Integrating Budgeting Models into Scheduling and Planning Models for the Chemical Batch Industry

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This paper addresses scheduling and planning with financial management in the batch chemical process industries. A cash flow and budgeting model is coupled with an advanced scheduling and planning procedure for a specific multipurpose batch specialty chemical plant. To motivate the use of an integrated model, a sequential scheme is first solved. Hence, the scheduling and planning problem of the batch specialty chemical plant is optimized in order to fulfill the due date policy. Then, a deterministic cash management model is optimized to maximize the enterprise earnings, using the cash flows of the scheduling−planning model as parameters. As a result, owing to the fulfillment of customer requirements, the solvency of the firm changes, and hence, the funding policy is affected. The results of the sequential approach are then compared with the integrated model highlighting the advantage of the latter option. Here, production scheduling−planning and cash management are optimized in unison with a common objective of maximizing earnings. The model development made in this paper and the results suggest that a new conceptual approach in enterprise management systems consisting of the integration of the enterprise finance models with the company operations models is a must to improve the firm's reliability and its overall earnings.

1. Introduction

Most companies are based in a functional organizational structure with separate departments for production, supply, logistics, service to customers, etc. At the enterprise level, most planning is done by functional area. In this situation, each functional area's plan is sequentially considered as input to the others according to a hierarchy. In this way, software enterprise-wide systems allow information-sharing and collaboration processes, but they do not develop real integration relationships. The synchronization of the interactions between functions of a firm can be solved only if the multiple functional plans are simultaneously considered taking into account all functional constraints in unison.

In this work, the optimal assignment of the most expensive limited resource, money, is considered as the common variable to integrate operations and finances functional areas. It is interesting that a simultaneous approach considering money as a limited resource is generally accepted as a method to plan jointly the supply chain activities among all the chain's trading partners. With this aim, the supply chain planning (SCP) software systems link financial/economic performance measures within the decision making process. However, at the enterprise-site level, the problem is not the object of the same attention using an economic common language by means of cash flow synchronization at the short-term cash budgeting and production planning time.

The simultaneous short-term production planning and finance optimization at enterprise level is a theme long considered in the literature. However, not many practical applications can be found. Charnes remarked that the rational deployment of a firm's resources requires simultaneous consideration.[1] Later on, Robichek developed simultaneous linear programming models of financial funds decisions and observed that the financing problem is divided into subproblems because it was too complex to be analyzed all at once.[2] Lerner and Orgler recognized the merits of joint enterprise financial modeling, but no practical applications for integration are presented.[3,4] Srinivasan remarks that academic research in cash management has been focusing more on the specific decision types and paying less attention to a broader integrated objective, based on how to use and interconnect the set of decisions necessary for simultaneous production and financial management.[5]

The supply chain-planning problem is the one that nowadays monopolizes the financial integrated attention at the academic level. Two academic examples of supply chain scope are the integrated approaches of Z. M. Mohamed and McDonald, that analyze and regulate the operative decisions within the supply chain on the topic of the best job assignment in multinational companies with multisite shops, evaluating accountancy performance measures.[6,7]

On the other hand, practice is nowadays going behind theory in financial integration, particularly in commercial software. In addition to the SCP systems, some off-the-shelf software systems have appeared to aid in the lack of links between plant and business level during

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planning in a rather empirical and iterative way (see for instance http://www.ibis-bis.com).

In the present, economy dynamics makes intractable the empiric management of financial resources at enterprise level. The problem of mobility and allocation of capital becomes the central problem of management today. New tools with empowered possibilities are now more necessary to decide the appropriate management actions, in a suitable time and amount, of the bundle of financial and operative decisions concerning the enterprise value-added chain.

If the optimization of financial decisions regarding different internal functions of a corporation, as the production management, is not jointly integrated, its benefits are not obtained. Two main types of advantages are obtained when integrating production and financial decisions; the first one is the advantage of synchronization of the cash flows. When the financial managers avoid insolvencies via synchronization of inflows and outflows, the peaks of cash needed are flattened, hence avoiding the urgent request of funds. Thus, the supposed situations of insolvency that would be created if the cash flows were not synchronized imply a savings equal to the potential cost dependent on the funds requested and its urgency. The second advantage is that when the financial revenues are maximized and the costs minimized by an optimized administration, extra revenues can be obtained.

