An analysis of process industry production and inventory management systems

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Abstract

The process industries — those firms that add value by mixing, separating, forming and/or chemical reactions by either batch or continuous mode — continue to lag behind the discrete industries in the identification and implementation of effective production and inventory management (P&IM) techniques. A contributing factor is that the process industries have traditionally been lumped together and contrasted from the discrete industries as a whole, thus leading to misunderstandings regarding individual process industries. From site interviews and the literature, we identified four critical dimensions — planning resource requirements for materials and capacity, tracking resource consumption, control of work-in-process (WIP), and degree of computerization — represented by seven variables by which to contrast and analyze process industries. Based on in-depth field studies of 19 diverse process plants, we find that there exist at least four distinct types of process industry P&IM systems: (1) simple, (2) common, (3) WIP-controlled, and (4) computerized. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Production and inventory management; Process industries

1. Introduction and background

Identifying the right kind of production and inventory management (P&IM) system for a manufacturing firm can be a difficult and complex task. Since the investment in a P&IM system is large and remains fixed over a considerable length of time, the correct system choice is critical to both a firm’s short and long-term profitability. Research on the selection and implementation of P&IM systems for different manufacturing environments has been extensive. The majority of the research, however, has been for industries handling discrete units that are fabricated and/or assembled during manufacturing. This research has resulted in numerous successful developments in taxonomies, P&IM systems, and implementation strategies for the discrete industries.

The process industries, consisting of firms that “add value by mixing, separating, forming and/or chemical reactions by either batch or continuous mode” [Wallace, 1992], continue to have difficulty realizing the benefits of many of the management system developments in the discrete industries. “The process sector, although more automated than discrete industries at the process control level, lags discrete when it comes to overall manufacturing
management systems tools” (Crow, 1992). The reasons for this are many and varied. A brief review of past and current research sheds some light on the essence of this problem.

Unfortunately, as shown in the left column of Table 1, the great majority of process industry research simply reports general characteristics of the industry without reference to their P&IM systems. There are three subgroups of research in this column. The research listed in item 1 focuses on the unique characteristics of the process industries and compares them as a whole to discrete industries. This group of research nevertheless provides some background understanding of the problems unique to the process industries that are caused by the handling of non-discrete materials involving variability, sequencing, co-products, shelf-life, and so on. A smaller segment of research, item 2, addresses the general problems that process industries encounter regarding P&IM. A very small segment, item 3, describes the varying degrees of success that specific process firms have had with material requirements planning (MRP) implementations.

A smaller overall group of research pertains to P&IM systems in process industries. The references in item 4 address specific P&IM problems that process firms have encountered and their solutions. Item 5 captures much of the current scheduling research on P&IM systems focused primarily on high volume process flow manufacturers and illustrates the application of a technique called process flow scheduling (PFS). PFS has been described both theoretically and analytically, and shown in certain circumstances to be successful in practice. However, the full extent of applicability of the PFS logic has not yet been established.

Item 6 includes three references, each of which provides a different perspective for creating a basic taxonomy of process industry P&IM systems. These three perspectives may be considered to constitute the entirety of current theory about different types of process industry P&IM systems. Robinson and Taylor (1986) classify P&IM systems by the primary resource that must be managed: material dominated, capacity dominated, or a combination of both. Knowing which resource is primary provides valuable P&IM information, particularly about scheduling priorities and resource constraints. In contrast, Vollmann et al. (1997) in their well-known manufacturing planning and control book categorize P&IM systems by distinguishing between time-phased and rate-based systems. The third categorization by Finch

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Process industry literature</th>
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<tr>
<td><strong>General process industry characteristics</strong></td>
<td><strong>Process industry P&amp;IM systems</strong></td>
</tr>
<tr>
<td>1 — process industry uniqueness</td>
<td>4 — specific P&amp;IM problems and solutions</td>
</tr>
<tr>
<td>Adelberg, 1984; Aiello, 1982; Allen, 1980; Allen and Schuster, 1994; Baumeister, 1997; Clark, 1983; Cohen, 1980; Cokins, 1988; Covey, 1984; Dayvolt and Symonds, 1994; Doganaksoy and Hahn, 1996; Duncan, 1981; Eads and Undheim, 1984; Fransoo, 1992; Fransoo and Rutten 1994; Haxthausen, 1995; Katayama, 1996; Nelson, 1983; Nichols and Ricketts, 1994; Parker, 1997; Rice and Norback, 1987; Rutten, 1993; Shelley, 1995; Swann, 1984; Tiber, 1981</td>
<td>Allen and Schuster, 1994; Baumeister, 1997; Daniels, 1983; Dayvolt and Symonds, 1994; Eads, 1989; Gerchak et. al., 1996; Katayama, 1996; Parker, 1997; Thompson, 1991</td>
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<tr>
<td>2 — general P&amp;IM problems</td>
<td>5 — high-volume P&amp;IM scheduling</td>
</tr>
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<td>3 — specific MRP successes</td>
<td>6 — basic P&amp;IM taxonomies</td>
</tr>
<tr>
<td>Cokins, 1988; Dibono, 1997; McKaskill, 1992</td>
<td>Robinson and Taylor, 1986; Vollmann et al., 1997; Finch and Cox, 1988</td>
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and Cox (1988) looks at whether the P&IM systems are driven by make-to-stock, assemble-to-order, or make-to-order requirements.

A primary goal of this research study was to help build operations management theory in this area by identifying the range of P&IM systems being used at individual plants in the process industries, the unit of analysis in this study. Since theory testing should not be conducted using the same data that built the theory (Green, 1978, p. 432; Meredith et al., 1989, pp. 301–303), no attempt was made here with this limited data set to also test the theory. Nor was it used to try to identify the “best” P&IM systems under various circumstances, such tests and applications thus being deferred for future studies.

