machine cell j during time period t, and define

$$T^{In}_{ijt} = \left[\sum_{k=1}^{t-1} (Z_{ijk} - P^{In}_{ijk}) + Z_{ijt} \right]^{+}$$

as the target number of parts type i that should be released to machine cell j up to period t.

The loading rule at any point of time during time period t is to load parts type i into cell j if

$$i = \arg\max \{[T^{In}_{ijt} - P^{In}_{ij}(\delta)]^{+}\} \quad (\delta \in (t-1,t)) \tag{1}$$

where the variable $P^{In}_{ijt}(\delta)$ is a continuous function of time and denotes the cumulative number of parts type i loaded into cell j at any point of time δ during period t. The relation between P^{In}_{ijt} and $P^{In}_{ij}(\delta)$ is that *at* $\delta = t, 2t, 3t, \ldots$ we make

$$P^{In}_{ijt} = P^{In}_{ij}(\delta), \quad P^{In}_{ij}(\delta) = 0$$

that is, we restart at zero every t time units.

The time index t is usually measured in weeks and corresponds to the time units used by the MRP system.

4.2.2 Part Dispatching

Once parts are loaded into the AMS machine cell, dispatching rules (or scheduling rules) are invoked for shared resources conflict resolution. We can derive an additional dispatching rule based on information taken from the MRP system. In this case the rule will attempt to minimise the difference between the parts produced and the parts that were planned to be completed based on MRP information, as given by the scheduled order receipts.

Define the discrete function of time P^{Out}_{ijt}, where

P^{Out}_{ijt} = final total number of parts type i produced by machine cell j during time period t, and define also

$$T^{Out}_{ijt} = \left[\sum_{k=1}^{t-1} (Q_{ijk} - P^{Out}_{ijk}) + Q_{ijt} \right]^{+}$$

as the target number of parts type i that should be produced in machine cell j up to period t.

Then at any point of time $\delta \in (t-1,t)$ when there is a conflict within the cell, we can choose to give a higher priority to parts type i if

$$i = \arg\max \{[T^{Out}_{ijt} - P^{Out}_{ij}(\delta)]^{+}\} \quad (\delta \in (t-1,t)) \tag{2}$$

In this case, *at* $\delta = t, 2t, 3t, \ldots$ we make

$$P^{Out}_{ijt} = P^{Out}_{ij}(\delta), \quad P^{Out}_{ij}(\delta) = 0$$

where the variable $P^{Out}_{ij}(\delta)$ is a continuous function of time and denotes the cumulative number of parts type i completed in cell j at any point of time δ during period t.

4.2.3 Part Tracking Control

The quantitative variables $P^{In}_{ij}(\delta)$ and $P^{Out}_{ij}(\delta)$ can be related to the binary representation of the AMS controller design in [1]. Hence, we can now define and increment function as

$$INC : R^{+} \times B \rightarrow N_0 = N \cup \{0\}$$

$$INC(x,b) = \begin{cases} x+1, & \text{if } b = \text{true} \\ x, & \text{if } b = \text{false} \end{cases} \tag{3}$$

Thus, the following functions can be developed as

$$P^{In}_{ij}(t) = INC(P^{In}_{ij}(t), Pin_i) \tag{4}$$

$$P^{Out}_{ij}(t) = INC(P^{Out}_{ij}(t), Pout_i) \tag{5}$$

where Pin_i and $Pout_i$ are logical variables from the AMS controller discription.

The dispatching rule can be used in conjunction with some of the other dispatching rules. which are also used for parts dispatching and which are discussed in [24]. Those rules are, for example. FIFO (first in first out), EDD (earliest due date), FBFS (first buffer first serve), etc.

The above control approaches permit controlling those desired materials distributed into AMSs to keep an exact match with the schedule planned for the global system and the integration model of forward push with backward Kanban paradigms.

5. Simulation and Results

5.1 Introductions And Problem Definition

Simulation is a powerful and widely used scientific management technique for the analysis and study of complex systems. The simulation technique is also used for non-destructive demonstration or model prediction. Simulation models have fewer restrictions than analytical models; thus, they allow the user greater flexibility in representing the real system. Once a model is built, it can be used to analyse different policies, parameters, or designs. This process can save the business millions of dollars and prevent errors in policy being made. A typical simulation procedure consists of formulating the problem, collecting the data, and developing a model, computerising the model, designing the experiment, performing the simulation runs, and comparing the results with a valid system if one exists.

