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# A DISCUSSION OF PRODUCTION PLANNING APPROACHES IN THE PROCESS INDUSTRY

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**Abstract**

In this paper, we discuss the literature on production planning approaches in the process industry. Our contribution is to underline the differences, as well as the similarities, between issues and models arising in process environments and better known situations arising in discrete manufacturing, and to explain how these features affect the optimization models used in production planning. We present an overview of the distinctive features of process industries, as they relate to production planning issues. We discuss some of the difficulties encountered with the implementation of classical flow control techniques, like MRP or JIT, and we describe how various authors suggest to solve these difficulties. In particular we focus on the concept of "recipe", which extends the classical Bill of Materials used in discrete manufacturing, and we describe how the specific features of recipes are taken into account by different production planning models. Finally,we give a survey of specific flow control models and algorithmic techniques that have been specifically developed for process industries.

Keywords: Production flow control, process industry, blending models

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# 1 Introduction: distinctive features of the process industry

## 1.1 Defining features

The APICS dictionary [9] defines *process manufacturing* as "production that adds value to materials by mixing, separating, forming or chemical reactions." This definition provides the key elements to classify industries as "process" or "manufacturing". The dictionary also proposes a further distinction between *batch* and *continuous* processing, where batch processing is defined as "a manufacturing technique in which parts are accumulated and processed together in a lot," while continuous flow production is "lotless production in which products flow continuously rather than being divided" [9]. Earlier versions of the dictionary added that processes "... generally require rigid process control and high capital investment" [8].

Hayes and Wheelwright ([77], [78], [79]) initiated a stream of research that stresses relations between product characteristics and technological processes adopted by firms. In the view of these authors, the successive production processes required to transform raw materials into consumer goods define a "commercial chain" linking raw material suppliers to providers of end-products. They state ([79, pp. 278-279]):

> "At the risk of oversimplification, as one moves from the upstream end of the commercial chain (raw material suppliers) toward the downstream end (the ultimate consumer), product variety increases and highly standardized commoditylike products evolve toward specialized consumer-oriented products. This evolution is accompanied by important differences in the production processes used at different points in the chain and the cost structures associated with them."

Hayes and Wheelwhright propose to position industries along two principal axes, respectively associated with product structure and product life cycle stage *vs.* process structure and process life cycle stage. As products and processes mature, industries move down along these two axes. These authors also highlight that some combinations of features (e.g., highly automated processes with broad, non standardized product lines) usually turn out to be nonprofitable. Safizadeh et al. [124] validate this assumption through a survey of American companies. The majority of firms their sample follow the expected patterns.

| Issue | Upstream | Downstream |
|---|---|---|
| Product | More standardized | More specialized |
| Extent of product line | Narrower | Broader |
| Length of production runs | Longer | Shorter |
| Type of production process | Automated, connected | Labor-intensive, disconnected |
| Capital intensity of production | Higher | Lower,then higher |
| Breakeven utilization point | Higher | Lower |
| Typical response to market downturns | Reduce prices | Reduce production |
| Variability of profit | Higher | Lower |

Table 1: Differences among links in the commercial chain according to Hayes and Wheelwhright [79, p. 278, Table 9-1].

Taylor, Seward and Bolander [157] propose the "matrix" displayed in Table 2, which is inspired by the work of Hayes and Weelwright and provides a convenient tool to emphasize some of the differences between process industries and manufacturing industries; see also Ashayeri, Teelen and Selen [11]. Boskma [34, p. 74] introduces a similar table classifying industries on the basis of their production type and turnover.

Traditionally, process industries have been mostly concentrated in the lower right part of Table 2, associated with commodity products and flow shop layouts. We should mention, however, that this traditional positioning has noticeably evolved in recent years, as process industries tend to adopt market oriented strategies that lead to diversified lines of products, displaying client-specific characteristics and produced according to a "make-to-order" policy. This trend is confirmed by the observations reported in Safizadeh et al. [124], where most off-diagonal companies belong to process industries (batch shop or continuous flow shop). Berry and Cooper [20] develop methods for measuring and diagnosing the quality of the alignment between marketing and manufacturing strategies in process industries.

## 1.2 Process industry vs. discrete manufacturing

Relatively few research papers are dedicated to production management in the process industry. Their authors usually focus on differences between "process industry" and "discrete manufacturing" (see e.g. [64], [100], [157], [158]) and develop new concepts to solve specific production management problems (e.g. [63], [116], [162]).