A detailed analysis of the P&IM systems of 19 diverse processing plants was carried out. The focus was on both the similarities and differences between the P&IM systems. Overall, this paper addresses the following three questions:

1. What are the relevant variables by which process industry P&IM systems can be differentiated?
2. How do these variables differ between different P&IM systems?
3. Can the different P&IM systems be put into manageable subgroups based on their P&IM variables and, if so, what are the subgroups and their characteristics?

The following sections provide the background for answering these three questions. In the next section, the choice of variables, the research sample, and the analysis process will be addressed.

2. Identifying the key P&IM system variables

In order to effectively compare the P&IM systems, the characteristics that best differentiate between different P&IM systems had to be identified. The challenge was to isolate those characteristics that would provide a parsimonious yet thorough description of the sites’ P&IM systems. Research suggests that this description must distinguish between materials and capacity. Many researchers (Plossl and Wight, 1967; Abraham et al., 1985; Dietrich, 1987; Vollman et al., 1997) recognize that the basic elements of any P&IM system include attention to both materials and capacity. Robinson and Taylor (1986) expand on this by suggesting that P&IM systems may be classified by the primary resource that must be managed: materials, capacity, or a combination of both. Knowing which resource is primary provides valuable information about scheduling priorities and resource constraints. As such, the variables used in this research always considered materials and capacity separately.

Any description of a P&IM system must also address both the planning and control of resources. Several researchers (Abraham et al., 1985; Dietrich, 1987; Vollman et al., 1997) illustrate the relationship between planning and control within P&IM systems using hierarchical frameworks. As one moves down these hierarchies, the required input and output information shifts from plans for resource requirements to the actual tracking of resources consumed. The information also become more detailed and comprehensive as the time horizon changes from long range to short range.

These two sets of research thus indicated the necessity for variables that measure the planning of material requirements (MAT-REQUIREMENTS), the planning of capacity requirements (CAP-REQUIREMENTS), the tracking of actual materials consumed (MAT-CONSUMPTION), and the tracking of actual capacity consumed (CAP-CONSUMPTION).

Plossl and Wight (1967) describe work-in-process (WIP) as one of the most significant inventories because of its direct effect on manufacturing lead times. They also indicate that tracking WIP can be difficult and complicated. Vollman et al. (1997) state that WIP can be determined by using detailed WIP systems based on shop order transactions at one extreme. At the other extreme, it may be simply calculated by exploding the bills of materials for whatever has been delivered into finished goods less whatever is left in raw materials. Because of the importance of WIP and the varied methods that may be applied to monitor it, the variable WIP-CONTROL was included to describe the manner in which WIP was tracked.

The final source was preliminary in-depth interviews with two separate firms. This information indicated that in addition to the variables identified
from the above sources, the fraction of materials and capacity planned and controlled by computerization is also an important characteristic because highly detailed and complex P&IM systems require computerization. As one plant manager stated: “We had to computerize this process to get good information. It was too complicated to keep track of manually.” Another manager said: “We need input from so many different areas that we had to develop an information system to manage it.” Both managers indicated that degree of computerization was an important factor in distinguishing P&IM systems. Thus, the variables MAT-COMPUTERIZATION and CAP-COMPUTERIZATION were added.

However, this characteristic was intentionally limited to P&IM elements; it was not meant to include general firm sophistication in computers, decision support, information systems, and other non-P&IM aspects. Moreover, given the quickly evolving nature of the computer area, this characteristic was intentionally kept as straightforward as possible. A great number of papers (e.g., Boyer et al., 1996, 1997) have investigated the impact of computerized technology on performance but again, that was not the purpose here. The aim here was to identify the most simple and straightforward characteristics that would distinguish between P&IM systems, and fraction of computerized control, again of both materials and capacity, was such a characteristic.

Combining all the above information resulted in the seven composite variables described in Table 2 that were believed to differentiate process industries’ P&IM systems from each other. These seven variables are: (1) planning of material requirements

<table>
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<th>Table 2</th>
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<td>P&amp;IM system variables</td>
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**MAT-REQUIREMENTS** (the level of detail and frequency used to generate material requirements)
1. knowledge of basic historical usage and visual observations of inventory levels; steady flow usage
2. use of fixed interval reorder system; weekly physical to update inventory records
3. use of fixed interval reorder system; daily physical updates of inventory records
4. use of explosions to reflect gross requirements in combination with multi-criteria ABC analysis
5. use of cumulative MRP with time phasing and net requirements in combination with multi-criteria ABC analysis

**CAP-REQUIREMENTS** (the level of detail and frequency used to generate capacity requirements)
1. capacity is fixed and known; steady flow usage
2. infinite load on an informal basis; orders are pushed into production
3. capacity planning using overall factors
4. capacity planning using overall factors in combination with general capacity bills (no routings)
5. capacity planning using overall factors and loading (product mix is not considered)

**MAT-CONSUMPTION** (the level of detail and frequency used to track material consumption)
1. monthly physical inventories
2. weekly physical inventories
3. standard consumption amounts are recorded for batches; weekly adjustments are made from physical inventories
4. actual consumption is recorded at the completion of a batch
5. standard consumption is recorded at the time of consumption; actual consumption is recorded at time of completion

**CAP-CONSUMPTION** (the level of detail and frequency used to track capacity consumption)
1. not formally tracked
2. track standard labor hours by backflushing
3. track standard labor and volume of output over time
4. track actual labor hours and/or machine hours for each product
5. track actual and standard machine and/or labor hours for each product; make comparisons to update standards

**WIP-CONTROL** (control of work-in-process)
1. no formal system; walk floor or make phone calls
2. physical inspections are supported by daily meetings and use of shift notes
3. can back into WIP information from other inventory information (backflushing); use of more detailed shift notes
4. batched starts are tracked at regular intervals
5. starts and completions are tracked on a perpetual basis

**MAT-COMPUTERIZATION** — the percent of material control P&IM tasks that are computerized

**CAP-COMPUTERIZATION** — the percent of capacity control P&IM tasks that are computerized
(MAT-REQUIREMENTS): (2) generating capacity requirements (CAP-REQUIREMENTS), (3) tracking material consumption (MAT-CONSUMPTION), (4) tracking capacity consumption (CAP-CONSUMPTION), (5) tracking WIP (WIP-CONTROL), (6) computerization used to plan and control materials (MAT-COMPUTERIZATION), and (7) computerization used to plan and control capacity (CAP-COMPUTERIZATION).