5.1.1 Case Description

The manufacturing system problem is large and complex. It deals with the selection of the most efficient controlling models and making feasible scheduling decisions in various businesses or operations. However, the problem in this paper is that there are three different production models and we would like to know if the proposed integrated model is the most feasible or not. The cases for simulation are simplified and will be created by the author.

This work was a simulator named ProModel, which stands for Production Modeler. ProModel is a powerful, Windows based simulation tool for simulating and analysing production systems of all types and sizes. As a discrete event simulator, ProModel is intended primarily for modelling discrete part manufacturing systems. In addition, this simulator is designed to model systems where system events occur mainly at definite points in time. Time resolution is controllable.

The case problem we created for constructing the discussed production models is described for further study. A fictional-factory named NPUST Toy Factory produces three types of

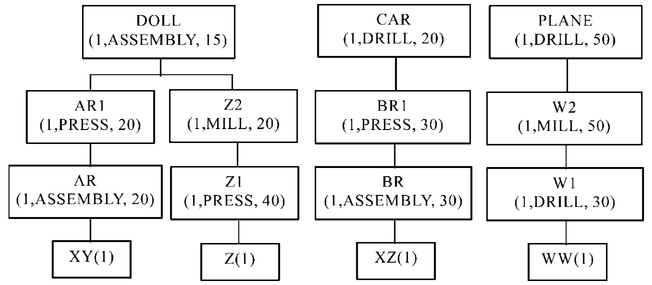

Fig. 3. Product structure and manufacturing flow. *Note*: parameters in parenthesis: (number of parts, manufacturing resource, process time).

product, which are doll, car, and plane respectively. Assume that the working period is five days a week and eight hours a day. The scheduled production quantities for both MRP and Push–Pull integrated models are doll = 15 units, car = 25 units, and plane = 15 units. For the JIT model, the scheduled production quantities are set to follow a normal distribution. There are four types of machines in production line, one press machine, one assembly machine, two mill machines, and two drill machines, respectively. For simplicity, we presume the transportation time required between machines is very small and can be overlooked and the set-up time is ignored. Only machine downtime is considered for simulation. The selling prices for the three products, doll, car, and plane, are $30, $40, and $60, respectively. The unit variable costs for those three products are $15, $34, and $45 dollars, respectively.

5.1.2 Model Construction and Data Collection

Here, the constructed simulation procedures for testing the production performances of those three models (i.e. MRP, JIT, and Push–Pull Integrated model) via simulator ProModel, are presented as follows. There are eight major actions that have to be taken for each simulating model:

Action 1. Create the production routine file based upon the product structure and manufacturing flow information. The routine file is based on route sheet information that includes the resources and process times needed in manufacturing processes.

Action 2. Based on the production routine file, the different standard process times for each product have to be established as the basis for calculating capacity loadings.

Action 3. Construct the master production schedule (MPS).

Action 4. Using both the standard process time file and MPS to calculate work loadings, check whether the production capacity is enough or not and where the bottleneck is located.

Action 5. If the production capacity is enough, then proceed to Action 6, otherwise, return to the rearrange MPS.

Action 6. Perform the detailed scheduling processes of those three simulating models.

Action 7. Employ the PorModel simulator to build those three simulation models.

Action 8. Analyse the simulation results.

The presumed and extended detail data for three simulating models are shown as follows in Figs 3 and 4, and Tables 5 to 9. The bill of materials and manufacturing flow information of the three products is presented in Fig. 3. The related layout of the virtual toy factory is shown as Fig. 4. All the calculated data and schedules are in Table 5 to 9. Total yield = 5(day) × 8 (hour per day) × 60 (min. per hour) = 2400. Loading rate (%) = One machine's process time/total yield.

5.2 Simulation Results

Major results as shown in Figs 5 to 8 and Table 10 and are discussed here. Figure 5 presents the difference of throughput