Nowadays, with the present lack of such adequate enterprise computer-aided systems capable of managing optimally the working capital, the chief financial officers (CFOs) make decisions using out of date, estimated, or anecdotal information.[8]

One possible improvement, illustrated in this paper, is a two-step procedure consisting of maximizing earnings at production operations level by incorporating an adequate synchronization of cash outflows as payable accounts (raw material, labor, etc.) and cash inflows as receivable accounts from sales. This output is in turn used as an input data for the budgeting problem. The budgeting model determines the periods of payments and manages loans and marketable securities to maximize its objective function. Srinivasan presents a review of such deterministic budgeting methods.[5]

However, the real improvement is achieved with the integration of both activities to use a single one-step procedure. It is evident that a good schedule, from an operations point of view, may create financial stress, while some other schedule may not generate a negative impact in the budgeting side. Since the largest earnings possible are the goal, it is also clear that the one-step procedure is the only one that guarantees them. In this paper, such integration of a cash flow management model with an advanced planning and schedule (APS) procedure is performed, tested, and proved to considerably increase revenues of a case study.

Peter Drucker remarks on some important aspects that are relevant to the approach of our work, like the fact that money is the most expensive resource constraint, though the less planned.[9]

The paper is organized as follows. First, a specific deterministic scheduling–planning model is presented and used to illustrate the advantage of the integration of models for a specific case study. Then, budgeting models are reviewed, and a budgeting model is presented. Following that, a motivating example, where the planning is done first followed by the budgeting model, is analyzed. Next, the integrated deterministic model is presented, and results are compared with those of the motivating example.

2. Scheduling and Planning

In the last 25 years, a huge number of models have been developed to perform short-term scheduling and longer-term planning of batch production plants. Their aim is to optimize quality or cost-related performance measures.[10–14] The financial matters are not still integrated to support decision making, and so, until today, scheduling–planning and budgeting modeling have been treated as separate problems and typically implemented in a sequential way. Therefore, lacking concrete links to financial matters, the output of the scheduling and planning routine, in terms of the batch-plant timing and amount to be produced, is typically obtained optimizing some operative performance function, like makespan, or some simplified economic objectives, like cost or revenues from sales.

In the chemical-processing context, production planning and scheduling refers to the routine of allocating resources and equipment over time to execute the process tasks required to manufacture products to satisfy a specific product demand. Production planning implies allocation decisions over longer time scales (months), while scheduling focuses on the shorter time scale allocation and the sequencing decisions required to satisfy the product demand. Typically, in the case of scheduling, a specific product is assigned to specific equipment at a given time, while in the case of planning, product fabrication and equipment allocation is decided in a given period of time without being specific on the sequence during such period.

In its most general form, the scheduling problem consists of obtaining an operating strategy applied to a set of plant equipment, a set of resources, using a set of product recipes and product precedence relations, specifications of resource availability and product requirements, and an optimization criterion.

Scheduling and Planning Model. We consider a multiproduct batch specialty plant with *n* different batch units. Here, each production recipe basically consists of the reaction phase. Hence, raw materials are transferred from stock to the batch unit, and at the end of processing, products are directly transferred to trucks or to stock to be transported to different customers. This scenario is excerpted from a real batch-producing company. Setup times are considered, and production orders are classified within three types: (1) Unexpected orders of difficult forecast and normally known very little in advance. Plant managers can choose their execution as a function of the actual plant capacity. Thus, to a certain degree the overall number of these orders can be forecasted, but the specific orders to come are less predictable. (2) The second type is regular orders, known about for many months in advance. (3) The third type is seasonal demand, consisting of specific orders for few weeks in advance. These can be often estimated quite accurately.

The model divides the planning and scheduling horizon H into two stages (see Figure 1): a first stage and period with a time horizon H1 (one week) where production is scheduled with known product demands, and a second stage of 13 periods, with a time horizon H2 (13 weeks), where production is planned using known as well as estimated demands.

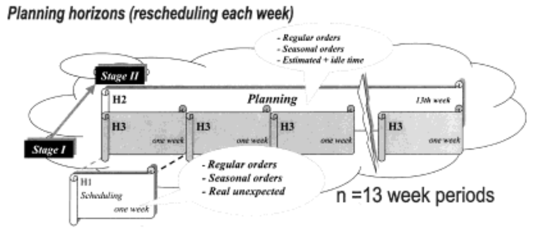

Figure 1. Scheme for the stages and scheduling and planning horizons.