3. The research sample

Three important issues with respect to the selection of the research sample are: deciding what constitutes a true process firm, determining how to select the firms, and deriving a procedure to determine what constitutes a separate type of P&IM system.

3.1. What constitutes a process firm

Approximately 50% of all firms consider themselves to be in the process industries (Novitsky, 1983). Many of these firms are actually hybrids due to the fact that their nondiscrete units become discrete at some point during the manufacturing process. How far into a manufacturing process a product becomes discrete can vary widely.

To eliminate most of the confusion that these hybrids can cause, this research was limited to firms with products that only become discrete at either the point of containerization or during the last process immediately prior to containerization (e.g., baked goods, tablets, capsules, and blended meat products). The materials of the firms chosen for this research are in the forms of gases, liquids, slurries, pulps, crystals, powders, pellets, films, and/or semi-solids and can only be tracked by weight or volume. Because of the similarities in the physical nature of the materials used, the firms share similar problems in the storing, tracking, and transporting of their materials.

At this early stage of theory building for identifying different kinds of process industry P&IM systems, it was decided that a limited but heterogeneous sample of firms would be necessary. The sample needed to be limited because the data was to be collected through a labor-intensive field study but heterogeneity was needed to be able to distinguish between different types of P&IM systems. In particular, heterogeneity was desired across firm size, process industries, and product types. In addition, firm size heterogeneity would likely include build-to-stock as well as build-to-order and assemble-to-order heterogeneity.

3.2. Selecting the firms

This issue was addressed in several steps. First, a list of firms that could potentially be considered for the research was compiled. Second, each firm was contacted to determine if it met the criteria for constituting a process firm described above. And third, the firm had to give its permission to be included in this research.

Several sources were solicited to assist in compiling a list of potential firms to consider for this research. The primary source was the American Production and Inventory Control Society (APICS). APICS has a special interest group (SIG) for process industries whose membership list is available upon special request. This source accounted for over half of the contact list. Another important source was the local Business-to-Business directory. Firms listed under products typically considered part of the process industries were added to the contact list. Finally, some participants provided referrals and contacts for other firms.

The initial contact with each of 62 potential firms was made by telephone. The primary purpose of these initial telephone contacts was to: (1) determine a willingness to participate, (2) find out what process industry the firm belonged to, (3) determine if the firm met the process criteria outlined above, (4) obtain some preliminary ideas on the kind of manufacturing systems used by the firm, (5) establish the existence of a functioning P&IM system, and (6) schedule an onsite meeting. It took at least two and as many as 12 telephone calls to obtain this information. About a third of the firms required some written explanation of the research before they would give the request further consideration.

These efforts resulted in onsite meetings with 14 different process firms. Of the 48 non-participating firms, about half were disqualified quickly because they were distribution centers or the production facil-
entities were too far away (more than a 2-hour driving radius). The rest of the non-participants were eliminated because they either did not want to share information they considered to be confidential or they simply did not want to invest the time required to participate.

To help ensure that appropriate and well-managed P&IM systems were being used, the P&IM systems were evaluated using Landel’s (1982) audit. The use of this audit provided information on whether the conditions related to the P&IM system were excellent, good, average, very poor, or unacceptable. Any firm that rated below average was disqualified from participating in the research study. After the results of this audit were considered, 13 firms qualified to be included in the research study.

To test for possible non-respondent bias, a two-wave test was conducted (Armstrong and Overton (1977)) since we had no data at all on the firms that declined to participate in the study. Four sites were very late holdouts in joining the study and thus used as our second wave, considered to be typical of the non-respondents. The overall MANOVA test was not significant ($p = 0.81$) so the two waves were treated as one group in the study.

3.3. What constitutes a separate type of P&IM system?

A particular firm may have one or more different types of P&IM systems in use in their plant. In some companies, the different P&IM systems are located in separate plants, the unit of analysis, making the distinction clear. In other companies, the different P&IM systems shared the same plant site. In these situations, considering only entirely different product lines, different types of processes, separate profit centers, and independent P&IM systems resulted in a clear separation. In each of the firms, the separation between the different P&IM systems was thus very apparent.

The 13 firms provided data on 19 different P&IM systems. In the firms where only one site existed, the site and the firm were considered to be equivalent research units. Six of the firms, however, provided two separate research sites resulting in two units of analysis each. To test for possible correlation between these six pairs of sites, Spearman non-parametric rank correlation coefficients were computed for each of the seven variables. The highest correlation obtained was 0.55 and none were significant. Moreover, in the cluster analysis described later, three of the pairs clustered in different clusters, almost what would be expected by chance. Thus, all 12 sites were treated as having independent P&IM systems.

The 19 research sites represent a wide variety of different process industries (see Table 3). The 19 sites vary in size, number of employees, available products, transformation system, and so on. All of these sites, however, share one very important characteristic described earlier — each of the sites use non-discrete materials throughout the majority of the manufacturing process. In all cases, the products do not become discrete until either containerization or the step immediately prior to it. For a complete description of the sites, refer to Dennis (1993).

3.4. Data collection

Each plant visit was extensively planned and combined interviews with physical tours, thereby resulting in the desired extensive documentation. Anywhere from 6 to 16 h were spent on-site asking questions. Between one and eight people were interviewed at each site. In addition, approximately 1 to 3 h were spent on the telephone for follow-up or clarification after each on-site visit. To minimize the use of everyone’s time, preliminary information about the company was obtained prior to the on-site visit. Information was acquired from the firm’s personnel department, stockholders’ reports, the library, and other such sources. Also, pre-set schedules were used to structure the day so that the sequence of information was obtained in the desired order.