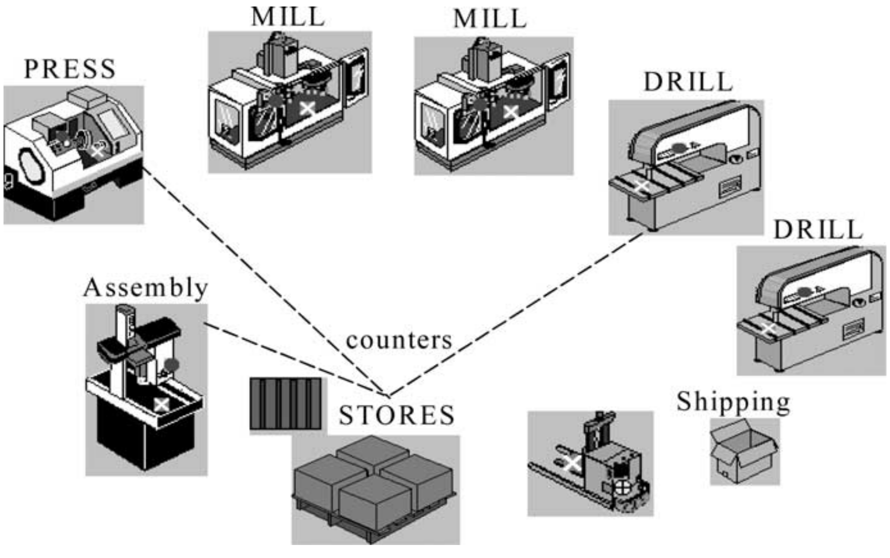

Fig. 4. The layout for a virtual toy factory.

Table 5. Different simulation conditions among MRP, JIT, and the integrated model

Comparing Item	MRP model	JIT model	Integrated model	Differences and commons
Simulation time	2400 min	2400 min	2400 min	Common
Runs	30 times	30 times	30 times	Common
Process batch	Same as MPS	Actual orders quantity	Same as MPS	Different
Transfer batch	Same as process batch	One unit	One unit	Different
Process time	Fixed constant	Fixed constant	Fixed constant	Common
Scheduling way	By product	By actual order received	By materials in bottleneck	Different
Bottleneck buffer	NA	NA	Yes	Different
Dispatching rule	FIFO	FIFO	FIFO	Common

Table 6. Routine sheets of three products.

Product name	Part	Manufacturing resource	Unit process time (min)	Output part
Doll	XY	Assembly	20	AR
	AR	Press	20	AR1
	Z	Press	40	Z1
	Z1	Mill	20	Z2
	AR1, Z2	Assembly	15	DOLL
Car	XZ	Assembly	30	BR
	BR	Press	30	BR1
	BR1	Drill	20	CAR
Plane	WW	Drill	30	W1
	W1	Mill	50	W2
	W2	Drill	50	PLANE

Table 7. Standard time of product.

Standard time (min) Product (per piece)	Manufacturing resource				
	Press	Mill	Drill	Assembly	Total
Doll	60	20	0	35	115
Car	30	0	20	30	80
Plane	0	50	80	0	130
Total	90	70	100	65	325

Table 8. Master production schedule.

Produce (piece)/Time	Week 1	Week 2	Week 3	Week 4	Total
Doll	15	15	15	15	60
Car	25	25	25	25	100
Plane	15	15	15	15	60
Total	55	55	55	55	220

rates among simulated models. The product throughput rate indicates the quantities of finished products produced within unit time. From Fig. 5, we can see that the throughput rate of the integrated model is higher than for the other two models and the throughput rate of JIT is fairly low.

However, the durations for WIP staying in buffers in the models shown in Fig. 6 shows us that the average time for a unit WIP staying in buffers for the integrated model is longer than for the JIT model, yet shorter than for the MRP model.

Analysing resources utilisation can help us to find out where the waste occurred. Except for the operation time of resources, usually the other time events (e.g., machine set-up time, idle time, downtime, waiting time, or blocked time) can be seen as waste or improved items. After simulating for 2400 min, the results of utilisation rate comparison for the three different models can be seen in Fig. 7. Figure 7 actually compares the operation time among resources. Although the trend for the three models is similar, the utilisation rate of the integrated model is the the highest.

For further study of the utilisation, we examine the utilisation of bottleneck resources for the three simulated models. From

Table 9. Capacity loading calculated.

Each manufacturing resource process time				
Product/Manufacturing resource	Press	Mill	Drill	Assembly
Doll (min per piece)	60	20	0	35
15 pieces of Dolls	900	300	0	525
Car (min per piece)	30	0	20	30
25 pieces of Cars	750	0	500	750
Plane (min per piece)	0	50	80	0
15 pieces of Planes	0	750	1200	0
Total process time (min)	1650	1050	1700	1275
Number of machines	1	2	2	1
One machine's process time	1650	525	850	1275
Total yield	2400	2400	2400	2400
Loading rate (%)	68.75	21.88	35.41	53.13

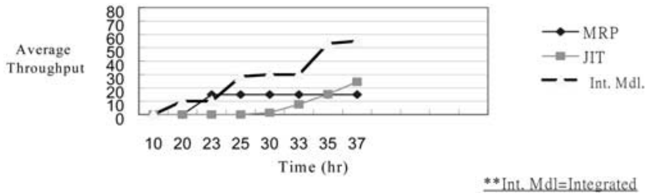

Fig. 5. Comparison of product throughputs of different models.