Excellent overviews of the main issues at stake can be found in [11],

| Process | Product: Custom — Low volume — High volume — Commodity |
|---|---|
| Job | Aerospace |
| shop | Industrial machinery |
| | Machine tools |
| | Drugs |
| | Specialty chemicals |
| | Electrical and electronics |
| Process | Automobile |
| | Tire and rubber |
| | Steel products |
| | Major chemicals |
| | Paper |
| | Containers |
| | Brewers |
| | Oil |
| Flow | Steel |
| shop | Forest products |

Table 2: Industry classification from Taylor et al. [157]

[64], [151], [157] or [158]. Ashayeri, Teelen and Selen [11], for instance, mention twenty-eight features distinguishing process industries from discrete industries. These features are listed in Table 3.

Several items could be added to Table 3. Among these are the following, which we believe are key differences between process industries and discrete manufacturing in terms of planning and scheduling activities.

- In process industries, *raw materials and goods are often perishable*; this places specific constraints on production planning and inventory management; on the other hand, perishability is usually not an issue in discrete manufacturing (although many exceptions could be cited; see [105]).

- For the purpose of long term or medium term planning, *detailed routing information is often required* in process industries, as products are commonly defined by (or identified with) the succession of production steps which they undergo; by contrast, routing information is usually disregarded until the scheduling phase in manufacturing industries. It is only implicitly considered in the value of leadtime parameters and

| | Process Industries | Discrete Industries |
|---|---|---|
| **Relationship with the market** | | |
| Product type | Commodity | Custom |
| Product assortment | Narrow | Broad |
| Demand per product | High | Low |
| Cost per product | Low | High |
| Order winners | Price | Speed of delivery |
| | Delivery guarantee | Product features |
| Transporting costs | High | Low |
| New Products | Few | Many |
| **The Product Process** | | |
| Routings | Fixed | Variable |
| Lay-out | By product | By function |
| Flexibility | Low | High |
| Production equipment | Specialized | Universal |
| Labor intensity | Low | High |
| Capital intensity | High | Low |
| Changeover times | High | Low |
| Work in process | Low | High |
| Volumes | High | Low |
| **Quality** | | |
| Environmental demands | High | Low |
| Danger | Sometimes | Hardly |
| Quality measurement | Sometimes long | Short |
| **Planning & control** | | |
| Production | To stock | To order |
| Long term planning | Capacity | Product design |
| Short term planning | Utilization capacity | Utilization personnel |
| Starting point planning | Availability capacity | Availability material |
| Material flow | Divergent + convergent | Convergent |
| Yield variability | Sometimes high | Mostly low |
| 'Explosion' via | Recipes | Bill of Materials |
| By and Coproducts | Sometimes | Not |
| Lot tracing | Mostly necessary | Mostly not necessary |

Table 3: Differences between process industry and manufacturing industry. From Ashayeri et al. [11]

of other aggregated parameters used for instance in master production scheduling and in rough-cut capacity planning.

- *Raw materials frequently play a very central role* in production management activities for process industries. They usually fall into two distinct classes, namely *main materials* on one hand and *auxiliary (or secondary) materials* on the other hand. Efficient management of the main raw materials is often a top priority in process industries; we return to this issue in Section 2.
- Sometimes, the sales mix of finished products has to be optimized due to the existence of *co-product links* (see [158]).

It should also be observed that much of the above discussion focuses on *continuous* process industries. Further differences emerge when one considers *batch* process industries, which can be viewed as positioned halfway between continuous and manufacturing industries. As a matter of fact, Fransoo and Rutten [64] propose Table 4, where several types of industries are positioned on a continuous axis ranging from batch process to flow process. Dennis and Meredith [52] similarly emphasize the need to distinguish between different types of process industries and propose seven classes of process industries based on sixteen discriminant characteristics [53].

| batch / mix | | | | | | | process / flow |
|---|---|---|---|---|---|---|---|
| drugs | speciality chemicals | rubber | major chemicals | paper | brewers | steel | oil |

Table 4: Process industries classification. From Fransoo and Rutten. [64]

From the more specific point of view of planning and scheduling, the following features of batch process industries should be mentioned.

- More and more process industries (even in traditional "heavy" sectors like the steel industry) are shifting to *specialties market* and are no longer basing their strategy on a "make-to-stock" approach only (see e.g. [96]). This is especially true of batch process industries, as these industries no longer restrict themselves to commodity products, but also attempt to customize their products and to move toward specific market niches with higher profit margins (e.g. pharmaceutical industries, chemical specialties).