Interviewees were chosen carefully and the firms themselves were heavily involved in the selection process. Titles were avoided, basing instead the interviewee selection on the types of information that would be gathered to determine who would be most knowledgeable in each area. Final interviewees included owners, manufacturing VPs, plant managers, production supervisors, information systems personnel, material managers, production and inventory control managers, schedulers, warehouse foremen, and plant foremen.
Table 3  
Firm profiles  

<table>
<thead>
<tr>
<th>Firm</th>
<th>Annual sales (M US$)</th>
<th>Employees: tot./mfg.</th>
<th>Primary products</th>
<th>Research sites*</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHARM</td>
<td>650</td>
<td>1500/500</td>
<td>PHARMACEUTICALS: TABLETS, MOUTH-WASHES, OINTMENTS</td>
<td>1 PHARM-TABLETS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>RESINS, PLASTICS, POME-COR, RESIMENE</td>
<td>2 PHARM-LIQUIDS</td>
</tr>
<tr>
<td>PLASTIC</td>
<td>400–500</td>
<td>900/300</td>
<td>3 RESINS</td>
<td>4 PLASTIC</td>
</tr>
<tr>
<td>MEATS</td>
<td>280</td>
<td>300/250</td>
<td>MEAT PRODUCTS</td>
<td>5 MEATS</td>
</tr>
<tr>
<td>INDUST CLEAN</td>
<td>250</td>
<td>112/98</td>
<td>SPECIALTY INDUSTRIAL CLEANING AND MAINTENANCE CHEMICALS</td>
<td>6 INDUST CLEAN</td>
</tr>
<tr>
<td>FLEXPAC</td>
<td>100–120</td>
<td>600/500</td>
<td>FLEXIBLE PACKAGING BY EXTRUSIONS AND PRESSING</td>
<td>7 FLEXPAC-EXTRUD</td>
</tr>
<tr>
<td>SPECIALTY CHEM</td>
<td>100</td>
<td>800/520</td>
<td>SPECIALTY ORGANICS, PAINTS, PIGMENTS INKS, VARNISHES</td>
<td>8 FLEXPAC-PRESS 9 ORGANICS</td>
</tr>
<tr>
<td>ICECRM &amp; BEV</td>
<td>60</td>
<td>130/85</td>
<td>FROZEN NOVELTIES, ICE CREAMS, BEVERAGES</td>
<td>10 COLORS 11 ICE CREAM 12 BEVERAGES</td>
</tr>
<tr>
<td>BREW</td>
<td>30</td>
<td>100/91</td>
<td>BEERS, ALES</td>
<td>13 BREW</td>
</tr>
<tr>
<td>FEED</td>
<td>30</td>
<td>70/40</td>
<td>FEED ADDITIVES, FUEL ALCOHOL, YEASTS, BACTERIA, ENZYMES</td>
<td>14 FEED-YEASTS 15 FEED-BLEND</td>
</tr>
<tr>
<td>COATINGS</td>
<td>25</td>
<td>200/70</td>
<td>CONTAINER COATINGS</td>
<td>16 COATINGS</td>
</tr>
<tr>
<td>PAINT</td>
<td>15</td>
<td>150/105</td>
<td>PAINTS</td>
<td>17 PAINT</td>
</tr>
<tr>
<td>BAKE</td>
<td>7</td>
<td>200/75</td>
<td>BAKED GOODS</td>
<td>18 BAKE</td>
</tr>
<tr>
<td>FINISHES</td>
<td>2.5</td>
<td>22/14</td>
<td>PAINTS, STAINS, LACQUERS, SEALERS, ENAMELS</td>
<td>19 FINISHES</td>
</tr>
</tbody>
</table>

*Identified by this descriptor through the remainder of this paper.

Triangulation was used to ensure reliability by obtaining the same piece of information from three different sources: oral statements from knowledgeable people, documentation, and visual observation. It was possible to obtain information from at least two of these sources for almost all of the data. Three sources, however, were possible for only a few of the characteristics.

Referring back to Table 2, it was possible to obtain direct and continuous measures for both MAT-COMPUTERIZATION and CAP-COMPUTERIZATION simply by estimating the percent of P&IM tasks that are performed manually and those that are performed by the computer systems. There are no direct measures, however, for the requirements and consumption variables MAT-REQUIREMENTS, CAP-REQUIREMENTS, MAT-CONSUMPTION, and CAP-CONSUMPTION, as well as WIP-CONTROL. Thus, it was necessary to establish the relative indirect measures shown in the table for these five variables. Since a cluster analysis was to be conducted on the variables, the indirect measures were scaled so that the site with the least amount of detail on each variable received the lowest score and the site with the greatest detail received the highest score. Each P&IM system was evaluated and then assigned a score between one and five where a 1 represents the least amount of detail and a 5 the most.

For example, the lowest score for MAT-CONSUMPTION, 1.0, is given when only monthly or less frequent physical inventories are taken. Since a 2.0 represents weekly inventories, biweekly could receive a 1.5. However, to get more than a 2.0 requires more rigorous attention to recording real-time data, either standard and/or actuals. In addition, the extensiveness of this attention is also important in terms of whether all materials receive real-time recording or only some of them. Thus, based on this information and the fact that inconsistencies in procedures are common in manufacturing, the final score could range anywhere between the integers as well as anywhere between the upper and lower values of the range.
4. Analysis of the P & IM system variables

The data for the P & IM system variables were examined in several ways. First, a non-statistical general overview of the raw data was performed. Next, Ward and Jennings’ (1973) clustering method was used to cluster the sites based on the P & IM system variables. Finally, an analysis of the means, standard deviations, coefficients of variation, medians, and ranges of the variables was conducted to provide information for within-group comparisons and between-group comparisons for each of the individual clusters.

4.1. Overview of the P & IM system data

Some interesting insights into the similarities and differences between the 19 individual process industry P & IM systems were gained from the raw data concerning the seven P & IM variables (see Table 4). Although our conclusions about the types of process industry P & IM systems can only be considered valid for the industries we investigated, because of the wide diversity of process firms included here, we believe that the sample provides a good cross-section of the process industries.