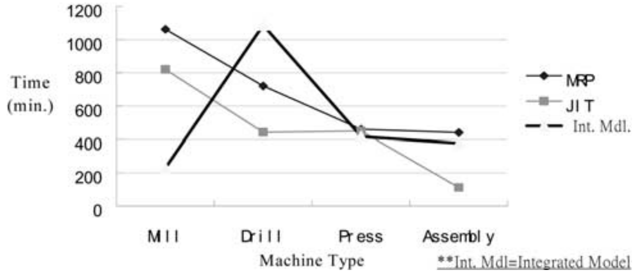

Fig. 6. The durations for WIP staying in buffers among models.

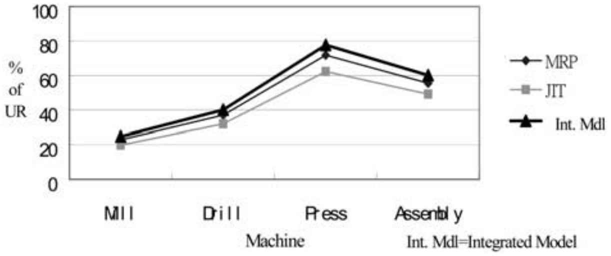

Fig. 7. Yield utilisation rate comparison for three different models.

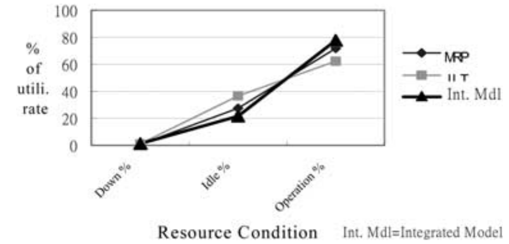

Fig. 8. Bottleneck yield utilisation rate comparison for three simulated models.

Table 10. Comparisons among production performances.

Comparison item	MRP	JIT	Integrated model
Max. product output (piece)†	58.5	59.3	62
Average staying time in buffer for every piece of WIP (min)	670.5	455.5	527.7
Bottleneck utilisation rate (%)	71.74	62.25	77.71

†The Max. product output is using 2400 min as the production cycle. The intention of the assumption is to try to increase the throughput of "Doll" and to apply this as the basis of simulation.

Fig. 8, we find that in the integrated model the utilisation rate of the bottleneck is the best of all.

Table 10 shows the total performance results for the studied models. We can see in the table that the maximum product output record indicates that the proposed integrated model has more output than the MRP and JIT models. It is worth noticing that the longer the staying time in the buffers, the more WIP will be accumulated in the buffers. From Table 10, the duration time for the integrated model is between MRP and JIT models. The proposed model is able to digest more WIP than the MRP model, however, it cannot reach the JIT model's goal of minimising the inventory. For bottleneck utilisation, the integrated model achieves the best utilisation among all three models. This means that it also meets the spirit of the theory of constraints (TOC). Therefore, from the simulation results just shown, the push–pull integrated model is the best model as we discussed.

6. Conclusions

In this paper we first reviewed the most popular production paradigms, i.e. push and pull systems. Employing a push production paradigm, has the system effects of increasing output rate and resource usage. However, it may result in higher WIP inventory. On the other hand, the pull system can minimise WIP and buffer spaces in a plant; but, it also has the effects of low throughput and facility usaged. Because of these difficulties when applying either push or pull systems, we then studied an optimised production technology which used the theory of constraint as the fundamental theory and tried to integrate these two popular systems into a new production paradigm.

It is interesting that OPT concentrates on constraint resources in local production lines. Therefore, a control structure was developed which coped with an MRP system to form a global system control scheme and to ensure entire system performance. This provides numerical computation for controlling materials or parts input and capacity analysis. Based upon the part loading and dispatching rules, materials were selected to match the scheduled demands as part of forward control. Such an initial stage forward control structure, combined with the basic OPT algorithm then forms the proposed framework of the integrated of push and pull paradigm.

In the final stage, we use the ProModel simulator and obtain the results from the simulation. We then can conclude that the push–pull integrated model has the best performances among the three models.

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