- The rate at which new products are introduced increases steadily in batch process industries, so that these industries commonly use key performance indicators such as the "*number of new products per year*" (see e.g. [16], [168]).
- As far as production planning is concerned, batch process industries must cope with *variable recipes* and *sequences of transformation processes*, as the flow of materials can change from one batch to the next.
- All materials, from raw materials to finished products, usually use *special storage equipments* that must be taken explicitly into account by planning and scheduling systems (temperature constraints, impossibility to store different products in a same tank, etc.; see [89]).
- *Scheduling is often more complicated* than in continuous process industries due to the broader diversity of products and, therefore, the greater variety of production paths and greater short-term variations in product demand.

## 2 Materials and information flow control models

Bertrand, Wortmann and Wijngaard [21] define *production control* as "the coordination of supply and production activities in manufacturing systems to achieve a specific delivery flexibility and delivery reliability at minimum cost". Fransoo [63] adapts this definition for continuous process industries into: "the coordination of production and order delivery activities (...) in order to maximize the profit". It should be stressed that the shift, in these definitions, from "minimizing cost" to "maximizing profit" is a major one. Constraints such as the availability of raw materials, the simultaneous production of final products and co-products or by-products, or the optimal usage of expensive equipments, strongly influence production control, so that demand satisfaction can no longer be enforced, as is often the case in discrete manufacturing. Thus, it becomes necessary to select the sales portfolio in order to maximize profit.

The above definitions subsume production and operations management activities with different time horizons, like production planning, scheduling and day-to-day (shop floor) control. In this section, we discuss the difficulties faced by classical flow control techniques in a process environment and the required adaptations with respect to discrete manufacturing.

## 2.1 Need for the integration of pull and push strategies

Many authors mention process industries as typical, even paradigmatic, examples of "push systems". They base this claim on several of the main characteristics of process industries: the major role played by raw materials (we examine this point in greater details in Section 2.3), the technological constraints placed by the transformation process (e.g., impossibility to store intermediate products), the plant topologies (production lines), the market characteristics (commodity products with high and stable or predictable demand) and the fact that such industries are very capital intensive, with little or no flexibility in capacity usage. Mirsky [96], for instance, describes as follows the key problem of implementing JIT (pull) techniques in process industries: Due to capital-intensive processes or resource constraints, capacity is fixed. But seasonality effects result in demand peaks which exceed capacity. Thus, planning is necessary to smooth production runs, contrary to the underlying philosophy of pull systems.

But in fact, as observed by other authors, a less extreme view may often be closer to reality. From a market perspective, there exists a trend, already mentioned above, according to which process industries tend to move away from make-to-stock and toward make-to-order strategies, while offering a more diversified, customized line of products. Under such conditions, firms may be tempted to adopt hybrid push-pull control systems in order to reduce in-process inventory levels while saturating bottleneck equipments. Planning objectives for the pre-bottleneck production stages are to feed the bottleneck with an uninterrupted stream of products, in order to keep this production stage busy. Thus, a pull strategy is used from the bottleneck up to the raw materials, as a way to control inventory levels. From the bottleneck stage down to the last production stages, a push strategy is used in order to optimize the utilization of the bottleneck.

It must be noticed, however, that such hybrid control strategies are difficult to describe or to implement rigorously (see e.g. [164]), as the push and pull strategies impose opposite requirements on the planning system. Decreasing demand for certain products, for instance, may temporarily require to slow down or to switch off certain equipments, contrary to the well-established push wisdom that calls for saturating them. The dairy co-ops supply systems are another example where integration is not easily achieved, as the co-ops have the obligation to accept milk collected and to transform it, independently of the demand for final products.

## 2.2 Need for a redefinition of basic concepts and principles used in classical MRP-JIT flow control models

The goal of flow control models is to manage the flows of products and related informations in order to optimize various production performance measures. Both Material Requirements Planning (MRP) and Just-in-Time (JIT) systems, as well as more recent Enterprise Resource Planning (ERP) systems, are accordingly designed to manage the flow of materials, components, tools, production processes and information. Much of the theoretical analysis and of the practical implementations of MRP and JIT systems, however, have focused on discrete manufacturing. As a consequence, these methods heavily rely on concepts and principles which, if relevant for discrete manufacturing, do not necessarily apply in a straightforward way in a process environment. This is generally true, in spite of the existence of some practical implementations of MRP-like or specific systems in process industries (e.g. [5], [18], [38], [41], [93], [107], [113], [160]). We discuss here some of these key concepts and principles : Bills of Material, work-in-process reduction, role of alternate routing at the planning level, separation of planning and scheduling, product costing, demand management

- Both JIT and (especially) MRP techniques use the concept of *Bill of Material*, defined by APICS [9] as "a listing of all the subassemblies, intermediates, parts, and raw materials that go into a parent assembly showing the quantity of each required to make an assembly (...)." The APICS definition further specifies that "the Bill of Material may also be called the formula, recipe, or ingredient list in certain process industries." Formulas or recipes, however, are quite different from discrete BOMs, and this difference may significantly hamper, or even prevent the implementation of JIT/MRP systems in process industries (e.g. [38], [41], [57]). We will come back, in Section 3, to the distinction between discrete BOMs and process recipes, and to its impact on flow control models.