First, an overall inspection of Table 4 illustrates the wide range of data collected. Some variables clump in the middle, others congregate at the ends and are sparse in the middle, others are relatively evenly dispersed, and still others are somewhat randomly spread along the scale. (The two computerization variables were transformed from their fractional range of 0 to 1, to match the other variables with a range of 1 to 5.) Also of interest is that no site scored consistently across all measures at the same values, although we tend to see some that stay closer to one end than the other, such as 12 near the bottom and 11 near the top. Some general insights are described below. Those variables that tended to be similar across the sites are discussed first, followed by those that tended to differ among the sites.

4.1.1. MAT-REQUIREMENTS

The inter-site diversity in the level of detail required for the generation of raw material requirements is large but most sites are at the middle score of 3. The simplest systems sites 1, 3, and 12 in Table 4 use methods of generating requirements that are based on knowledge of historical usage combined with visual observation of what is on hand.

Table 4
Comparing the P & IM systems of the 19 sites

<table>
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<tr>
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<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<tbody>
<tr>
<td>MAT-REQUIREMENTS</td>
<td>1 3</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>CAP-REQUIREMENTS</td>
<td>3 12 14</td>
<td>13</td>
<td>19</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>MAT-CONSUMPTION</td>
<td>3 13</td>
<td>7 12</td>
<td>5 13</td>
<td>4 13</td>
<td>8 12 14</td>
</tr>
<tr>
<td>CAP-CONSUMPTION</td>
<td>14</td>
<td>13 12</td>
<td>18 19</td>
<td>4 1 16</td>
<td>5 12</td>
</tr>
<tr>
<td>WIP-CONTROL</td>
<td>2 18 14 12 19</td>
<td>3 17</td>
<td>5 16</td>
<td>1 15 9 10</td>
<td>8 7 6</td>
</tr>
<tr>
<td>MAT-COMPUTERIZATION</td>
<td>14 12 15</td>
<td>5 10 13</td>
<td>6 14</td>
<td>7 8 11 16 17</td>
<td></td>
</tr>
<tr>
<td>CAP-COMPUTERIZATION</td>
<td>14 13 12 18 19</td>
<td>6 3 5 7 8</td>
<td>4 1 11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

...
This can be done effectively because of steady usage.

The most detailed systems use a combination of methods including a form of cumulative MRP and multiple-criteria ABC analysis. In these systems, regular bills of materials are used but the time buckets are monthly. Material requirements are met by maintaining appropriate days of on-hand levels. If amounts fall below the desired days of on-hand levels, materials are ordered regardless of what the monthly MRP explosion calls for. Multiple-criteria ABC classifications influence the decisions on what amounts of raw material inventories to maintain. This method cannot function as a regular MRP system because the computerized inventory tracking is not perpetual. Inventory changes to the computer are batched and therefore not timely enough to rely on for ordering purposes. Even though the range for MAT-REQUIREMENTS is large, over half of the sites received a score of three out of five for this variable reflecting their use of some sort of fixed interval reorder system with set min/max inventory levels. Within these P&IM systems, the inventory levels are updated from either physical inventories or a batched method and are not in real time.

4.1.2. CAP-REQUIREMENTS

The distribution on this variable is very similar to that on MAT-REQUIREMENTS. At three of the sites (3, 12, and 14) the capacities are fixed and known and production is run at basically the same capacity all the time.

Eleven of the sites use capacity determination methods that are so similar that there were no significant differences noted for the variable CAP-REQUIREMENTS. At these eleven sites the capacities are not fixed and are quite difficult to measure. In each, the capacity varies with the product mix and the rough-cut capacity planning technique called capacity planning using overall factors (CPOF) is used. Individual work centers are scheduled by knowledgeable people using historical information. The capacity scheduling process is informal and manual; problems due to insufficient capacity are dealt with as they arise.

The most sophisticated methods (sites 4 and 11) for determining capacity requirements go through the mechanics of finite loading. The results, however, provide only approximate figures because the effects of product mix and sequencing are not taken into consideration. In these systems, forecasted information is used to plan overtime or inventory buildsups. However, once the aggregate capacity is set at these levels, actual orders are infinite loaded at the aggregate level. Again, problems due to insufficient capacity are dealt with as they arise.

4.1.3. MAT-CONSUMPTION

The inter-site diversity in the tracking of raw material consumption is quite large. Also, the distribution across this variable from the site using the simplest method (19) to the site using the most sophisticated raw material consumption tracking method (6) is fairly even. In the simplest methods, consumption is not even tracked on a batch basis; a monthly inventory is conducted primarily for accounting purposes. Most of the firms that fall in the middle of the distribution use a backflushing technique to calculate estimated raw material consumption based on yields.

The most sophisticated method tracks inventory on almost a perpetual basis. The standard amounts of raw materials consumed are sent to the computer at the time of consumption and actual amounts are reported when the batch is completed. The lead times are short so the information is fairly timely. It is interesting to note that even though this system is supported by the most accurate and timely inventory records, it still does not use MRP. The raw materials are ordered based on reorder points.

4.1.4. CAP-CONSUMPTION

Three of the sites have P&IM systems that employ very simple methods for tracking capacity consumption and do not measure consumption directly. Production is run full out all the time and only the aggregate volumes of materials produced over time are measured. The majority of the sites have P&IM systems that use a tracking method where labor hours are tracked and the exact quantities of materials produced over time are recorded. Some of these methods measure labor at standard while others measure it at actual. The most sophisticated method tracks actual on a batch basis for both labor and machine hours and compares them to standard. No site has a P&IM system that employs a real time capacity consumption tracking method.
4.1.5. WIP-CONTROL

Six of the sites were ranked at the lowest level for the tracking of WIP. These sites have P&IM systems that do not track WIP on a formal basis. Walking the floor or making telephone calls are the primary sources of information for WIP at these sites. Only one site (6) was ranked at the highest level of detail for tracking WIP. This site tracks WIP on a board that is kept in production where the exact location of all batches is recorded. All movement, stages, and locations are tracked on a real time basis. It is interesting that this most sophisticated WIP tracking method is a manual one.