For this second stage, forecasts of regular and seasonal orders are used. However, to deal with unexpected demands on the planning horizon H2, which are known within, for example, one week's notice, only their overall numbers are estimated, and hence, the model assumes certain idle time to accommodate them. In addition, it is assumed that unexpected orders may or may not be fulfilled depending of the actual plant capacity. However, seasonal and regular orders are executed on time if possible.

The model is to be rerun every H1 period as forecasts become real orders. Therefore, the results of planning horizon H2 will never reach execution. However, they are important to be considered when solving the scheduling horizon H1, because one could schedule in H1 the fabrication of materials needed in period H2 and keep them as inventory. At the financial side, the weekly reschedule provides a reliable forward-looking scenario aiding the synchronized financial decision making and the optimized application of the long-term capital budget postulates. The model is described in detail next.

First Stage: Production Scheduling. This first stage is exact. Production demands and raw materials and final product stocks are known. Here, orders to be produced are scheduled considering setup times (cleaning times). The sequence of orders to satisfy customer requirements and the equipment unit assignment to orders are calculated. The equations of the model are the following:

$$\mathrm{TPfw}_e = \sum_o \sum_p \mathrm{TOP}_p nx_{p,o,e} + \sum_o \mathrm{CT}_{o,e} \qquad (1)$$

$$\mathrm{TPfw}_e \leq \mathrm{H1}\ \text{(week production span)} \qquad (2)$$

$$\mathrm{CT}_{o,e} = \sum_p \sum_{p'} \mathrm{CL}_{p,p'} x_{p,o,e} x_{p',o-1,e} \quad o > 1 \qquad (3)$$

$$\mathrm{CT}_{o,e} = 0\ \text{(initial required cleaning time)} \quad o = 1$$

$$\sum_p x_{p,o,e} \leq 1 \qquad (4)$$

$$\sum_o x_{p,o,e} \leq 1 \qquad (5)$$

$$\sum_p x_{p,o,e} \leq \sum_p x_{p,o-1,e} \qquad (6)$$

$$x_{p,o,e} \leq nx_{p,o,e} \qquad (7)$$

$$M \cdot x_{p,o,e} \geq nx_{p,o,e} \qquad (8)$$

$$x_{p,o,'e'} = 0 \text{ if product } p \text{ cannot be performed at equipment unit } e \qquad (9)$$

In these equations, TPfw_e is the production time available for every equipment unit e in this first stage and is a function of the number of orders produced within the stage, hence, of the operating time required plus the required cleaning times (eq 1). This time cannot be greater than stage-horizon H1 (eq 2). Equation 3 determines the required cleaning time after sequence o at equipment unit e ($\mathrm{CT}_{o,e}$) from the required cleaning time between two products, p and p' ($\mathrm{CL}_{p,p'}$). The binary variable $x_{p,o,e}$ represents the assignment of product p to sequence o within the week at equipment unit e. Thus, eq 4 imposes that at position o of an equipment unit e just one product p can be produced, eq 5 assigns only one sequence to a product p at equipment e, and eq 6 forces that several batches of the same product that need to be produced at one equipment unit e be produced consecutively. An integer variable ($nx_{p,o,e}$) represents the number of batches of product p (corresponding to one or several orders i) produced at sequence o within the week at equipment unit e. Thus, eqs 7 and 8 relate $nx_{p,o,e}$ to $x_{p,o,e}$; that is, when $nx_{p,o,e}$ is not zero, $x_{p,o,e}$ is forced to take the value of one, while when $nx_{p,o,e}$ is zero, $x_{p,o,e}$ is also zero. M is a large enough number, higher than the maximum number of batches of a product that might be performed in a week. Finally, eq 9 constrains the use of equipment units to some products in function of their specifications.

Second Stage: Production Planning. The planning horizon H2 is divided into n periods of length H3. Here, orders are just assigned to periods and to equipment units, and no exact sequence is calculated within every period, so no setup (cleaning times) can be exactly calculated, but estimated. For this reason, the production horizon in every period to be considered should be less than H3, just to permit setup times and unexpected orders to be accommodated. The corresponding equations are

$$\mathrm{TP}_{k,e} = \sum_i TOP_i \cdot nw_{i,k,e} \quad k > 1 \qquad (10)$$

$$TP_{k,e} \leq (\mathrm{H3} - \theta_k) \quad k > 1 \qquad (11)$$

$$w_{i,k,e} \leq nw_{p,k,e} \quad k > 1 \qquad (12)$$

$$M \cdot w_{i,k,e} \geq nw_{p,k,e} \quad k > 1 \qquad (13)$$

$$w_{p,k,'e'} = 0 \text{ if product } p \text{ cannot be performed at equipment unit } e,\ k > 1 \qquad (14)$$