- In manufacturing industries, value is added to the product in large part through direct labor and reducing work-in-process is often one of the high priorities. This helps explaining why discrete manufacturers are so concerned with Just-In-Time and materials planning issues. On the other hand, process manufacturers are usually more concerned about the efficient use of equipment, in particular because of the importance of set-up times/costs and of capital investments [74],[79, pp. 278-279].

- Most of the literature on planning models does not deal with routing and capacity issues. It is implicitly assumed that, in a manufacturing environment, these issues can be disregarded at the planning level. They are only explicitly handled at the scheduling level. This assumption is usually invalid in the process industry, where products are typically defined by the sequence of transformations and operations which they undergo (i.e., by their routing).

- The dividing line between planning and scheduling issues is not always drawn unambiguously in the production management literature. It is usually agreed, in particular, that the distinction between planning and scheduling should not be based only on the horizon length, but should also account for production conditions. For instance, if a production run takes many days, as is frequently the case in process industries, then the scheduling problem may be defined on a horizon of more than one week [63]. Similarly, when setups are time-consuming, lot sizing issues may become crucial and cannot always be deferred to short-term planning models. As a consequence, planning and scheduling issues arising in the process industry are tightly intertwined. In extreme cases, lot sizing (a planning issue) and job assignment (a scheduling issue) can even merge completely into the design of production "campaigns". When this is the case, classical mathematical models must be adapted accordingly. Birewar and Grossmann [23] provide an illustration of these comments. Demeulemeester and Herroelen [51] use a graph approach to incorporate setup times and batching in production planning and scheduling. Allen and Schuster [6] propose an aggregation-disaggregation algorithm to reach the same objective.

- In manufacturing industries, planning is classically based on direct costs, among which labor costs are the most important. MRP systems also rely on direct costing procedures for planning and cost reporting. In process industries, and especially for continuous processes, direct costs only represent a small part of the total product costs (e.g. Moran [100]) due to the high level of capital investment, measured by the sales/asset ratio ([79, pp. 278-279]), and to large setup and changeovers costs. Cost management experts debate on how to calculate the cost of products which share common raw materials or common production stages, and how to take investments into account in product costing (see e.g. [40], [81], [99], [130]). Sandretto [126] promotes mathematical programming techniques to decide which products to make in the case of joint products. Aiello [3] highlights the benefits of a costing method based on the analysis of the variance of the production costs across batches, as opposed to the product costing approach.

- Demand management sometimes requires specific approaches. Production constraints such as setup time and changeovers, which impact the cycle time, must be integrated with demand management in order to select products that maximize profit. In this context, Fransoo [62] develops a heuristic to optimize the production cycle time. Venkataram and Nathan [166] develop a weighted integer goal-programming model taking into account minimum batch sizes for master production scheduling.

- Often in process industries, as in repetitive manufacturing, the quality of raw materials or end products can be variable. Moreover, specifications differ from one customer to another (see e.g. [57], [160]). Higher quality products can be used to satisfy demand for lower quality ones, and planning and scheduling have to take these aspects into account when determining the optimal lot sizes and schedule. For example, Gerchak et al. [67] examine this problem in the case of random yields.

For all the above reasons, MRP and JIT are not very well suited to the needs of process industries. Schuster and Allen ([131],[133]), for instance, document the shortcomings of an MRP system in a food processing company (see also [38], [132]).

Nevertheless, and in spite of these obstacles, some of the underlying basic principles of JIT models have been used in process industries to increase the performance of supply chains and processes (e.g. [22], [39], [54]). Typically, purchasing and quality improvement, inventory reduction, people involvement and waste elimination programs can be applied in process industries as well as in discrete manufacturing (e.g. [101]). For instance, Hougton and Portougal [82] describe the reengineering of a production planning process by JIT techniques in a food company whose production process consists of packaging lines.

Some papers (see e.g. [19], [110], [141], [148], [149]) discuss the integration of MRP and JIT techniques, but none of them is oriented toward the process industry, except for the analysis proposed by Mirsky [96].