4.1.6. MAT-COMPUTERIZATION

The fraction of computerization of the materials control methods (MAT-REQUIREMENTS, MAT-CONSUMPTION, and WIP-CONTROL) varies widely. Two sites use methods for the control of materials that are completely manual. Eleven of the P&IM systems use methods that are less than half computerized. The most computerized systems have about three-quarters of their material control methods computerized.

4.1.7. CAP-COMPUTERIZATION

Three sites have not computerized any of the methods used for capacity control in their P&IM systems. Ten sites are less than half computerized. The most computerized systems with respect to capacity control methods are almost fully computerized.

5. P&IM system subgroups

The third research question is answered in this section: can the different P&IM systems be put into manageable subgroups based on their P&IM variables and, if so, what are the subgroups and their characteristics?

5.1. Clustering the 19 P&IM systems

The full clustering sequence for the 19 P&IM systems based on the seven P&IM variables is shown in the dendrogram in Fig. 1. Ward and Jennings’ (1973) hierarchical clustering method was used to identify the P&IM system clusters. In this method, the distance between two clusters is the sum of the squares between the two clusters summed over all the variables. This method was chosen primarily on the recommendation of Anderberg (1973), and because it is hierarchical.

Since Ward’s method uses the sum of the squares of distances, it is not necessary for the data to have normality. However, for this same reason, it was necessary to standardize the data to keep certain variables from influencing the results more heavily than others. All the variables were thus standardized to a mean of zero and a standard deviation of one. SAS (1988) was the statistical package used to perform Ward’s method.

After Ward’s method was used on the data, it was necessary to determine how many different clusters were actually formed. Deciding on a method to use for this determination is not straightforward (Everitt, 1979, 1980). SAS Institute (1988), however, suggests that when cluster analysis is used for the purpose of dissection, the $R^2$ value provides an appropriate cut-off point. Thus, the criterion chosen to determine the final number of clusters in this analysis was the $R^2$ value. The $R^2$ values in Fig. 2 show the amount of explained variance that is lost by reducing the number of clusters. The plot of the number of clusters versus the $R^2$ values in Fig. 2 shows that a substantial drop-off in the $R^2$ values occurs below four clusters (only 0.088 from 5 to 4 versus 0.111 from 4 to 3). Consequently, the number of clusters should not be reduced beyond four. The dendrogram in Fig. 1 shows the final four P&IM system clusters on the left (Cluster 1 through Cluster 4) that were formed by using this cutoff point.

5.2. Four types of P&IM systems

It is apparent that a large amount of diversity was captured in the sample of 19 process industry sites. In fact, four distinct types of P&IM systems, described in detail below, were identified within the 19-site sample of this research. Thus, it can be concluded that there are at least this many different types of P&IM systems in the entire population of process industries. The major contribution of this research is the development of this taxonomy of process industry P&IM systems based on the seven distinguishing variables.
Table 5 gives the actual values and standard deviations of each of the seven variables. An ANOVA test was performed on the clusters for each variable and the $p$-values are listed at the right side of Table 5, along with the clusters that were identified as significantly different on that variable from a post-hoc Scheffe test. As can be seen, there were highly significant differences on all the variables except capacity requirements, which was only significant at the 0.10 level rather than 0.05 as used in this Scheffe test. (If the 0.10 level had been considered significant, the corresponding different clusters would have been 3 and 4.) As might be expected, Clusters 3 (the “computerized” cluster) and 4 (the “simple” cluster) were found to be the most different, differing significantly on five of the seven variables. Clusters 2 and 3 were also quite different, differing on four of the seven variables. Considering all the variables at once, all of the clusters differed significantly from each of the other clusters, often on multiple varia-

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**Fig. 1.** Dendrogram for P&IM systems (Clusters 1 through 4).

**Fig. 2.** Determining the number of P&IM system clusters.
Table 5
Variable means and standard deviations for P & IM system clusters

<table>
<thead>
<tr>
<th>Variables</th>
<th>Cluster 1: common</th>
<th>Cluster 2: WIP-controlled</th>
<th>Cluster 3: computerized</th>
<th>Cluster 4: simple</th>
<th>p-Value</th>
<th>Significantly different clusters</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAT-REQUIREMENTS</td>
<td>3.33/0.52</td>
<td>2.88/0.25</td>
<td>4.38/0.95</td>
<td>2.00/1.00</td>
<td>0.0021</td>
<td>3–4</td>
</tr>
<tr>
<td>CAP-REQUIREMENTS</td>
<td>3.00/0.0</td>
<td>2.63/0.75</td>
<td>4.38/0.75</td>
<td>1.80/1.10</td>
<td>0.1090</td>
<td></td>
</tr>
<tr>
<td>MAT-CONSUMPTION</td>
<td>3.25/0.74</td>
<td>2.88/1.70</td>
<td>3.88/0.63</td>
<td>1.90/1.34</td>
<td>0.0010</td>
<td>2–3, 3–4</td>
</tr>
<tr>
<td>CAP-CONSUMPTION</td>
<td>4.08/0.38</td>
<td>1.38/0.25</td>
<td>4.25/0.96</td>
<td>1.50/0.50</td>
<td>0.0001</td>
<td>1–2, 1–4, 2–3, 3–4</td>
</tr>
<tr>
<td>WIP-CONTROL</td>
<td>2.67/0.75</td>
<td>4.13/0.85</td>
<td>2.00/1.41</td>
<td>1.10/0.22</td>
<td>0.0020</td>
<td>2–3, 2–4</td>
</tr>
<tr>
<td>MAT-COMPUTERIZATION</td>
<td>2.70/0.48</td>
<td>3.56/0.84</td>
<td>4.00/0.12</td>
<td>1.64/0.60</td>
<td>0.0001</td>
<td>1–3, 1–4, 2–4, 3–4</td>
</tr>
<tr>
<td>CAP-COMPUTERIZATION</td>
<td>2.28/0.60</td>
<td>2.68/0.64</td>
<td>4.52/0.36</td>
<td>1.52/0.88</td>
<td>0.0001</td>
<td>1–3, 2–3, 3–4</td>
</tr>
</tbody>
</table>

Variables. For example, Cluster 3, the computerized cluster, was found to differ more than all the other clusters, differing eleven times from the other clusters among the seven variables. Cluster 4, the simple cluster, was next most different, differing nine times. Not surprisingly, Cluster 1, the “common” cluster, differs the least from the other clusters, being significantly different only five times.