$$nw_{p,k=0,e} = \sum_o nx_{p,o,e} \qquad (15)$$

$$w_{p,k=0,e} = \sum_o x_{p,o,e} \qquad (16)$$

In eq 10, the production time for every equipment unit e in each period k ($\mathrm{TP}_{k,e}$) is calculated. For $k = 1$, product assignment has been already solved by the first stage of the algorithm. In eq 11, the production time ($\mathrm{TP}_{k,e}$) is constrained to be smaller than a time horizon H3 minus a certain idle time, θ_k, introduced to account for the required setup times not contemplated in this part of the model. The number of batches $nw_{p,k,e}$ is linked to a binary variable assigning products p to periods k and equipment units e in eqs 12 and 13. Equation 14 constrains the use of equipment units to some products in function of their specifications. Finally, equations 15 and 16 link the first stage production scheduling decisions with the second stage production planning stage variables.

Demand Satisfaction. To determine if an order in period H1 will be fulfilled, a binary variable (satisfaction$_i$) is introduced. Equation 17 sets the variable for those orders that will be fulfilled:

$$\text{satisfaction}_i = 1 \mid i \in (\overline{I \cap I_{\text{sudden}}}) \qquad (17)$$

where I is the set of orders and I_{sudden} the subset of sudden orders of the set I.

Stock of Products. The amount of final products stored at every period depends on the amount stored in the precedent period, the amount produced, and the amount sold in that period:

$$P\_\text{stock}_{p,k} = P\_\text{stock}_{p,k-1} + \sum_e B_e \cdot nw_{p,k,e} - \sum_{\substack{i|k=D_i+\delta_i \\ i|\text{prod}_i=p}} qp_i \cdot \text{satisfaction}_i + \text{ext}N_{p,k} \qquad (18)$$

$$P\_\text{stock}_{p,k} \geq 0$$

$P\_\text{stock}_{p,k}$ is the amount of product p being stored at period k. Here, D_i is the due-date week for order i, δ_i represents the delay in order delivery, and prod$_i$ is the product to be produced at order i. The term ext$N_{p,k}$ is the amount of product p purchased from other suppliers or another plant and received at period k.

Stock of Raw Materials. The amount of raw material stored at every period depends on the amount stored in the precedent period, the amount consumed, and the amount bought in that period:

$$R\_\text{stock}_{r,k} = R\_\text{stock}_{r,k-1} - \sum_e \sum_{p|R_p=r} qr_p \cdot nw_{p,k,e} + qb_r \cdot rb_{r,k-1} \qquad (19)$$

$$R\_\text{stock}_{r,k} \geq 0 \qquad (20)$$

Equations 19 and 20 define the amount of raw material r being stored at period k ($R\_\text{stock}_{r,k}$), which is equal to the amount stored at period $k - 1$ minus the amount consumed during period k plus the amount of material received during period $k - 1$, and always positive. Here, qr_i is the amount of raw material R_p consumed for producing a batch of product i, qb_r is the amount of raw material r in a purchased lot, and $rb_{r,k}$ is an integer variable representing the number of lots of raw material r to be received at period k. Thus, the model determines when raw materials should be ordered.

The objective function of the scheduling and planning model is to maximize overall revenues, ignoring the possible negative and positive effects on cash. Therefore, this performance is calculated as the sum of cash incomes from sales of product (saleP_i) minus the liabilities incurred at all periods. Liabilities at a specific period k are incurred by the purchase of raw materials (PriceRaw$_r$), the cost of running batches (cost_batch_hour$_{p,k}$), and, the cost of buying part of the needed final product from another supplier or another plant (ext$N_{p,k}$). This cost is assumed to be $(1 + \alpha_p)$ higher than the regular one.

$$\text{objective\_function} = \sum_i \text{satisfaction}_i \cdot qp_i \cdot \text{sale}P_i - \sum_r \sum_k qb_r \cdot rb_{r,k} \cdot \text{CostRaw}_r - \sum_e \sum_p \sum_k \text{cost\_batch\_hour}_{p,e} \cdot nw_{p,k,e} \cdot \text{TOP}_p - \sum_p \sum_{i|pr(i)=p} (1 + \alpha_p) \cdot \text{sale}P_i \cdot \text{ext}N_{p,k} \qquad (21)$$