## 2.3 Key importance of raw materials management

In many industries, raw materials are managed via the Bill of Material (BOM) data and are essentially viewed as providing a link (or, sometimes, a barrier or frontier!) between the purchasing and production departments (see e.g. [37]). In process industries, raw materials frequently play a more active role for production management activities.

Raw materials consumed by process industries usually fall into two distinct classes, say *main materials* on one hand and *auxiliary (or secondary) materials* on the other hand. For instance, in the steel industry, iron ore and coal could be viewed as main materials, whereas various additives would be treated as auxiliary materials. In the dairy industry, milk and cream are main materials, whereas chemical tracers and packaging components are auxiliary materials.

In many cases, the auxiliary materials can be managed using classical BOM-based approaches. But main materials, by contrast, display several distinguishing features which require to manage them more carefully (see e.g. [64], [79], [157]):

- Typically, there are very few types of main materials and they constitute the key elements in the definition of the products.
- They often place the main constraints (related to capacity, availability, price,...) on production management.
- Their cost represents a major part of the total marginal production cost, sometimes up to 90 percent of the sales value.
- Their market is frequently highly competitive and speculative.
- Composition varies from batch to batch (e.g., sulfur and naphta contents of oil, iron content of ore, fat content of milk, etc.).
- Only some of the characteristics or attributes of raw materials are valuable and are used in the end product (e.g. the iron content of ore).
- Often, the supply flows of raw materials are not totally under control, and deliveries are not necessarily linked to specific orders. Moreover, the raw materials can be perishable and have to be transformed within a short time span (say a few days) into finished products. This lack of control over supply is for instance observed in the case of dairy co-ops where the milk collected has to be pushed in the process. The same problem is highly present in the fish industry and Jensson [84] develop

a production scheduling decision system to deal with the randomness of fish supply.

When the "core" raw material is a scarce resource, its management becomes an essential but complex task and the company often delegates this task to a cross-functional committee (see [133]). This committee is responsible for assigning raw materials to plants or production lines and for selecting production recipes depending on the demand and on raw materials availability. In other cases, recipes are defined by an operational manager, sometimes assisted by ad hoc decision support systems (see e.g. [4], [12], [43], [95], [159] and Section 3).

This implies, in particular, that decisions related to production planning, inventory control and product definition must be more tightly interconnected in process industries than in discrete manufacturing industries.

### 2.4 Need for detailed planning/scheduling of storage facilities

Finally, in this section, we briefly mention some of the work that tries to account for limited storage availability. Of course, limited storage is not unique to process industries. Many classical planning and scheduling models, for instance, explicitly model finite capacity buffers; see for instance [73], [112]. Storage availability, however, often takes a special importance in the process industries because of its highly constraining features:

- As opposed to industrial warehouses or shelf-space, where "one additional" item can often be squeezed without too much difficulty, the capacity of tanks for liquid products (oil, juice, chemicals, ...) places a hard constraint which cannot be violated under any circumstances.
- Different products cannot be mixed in a same tank.
- Tanks and containers may require to be cleaned when switching from one product to another.
- As part of their processing requirements, semi-finished products may require to be stored for some (usually, flexible) amount of time in intermediate storage facilities.

All these characteristics translate into complex restrictions on feasible routings, schedules and batch sizes for the mix of products produced over a given horizon of time.

Ballintijn [15], for instance, introduces tank allocation issues into a mixed-integer programming model for refinery scheduling. Snyder and Ibrahim [140] investigate tank capacity restrictions by statistical analysis and simulations techniques for a large bulk storage investment analysis. Pantelides [111] considers tank capacity and availability as elements of the resource set in a State Task or Resource Task Network. Daellenbach [45] describes and solves an assignment problem with storage capacity under stochastic demand. Northrop [109] presents an application of the OPT (Optimized Production Technology) approach to tank allocation in a brewery.

# 3 Bill of Material and recipes

In this section, we examine in more detail the peculiarities of the Bill of Material (and its close relatives) in the process industries and we provide a brief review of the models proposed in the literature.

## 3.1 Main features of product recipes

The Bill of Material concept has been already defined and discussed. Further discussions of this concept in the discrete manufacturing framework are provided in numerous references, e.g. [75], [94], [127].

In process environments, the role of the BOM is played by *product recipes* or *formulas*. The main distinguishing features of recipes, as opposed to classical BOMs, can be described as follows.