Cluster 4 was termed the “Simple” cluster because it had the lowest scores on almost all the seven variables, only once slightly exceeding another cluster (Cluster 2 on CAP-CONSUMPTION). Cluster 3 was termed the “Computerization” cluster because it had the highest scores on both computerization variables. As might be expected due to the demonstrated need for computerization, this cluster also scored high on both measures of requirements, as well as consumption. Cluster 2 was termed the “WIP-CONTROL” cluster due to its exceedingly high score on that variable whereas its other scores were close to those of the Simple cluster. Finally, Cluster 1 was termed the “Common” cluster due to its having more sites than any other cluster and scoring in the middle of all the variables.

Fig. 3. Comparing the P & IM system clusters.
Given the difficulty of seeing the patterns in Table 5, the relative positions of the clusters are more clearly displayed in terms of the seven variables in the graph of Fig. 3. Here, each cluster is plotted against the seven variables at the bottom. The figure more clearly illustrates the points made in the previous explanation such as the Simple cluster having the lowest scores, the WIP-Controlled cluster being substantially higher in WIP-CONTROL than the other clusters, and so on.

5.3. Validating the clusters

To validate the clusters, two methods suggested by Jobson (Jobson, 1992, p. 564) were employed: validating the cluster results by conducting other forms of cluster analyses to see if they form the same clusters, and running a split-half cluster analysis to see if both halves form the same set of clusters. The two additional clustering analyses to validate Ward’s method were centroid hierarchical cluster analysis and average linkage cluster analysis. Both methods resulted in the same identical four clusters as Ward’s method. We also used Ward’s method to run the split-half analysis, both halves again resulted in the same four clusters.

In addition, the observations themselves tend to validate the clusters in the following sense. Three sets of variables in Table 5 have two items each that might be expected to run somewhat similarly within each cluster: material and capacity requirements, material and capacity consumption, and material and capacity computerization. Although these pairs need not be highly correlated within a cluster, it would be surprising if one variable of a pair was quite high while the other was quite low. As it happens, in all four clusters, all three pairs of variables tend to be near the same values and the same rank among the four clusters. For example, cluster 1 is ranked second on material requirements and also second on capacity requirements, it is ranked third on material computerization and also third on capacity computerization, and finally, it is ranked second on material consumption and second on capacity consumption. The same can be seen in Fig. 3 for the other clusters.

5.4. Interpretation of the clusters

The interpretation of the characteristics of each of the clusters is next described in more detail.

5.4.1. Cluster 1: common

The site members of this cluster are COLORS, COATINGS, ORGANICS, FEED-BLEND, MEATS, and PAINT. The means of the planning and control variables — MAT-REQUIREMENTS, MAT-CONSUMPTION, CAP-REQUIREMENTS, CAP-CONSUMPTION — all rank second indicating that this cluster is the second most detailed with respect to the generation of materials and capacity requirements and the tracking of materials and capacity consumption. The specific characteristics implied by the means of these four variables are: (a) a fixed interval reorder point method is used to generate raw material requirements; updates to records are made daily; (b) material consumption is tracked by recording standard consumptions with periodic actual adjustments; (c) the capacity requirements are generated by CPOF; and (d) actual labor hours and/or machine hours are tracked for each product.

The mean score for the variable WIP-CONTROL also ranks second and suggests that WIP is tracked by physical observations supplemented with detailed shift notes. The computerization variables MAT-COMPUTERIZATION and CAP-COMPUTERIZATION both rank third and indicate that somewhat less than half of their materials and capacity control systems are computerized.

5.4.2. Cluster 2: WIP-controlled

The members of this cluster include: FLEXPAC-EXTRUDE, FLEXPAC-PRESS, BREW, and INDUST CLEAN. The means of the planning and control variables suggest the following characteristics: (a) raw material requirements are generated by the use of a fixed interval reorder point system with set min/max inventory levels; material updates occur somewhere between weekly and daily (less frequently than for cluster 1); (b) raw material consumption is tracked by a combination of physical inventories and standard consumption recording at the start of each batch; (c) the generation of capacity requirements falls between informal infinite load to use of capacity planning using overall factors (CPOF); and (d) the tracking of capacity consumption falls between not being tracked at all and keeping track of some standard labor hours. Cluster 2 has the highest mean score for WIP-CONTROL of the five clusters. The mean score of 4.13 implies that the
starts of batches are tracked and that some of the tracking is actually done by the processing equipment. The variables CAP-COMPUTERIZATION and MAT-COMPUTERIZATION rank second, with materials control being somewhat over half computerized and capacity being somewhat less than half computerized.

5.4.3. Cluster 3: computerized

The members of Cluster 3 are PLASTIC, PHARM-LIQUIDS, PHARM-TABLETS, and ICE CREAM. All the planning and control variable means — MAT-REQUESTS, MAT-CONSUMPTION, CAP-REQUESTS, CAP-CONSUMPTION — for Cluster 3 rank first, implying that this cluster uses the greatest amount of detail for generating materials and capacity requirements and tracking materials and capacity consumption. This amount of detail is obviously what generates the need for the high degree of computerization. The characteristics, as implied by the means, are: (a) raw material requirements are generated by a combination of methods including some use of explosions for gross requirements, multiple-criteria ABC analysis, and fixed reorder point methods; materials are updated frequently (almost real time); (b) the actual consumption of raw materials is tracked at the completion of a batch; (c) capacity requirements are generated by finite loading using approximate values; and (d) capacity consumption is tracked by recording actual labor hours and machine hours for each product. The mean for the WIP-CONTROL variable is exceptionally low and suggests that WIP is tracked very simplistically by the use of physical inspections, meetings, and shift notes. Both of the means for the computerization variables rank first, of course, and their control is highly computerized.