3. Cash Management

Most of the variables that are determined in connection with the cash balance are time-dependent. They are inter-related over successive time periods and also within each time interval; e.g., delays in payments can substitute part of financing requirements. Similarly, sales of securities prior to maturity offer a source of cash while a change in the minimal cash balance requirement may affect both financing and investment decisions. Many of these decisions are made weekly and daily. Therefore, a cash management model should provide decision-making information on a high frequency basis. The data necessary for managing cash of a business firm includes short sales, collections on accounts receivable, purchases, sources of short-term financing, yields on short-term marketable securities, and others. This information is only partially known and, consequently, requires the use of forecasts, which introduce an element of uncertainty to the cash management problem. At the same time, it has to cover the entire cash-planning period and incorporate all the relevant inter-period relationships.

In our approach, the short-term management of cash will be analyzed looking forward on a yearly basis, which creates a validation link with the long-term capital budget.

A number of budgeting models appear in the literature of the late 1960s, when linear programming computation methods also emerged. While Baumol's model is an example of a deterministic inventory budgeting model, Miller and Orr's model considered a way to handle uncertainty.[15,16] They assumed that the timing of cash-inflows depends on payments of customers, considering a large portion of the inflows just predictable while others consist of controlled inputs, e.g., selling marketable securities from the initial portfolio prior to maturity. This model uses a maximum cash (A) and a minimum cash (B) (Figure 2), and when cash goes higher than A, marketable securities are bought whereas when a lower bound (B) is reached, sales of marketable securities or even short-term borrows are used to restore the minimum cash. These bounds (A and B) are estimated as a function of the cost of marketable securities transactions and cash flows variability from historical enterprise budgeting results.

Ideally, cash management should provide a steady level, without upper and lower bounds, remaining at the level of best minimum cash with positive peaks of cash (Figure 3). These peaks are due, for instance, to the short span between cash inflows and outflows provoked by the transactions as buys or sales of marketable

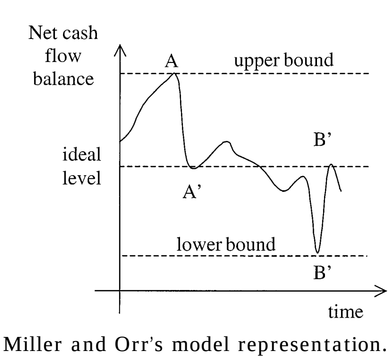

Figure 2. Miller and Orr's model representation.

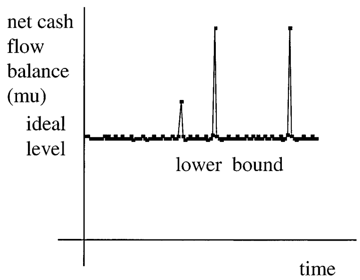

Figure 3. Ideal cash flow mode.

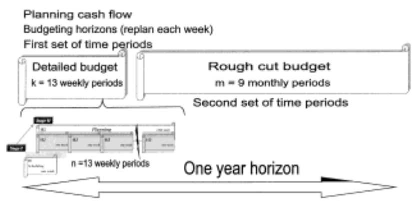

Figure 4. Budgeting horizons and its link with operative planning model.

securities, sales of final products, the payment of liabilities, and so on. If such delays do not occur, then the profile is flat. Minimum cash is required to handle uncertain events, like delays in customer payments to ensure enterprise liquidity, and also because banks require compensating balances during financing operations.

Orgler used an unequal period linear programming model to capture the day-to-day aspect of the cash management problem. In this model, the objective is to minimize the cash budget expenses over the planning horizon subject to the constraints involving decision variables: payments, short-term financing, cash balance, and securities transactions subject to institutional constraints, like minimum net cash flow.[17] His model can be extended to other financial operations and connected to the production line or the supply chain through the dates and sizes of purchases of raw materials to suppliers and the sales of final products to the customers. As a result of the use of the model, payments to providers, short-term loans, and the buying/selling of securities are scheduled.

In this work, instead of minimizing budget net cost, it is proposed to maximize the overall cash earnings that can be withdrawn from the company budget in a year basis as dividend to shareholders. To accommodate this, such objective constraints representing balances of cash, debt, securities, and so on, are used. The model is presented next.