- The classical description of a Bill of Material, typical of discrete assembly processes, is through an acyclic oriented graph indicating the relation between each unit of the finished product and the components necessary to manufacture it. The graph structure converges into the top node (associated to the final product), as *all* units of raw materials, parts and subassemblies eventually "merge" into one unit of the parent assembly. In process industries, product structures are often divergent rather than convergent, reflecting e.g. the existence of splitting operations and the generation of *co-products* (or *by-products*) as part of the production process. Fransoo and Rutten ([64]) conducted a survey and analyzed the typology of BOM in the process industry. They summarize the different types of BOMs by Figure 1. Cycles also frequently appear, as some materials flows must revisit previous process stages (see e.g. [127] for an example in the chemical industry).

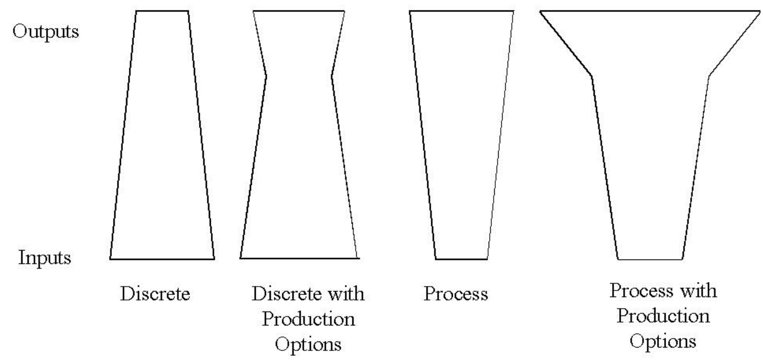


Figure 1: Different types of Bill of Material

- A most important feature of recipes is that they usually allow for *alternative* ways of obtaining a certain final product. This opens the possibility to design the product during the planning phase, or even in the course of production, depending for instance on the availability or on the cost of the required ingredients. Of course, alternative process plans are also commonplace in the manufacturing industry (e.g., in metal-cutting activities), but they usually translate into the possibility to use various routings rather than different BOMs. Their impact on tactical (medium-term) production planning remains quite marginal, as the choice of routing is typically done during the scheduling phase. In process industries, alternative recipes arise in one of two ways: either a finite collection of fixed admissible recipes is established (as in [43], [123]) or the final product is characterized by a set of attribute values and any production plan yielding these attribute values is considered admissible (e.g., the final product must contain at least 50% of cacao powder and less than 10% of fat). The latter type of recipes leads to the formulation of *blending* models, in the line of the famous diet model discussed in Dantzig [46]. We provide a review of the literature on blending models in Section 3.3. It is crucial to notice that different blending recipes may lead to different consumption patterns for the various ingredients, may generate different quantities of co-products and may result in very different costs [123]. These recipes capabilities must be validated by quality control or product design departments (see e.g. [56]).

- Just as in discrete manufacturing, the existence of alternative recipes also affects the available process routings. Product and process should still be considered as different concepts. However, the distinction between them is often blurred, as production managers do not *distinguish the product specification and the way (or routing) to obtain it*. For example, the ISA SP88 standard ([47], [61], [76]) defines a recipe as "the necessary set that uniquely defines the production requirements for a specific product".

- Finally, the description of product recipes is frequently complicated by variable yields, variable concentrations, distinct unit ranges at different production stages (e.g. tons, liters and packaging units), etc. (see e.g. [41], [64]). As a result, monitoring "flow conservation" and "material balance" constitutes a non-trivial challenge for mathematical models used in production planning.

## 3.2 Bill of Material and operations

A basic tool used in the chemical engineering literature to deal with the BOM is the *State-Task Network* (or STN), proposed by Kondili et al. [88] as a way of representing chemical processes by two types of nodes: state nodes representing materials and task nodes representing process activities (see Figure 2). The State-Task Network can be called an "co-products BOM", since it is a natural extension of the BOM obtained by introducing operations that consume several products and/or produce several co-products at the same time in fixed proportions.

Pantelides [111] proposed a framework unifying the two node types, viz. the *Resource-Task Network* or RTN. This framework is used extensively for formulating short term scheduling problems in the chemical industry (see e.g. [55], [88], [173], [174]).

## 3.3 Blending models and recipe optimization: a literature classification

As explained above, production recipes are often flexible in process industries. Flexible recipes are not adequately captured by the "co-products