5.4.4. Cluster 4: simple

The members of Cluster 4 are RESINS, BEVERAGES, FINISHES, BAKE, and FEED-YEAST. The planning and control variable means generally rank last and suggest the following: (a) the methods used for the generation of raw material requirements fall between knowing the steady flow usage and the occasional use of fixed interval reorder points with semi-weekly updates; (b) raw material consumption is tracked by a combination of taking weekly physical inventories and recording standard consumptions at the completion of a batch for “key” raw materials; (c) capacity requirements are either known and fixed or generated by using CPOF; and (d) the methods used to track the consumption of capacity are either a combination of informal tracking (e.g., meetings, shiftnotes) plus tracking of standard labor hours or are not tracked formally at all. The mean for the WIP-CONTROL variable also ranks last implying the WIP is tracked by walking the floors, making phone calls, or through informal discussions in production meetings. Understandably, this cluster also ranks last on both computerization variables.

5.5. Managerial interpretation of the four clusters

In managerial terms, these four basic types of P&IM systems generally make sense for process industries, although they cannot be confidently extrapolated beyond the industries investigated here. There is a Simple P&IM system for those process industries that are relatively straightforward and a Common system for those that are more normally demanding, especially in terms of their materials and capacity requirements and consumption. However, many firms that have the most complex and demanding production processes have turned to computerized technology to more precisely monitor and control those processes; these more technologically sophisticated P&IM systems are thus called Computerized. However, there is yet another type of P&IM system that does not have especially high demands for generating and tracking the consumption of materials and capacity but very closely monitors WIP, usually through the processing equipment itself. Their goal is often to maintain short lead times; this P&IM system is thus called WIP-Controlled. As might be expected, the level of computerization of this system is relatively high.

In addition to the variables that distinguished between the clusters, it is interesting to note that neither size nor product gives any indication of the similarity of P&IM systems. For example, the largest plants, pharmaceuticals, clustered with ice cream, one of the smallest. And the smallest, finishes, clustered with the second largest, resins. Equally interesting is the unexpected similarities of firms within each cluster and the kinds of differences across
clusters. For example, beverage P&IM systems have more in common with baking systems due to their simplicity than they do with brewing (close control of WIP), ice cream (computer controlled), or paints (common demands), all of which are liquids like beverages. Similarly, the P&IM system for paints is more like that for meats (common demands) than it is for other chemicals like finishes (simple demands) or industrial cleaning chemicals (close control of WIP). What this means for the manager is that some analysis of the seven variables identified here is required to determine which P&IM systems would be best to benchmark, or what colleagues to talk to about similar problems in their production process. Based on this research, what might seem like an industry with a similar P&IM system may lead a manager into taking precisely the wrong actions.

6. Conclusion

As stated in the Introduction, the goal of our research here was to identify dimensions that could discriminate between process industry P&IM systems, determine how these systems differ from one another, and identify major subgroups of such systems and their characteristics. An essential step required to accomplish this goal has been offered here: the detailed analysis and categorization of 19 process industry P&IM systems. The systems were shown to differ significantly on six of the seven identified variables: materials requirements, materials and capacity consumption, WIP control, and degree of materials and capacity computerization. The categorization resulted in four distinct groups of P&IM systems: (1) common, (2) WIP-controlled, (3) computerized, and (4) simple. Since these 19 sites exhibited four clearly understandable P&IM systems, they appear to be relatively generic to the process industries, though we cannot confidently extrapolate beyond our sample. A larger sample might, of course, uncover more unexpected types (similar to the largely unexpected WIP-controlled cluster here) but those identified here would probably surface also. For example, a “simple” cluster and a “computerized” cluster would certainly represent two expected extremes. However, there may be more subclasses of what we have identified here as the “common” cluster. Future research should be directed toward testing the results of this study, extending the results with larger and more varied groups of sites, and eventually determining the “best” P&IM system under various processing circumstances.

In addition to the categorization, this phase of the research provided other important insights, particularly in the realm of existing theory. Some researchers (Bolander, 1981a,b, 1983; Taylor and Bolander, 1991) have suggested that process industries need to focus primarily on capacity (based on the assumption that they tend to be capital intensive) and that materials should be considered secondarily. In this sample, only 53% of the firms considered themselves to be capital intensive and only one site (FEED-YEASTS) considered maximizing the use of capacity to be a particularly important goal. Also, in this sample, the level of detail exercised for capacity planning and control was generally less than that required for materials planning and control. In fact, it was secondary to material control at most sites. Finally, an increased level of sophistication in capacity control was associated with an increased level of sophistication in materials control, implying that as materials are more closely controlled, so are capacities. That is, as firms invest in their P&IM system, they tend to invest in both capacity and material control.

In general, dividing process industry P&IM systems between material-dominated versus capacity-dominated, or time-phased versus rate-based, or even make-to-stock versus make-to-order versus assemble-to-order, as existing theories advocate, provides insufficient guidance for managers to identify P&IM systems similar to their own. As indicated above, selecting another plant that also has a rate-based system (or capacity-dominated or make-to-stock) may well result in selecting a system from a totally different cluster that is not at all comparable to one’s own. Thus, existing theory is not only insufficient; it may be wrong. That is, if you have a rate-based system and find another to compare yours to, it is not just that not all rate-based systems will be appropriate, the most appropriate comparison may well be to a time-based system.

In summary, the categorization developed in this research study provides an improved understanding of process industries’ P&IM systems. It is hoped
that this understanding provide firms with an enhanced ability to share P&IM system accomplishments with other similar types of process firms and foster additional study in this critical and largely under-researched area.

Acknowledgements

We would like to acknowledge the statistical help rendered us by Mark Weaver and Clinton Dart, and the SAS data analysis by Alex Wilson.

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