Budgeting Model. In order to integrate a one-year horizon budgeting model with the scheduling–planning model presented, two sets of time periods are considered. In the first set of time periods, the budget is performed with precision (detailed budgeting), using the specific information given by the scheduling and planning model, while in the second set the model has less detail (rough-cut budgeting). The first set time period corresponds to the scheduling and planning period, while the second set expands beyond the end of the planning horizon up to one year budgeting (see Figure 4).

Budgeting decisions can be taken every period. Production supply during the period will take into account the inventory of raw material and products. An initial portfolio of marketable securities and term loans will also be considered. A minimum net cash flow is considered beneath which a short-term loan must be used if any other solution is not available.

Detailed Budgeting. The cash balance for these periods is the following:

$$\text{exogenous\_cash}_k - \text{liability}_k + \text{loan\_net}_k + \text{MS\_net}_k + \text{Wcash}_{k-1} = \text{Wcash}_k \quad (22)$$

Equation 22 describes the cash for each period k (Wcash_k). Here, Wcash_k is a function of the exogenous cash from the sale of products, assets, pledging, or any other inflow of cash (exogenous_cash_k), production liabilities (liability_k), the amount borrowed or repaid to the credit line (loan_net_k), and the sales and purchases of securities transactions (MS_net_k).

$$\text{Wcash}_k \geq \text{min\_cash} \quad (23)$$

Equation 23 limits the cash in each period (Wcash_k) to be larger than a minimum value (min_cash).

$$\text{debt}_k \leq \text{max\_debt} \quad (24)$$

$$\text{debt}_k = \text{debt}_{k-1} + \text{loan\_net}_k + F\cdot\text{debt}_{k-1}$$

$$\text{loan\_net}_k = \text{borrow}_k - \text{out\_debt}_k$$

Equations 24 make a balance on borrowings considering the updated debt (debt_k) from the previous k period and the loan_net_i balance between borrows and repayments. A short-term financing source is represented by an open line of credit constrained by max_debt. Under an agreement with the bank, loans can be obtained at the beginning of any period and are due after one year at a monthly interest rate (F) depending on the bank agreement. The bank requires a compensating balance, normally of not less 20% of the amount borrowed. Therefore, the minimum cash (min_cash) has to be higher than the compensating balance imposed by the bank.

$$\text{MS\_net}_k = -\sum_{k'=k+1}^{13} (\text{MSinv}_{k',k} - \text{MSsale}_{k',k}) + \sum_{k'=1}^{k-1} (d_{k,k'}\text{MSinv}_{k,k'} - e_{k,k'}\text{MSsale}_{k,k'}) \quad (25)$$

Equation 25 makes a balance for marketable securities. The portfolio of marketable securities held by the firm at the beginning of the first period includes several sets of securities with known face values in monetary units (mu) with a maturity period k' and incurred at period k. $\text{MSinv}_{k,k'}$ is the cash invested at period k maturing at period k'. $\text{MSsale}_{k,k'}$ is the security sold at period k maturing at period k'. All marketable securities can be sold prior to maturity at a discount or loss for the firm. Revenues and costs associated with the transactions in marketable securities are given by technical coefficients $d_{k,k'}$ and $e_{k,k'}$ where $d_{k,k'} > 1$ and $e_{k,k'} > 1$.

A certain proportion of the accounts receivable may be pledged at the beginning of a period. Pledging is the transfer of a receivable from the previous creditor (assignor) to a new creditor (assignee). Therefore, when a firm pledges its future receivables, it receives in the same period only a part, normally 80%, of their face value. Thus, it can be assumed that a certain proportion of the receivables outstanding at the beginning of a period is received during that period through pledge. This represents a very expensive way of getting cash that will only be used when no more credit can be obtained from the bank.

The exogenous_cash$_k$ values depend on the receivables maturing at period k and on the receivables being pledged. Exogenous cash flows incurred in every period k are as follows:

$$\text{exogenous\_cash}_k = \sum_{i|D_i+\xi_p=k} (1 - \sum_k \phi_{i,k})\text{satisfaction}_i \cdot qp_i \cdot \text{sale}P_i + \psi \cdot \sum_{i|D_i>k} \phi_{i,k} \cdot \text{satisfaction}_i \cdot qp_i \cdot \text{sale}P_i \quad \forall k \quad (26)$$

$$\sum_k \phi_{i,k} \le 1 \quad \forall i \quad (27)$$

where ξ_p represents the time span agreed with the customers in which they are paying to the firm the products purchased (receivables), Ψ represents the face value of receivables to be pledged, normally 0.8, and $\phi_{i,k}$ is a binary variable that defines if receivable i is being pledged at period k. Equation 27 constrains each receivable to be pledged at most once.