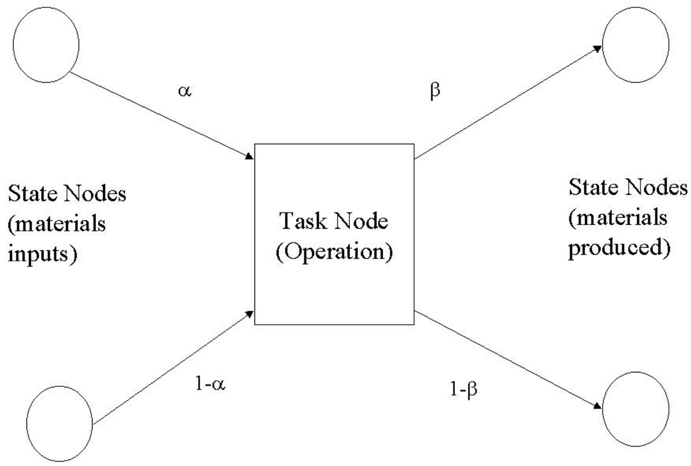


Figure 2: co-products BOM

BOM" described in the previous section, as the type and rate of the products which are consumed and/or produced may vary. On the other hand, a large body of literature on *blending models* has emerged to deal with flexible recipes.

Generally speaking, blending models require the determination of a cheapest blend, or recipe, subject to a collection of constraints regarding the availability of raw materials and the target characteristics (nutrient contents, octane grade,...) of the final product. Based on a literature review, we propose a classification of blending models along two dimensions: the type of industry and the hierarchical level of the model within the production planning procedures.

- Type of industry: we found that blending models differ according to the industrial sector in which they are used. Therefore, we classify process industries in different classes depending on their core business. We also decompose the oil sector into sub-sectors, depending on the type of process where blending models are encountered.

- Degree of integration of the model. We distinguish three classes of applications:

– Product design and other applications: the blending model is self-supporting and isolated from other production planning models.
– Long- or mid-term planning: the blending model is integrated in a mathematical model for long-term or mid-term (master) planning. We group both types of models, since they were found to be quite similar.
– Short-term planning and scheduling. As discussed in Section 2.4, these two levels are frequently intertwined or sometimes completely merged. Therefore, we group both levels into one class.

Table 5 displays the results of this classification.

| Industry | Product design and other applications | Long- and mid-term planning | Short-term planning and scheduling |
|---|---|---|---|
| Food | [24], [58], [66], [121], [143] | [121], [169, pp 272-279], [170] | [122] |
| Feed | [48], [68], [104], [117], [163], [171] | [150] | [68] |
| Oil: Gasoline-blending | [36], [70], [71], [92], [14] | [49] , [119] | [42] |
| Oil: Refining | | [7], [14], [42], [92], [136, pp 397-404], [80, pp 73-75] | [15] |
| Oil: Pooling | [2], [7], [91], [136] | [14], [91] | |
| Oil: Unloading and allocation | | | [90] |
| Oil: Overview | [14], [27] | | |
| Steel industry | [36], [50], [138], [145] | [59], [137] | |
| Chemical (mostly paint industries) | [4], [85], [95], [120] | [120] | [35], [159] |
| Energy | [138] | | [114] |
| Agriculture | [12], [48], [69], [104], [117], [163], [171] | [150] | [68] |
| General applications | [60], [108], [144] | | |

Table 5: Classification of blending models

# 4 Specialized approaches for flow control

So far, we have highlighted the differences between the planning concepts, requirements and models in discrete manufacturing and process industries. Here we present models and algorithms that have been proposed to tackle specific planning and scheduling problems for the process industries. Due to the above limitations, many new algorithms, often optimization-based, have been developed for production planning problems arising in process industries (see e.g. [27], [118], [136] for a presentation). Therefore, we classify these contributions by type of algorithms used. For each approach, the intended area of application may be quite generic or, on the contrary, very specific to a certain industry or company context.

### Mathematical progamming models and algorithms

Some authors propose to build integrated planning and scheduling models by interconnecting several classical mixed-integer linear programming models; see e.g. Coxhead [42] for a refinery plant. Birewar and Grossmann [23] develop linear models coupled with rounding policies for defining production campaigns in the case of multi-products manufacturing lines. Nembhard and Birge [108] propose a multiobjective nonlinear model for costly startup optimization. Schuster and Allen [133] formulate a linear programming model to allocate scarce resources in a food company. Adelman et al. [1] use integer programming techniques to allocate fibers in a cable manufacturing company. Jensson [84] uses linear programming models to schedule production in fish industries in which the randomness of raw materials is the most difficult parameter. Allen et Schuster [6] develop an aggregation-disaggreation procedure before using classical scheduling models. Sahinidis and Grossmann [125] develop mixed-integer linear programming models coupled with variable disaggregation to analyze strategic production planning for chemical companies (see also Köksalan and Süral [87] for a drink company and Sinha et al.[139] for a steel industry).

### Graph and network models

In most cases in which either raw materials are scarce resources or the production flexibility is limited, planning and scheduling models incorporate the issue of recipe management (product design) and describe the flow of materials through all process stages, from raw materials to finished products. Graph models are often used to describe these flows, and to facilitate the modular construction of the associated optimization models. This is for instance the case of the *process flow scheduling* approach proposed first by Bolander ([28], [29]) and further developed in [30], [31], [32], [83], [152], [153], [154], [155], [156], of the *product routing* approach in [165] and of the *process train* approach in [33].

Resource-Task Networks or State-Task Networks are used in [44], [51], [88], [111], [134] to formulate and solve planning and scheduling problems in process environments. The STN is most broadly used for planning and the RTN for short-term scheduling. Recent papers are dedicated to these network representations and focus on how to solve the huge MILP or MINLP problems to which they give rise; e.g. [25], [26], [35], [55], [135]. Another interesting research direction is to investigate efficient ways to model time in such scheduling problems, e.g. by uniform discretization ([173]), or by nonuniform discretization ([97]), or continuously ([13], [98], [128], [129], [147]), or by event sequencing ([174]).

**Optimization heuristics**

Tadei et al. [146] present a partitioning algorithm and local search techniques for aggregate planning and scheduling in the food industry. Stauffer [142] develops meta-heuristics to schedule steel processes. Graells et al. [72] and Van Bael [161] use simulated annealing to solve chemical scheduling problems.

**Expert systems and simulation techniques**

Artiba and Riane [10] combine expert system techniques, simulation, optimization algorithms and heuristics to develop a planning and scheduling system for batch chemical industries. Baudet et al. [17] combine discrete events simulation techniques with meta-heuristics algorithms to schedule job-shop plants (chemical and computer industries). Verbraeck [167] develops an expert system for scheduling in a metal transforming industry. Moreira and Oliveira [102] use expert system techniques in combination with an MRP model for short term planning in a petrochemical environment. Nakhla [106] proposes a rule-based approach for scheduling packaging lines in a dairy industry. Some authors (e.g.Winkler[172]) propose to combine visualization tools and optimization techniques for solving scheduling problems.

**Neural networks and fuzzy sets**

Puigjaner and A. Espuña [115], as well as Katayma [86], propose production control tools based on neural networks for the batch process industry. Müller [103] uses fuzzy sets to solve production scheduling problems in the dairy industry.

**Theory of Constraints**

Schuster and Allen [132] propose a "Theory of Constraints" approach to handle scheduling problems arising in packaging lines for the food industry. Northrop [109] presents an application of the OPT (Optimized Production Technology) approach to tank allocation in a brewery. Both focus on optimal usage of scarce resources.

**Control theory**

Control theory has been used for bottlenecks and supply chain optimization, see e.g. [21], [131].

**Statistical and probabilistic analysis**

Fransoo, Sridharan and Bertrand [65], Rutten [121], Rutten and Bertrand [123] describe probabilistic approaches for demand management in continuous process industries and in the dairy industry.

The relation between methodologies and areas of application is summarized in Table 6. Each cross "x" indicates that we have found paper(s) examining the applicability of a technique to the corresponding area.

## 5 Conclusion

The above discussion points toward the need for a more thorough investigation of the specificities of planning models in process industries. In particular, the integration of the scheduling phase, of a finer description of the production process itself, and of recipe management within long term and hierarchical planning deserve further attention.

From the brief overview done in section 4, it appears that mathematical programming approaches provide a rather versatile tool for modelling and solving a variety of production planning problems in the process industry. This is especially true when such approaches are coupled with flexible and

| | Math Prog & Algo | Graph STN RTN | TOC | Heuristic | Stat & proba | control theory | Expert Sys- tem | Neural Net- work |
|---|---|---|---|---|---|---|---|---|
| planning | X | X | | | | | | X |
| scheduling | X | X | | X | | | X | X |
| integrated plan- ning / schedul- ing | X | X | | | | | X | |
| demand | | | | | X | | | |
| complex mate- rials flow | | X | | | | | | |
| bottleneck usage | | | | | X | X | | |
| scarce resource | X | | | | | | | |
| storage | | X | X | | | | | |
| supply chain | | | X | | | X | | |

Table 6: Areas of application vs. techniques

powerful modelling techniques, like graph-based representation tools of the STN-RTN type.

Currently, we investigate how to optimize product design (and quality) as a function of the raw materials quality by using more detailed non-linear production process models (physico-chemical mass balances, ...).

We also investigate extensions of the STN tool to support co-product BOM with flexible recipes (variables input proportions) and their integration in the planning process (strategic to operational).

In these investigations, tighter integration of planning and scheduling is obtained by considering detailed recipes at all levels of the planning process.

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