Liabilities at a specific period k are a function of the price of raw materials ($rb_{r,k}$), the cost of running a batch (as a function of $nw_{p,k,e}$), and the cost of having to purchase part of the final product from another supplier or another plant (ext$N_{p,k}$). This cost is assumed to be (1 + α_p) higher than the cost of a regular one.

$$\text{R\_liability}_k = \sum_r qb_r \cdot rb_{r,k} \cdot \text{PriceRaw}_r + \sum_e \sum_p \text{cost\_batch\_hour}_{p,e} \cdot nw_{p,k,e} \cdot \text{TOP}_p + \sum_p \sum_{i|pr(i)=p} (1 + \alpha_p) \cdot \text{sale}P_i \cdot \text{ext}N_{p,k} + \text{others}_k \quad (28a)$$

In eq 28a, all payments of materials are assumed to be fulfilled within the same week of receiving raw materials. However, a more general situation is that all bills can be paid either in the same period with a discount of 2% or at a face value (ϵ) after ξ periods since the raw materials delivery. In this last situation, the following equation is used:

$$\text{R\_liability}_k = \sum_r Y_r \cdot qb_r \cdot rb_{r,k} \cdot \text{PriceRaw}_r + \sum_r (1 + \epsilon) \cdot Yd_r \cdot qb_r \cdot rb_{r,k-\xi} \cdot \text{PriceRaw}_r + \sum_e \sum_p \text{cost\_batch\_hour}_{p,e} \cdot nw_{p,k,e} \cdot \text{TOP}_p + \sum_p \sum_{i|pr(i)=p} (1 + \alpha_p) \cdot \text{sale}P_i \cdot \text{ext}N_{p,k} + \text{others}_k \quad (28b)$$

$$Y_r + Yd_r = 1$$

where Y_r and Yd_r are binary variables that determine if an order of received raw material r is to be paid with prompt payment or after ξ periods time. It remains to be decided upon what part of the bills to pay in which period.

Rough Cut Budgeting. The longer-term budgeting model is similar to the detailed short-term one, only differing in the way the inflows (exogenous_cash$_m$) and outflows of cash (liability$_m$) are calculated at each period m. For the detailed one, these are calculated as a function of the scheduling and planning model results, if a sequential approach is taken, or its variables, if integration is performed. For the rough cut one, exogenous cash and liabilities are calculated as a function of forecasted sales of products and production costs (net_production_incomes$_m$). Accordingly, this longer term budgeting is calculated using eqs 29−33.

$$\text{net\_Production\_incomes}_m + \text{loan\_net}_m + \text{MS\_net}_m + \text{MCash}_{m-1} \ge \text{Mcash}_m \quad \forall m > 3 \quad (29)$$

$$\text{Mcash}_m \ge \text{Min\_Cash} \quad \forall m > 3 \quad (30)$$

$$\text{MS\_net}_m = -\sum_{m'=m+1}^{12} (\text{MSinv}_{m',m} - \text{MSsale}_{m',m}) + \sum_{m'=1}^{m-1} (d_{m,m'}\text{MSinv}_{m,m'} - e_{m,m'}\text{MSsale}_{m,m'}) \quad \forall m > 3 \quad (31)$$

$$\text{debt}_m \le \text{max\_debt} \quad (32)$$

$$\text{debt}_m = \text{debt}_{m-1} + \text{loan\_net}_m + F \cdot \text{debt}_{m-1} \quad \forall m > 3$$

$$\text{loan\_net}_m = \text{borrow}_m - \text{out\_debt}_m$$

$$\text{MCash}_{m=3} = \text{WCash}_{k=13} \quad (33)$$

$$\text{debt}_{m=3} = \text{debt}_{k=13}$$

Equation 29 represents the balance of cash. It differs from eq 22 in that production net incomes are due to expected (forecasted) orders. Cash is also constrained as in the detailed model (eq 30). In the same way, the portfolio of marketable securities held by the firm at the beginning of the first period includes several sets of securities with known face values in monetary units (mu) and maturity month-periods m' incurred at month-period m. MSinv$_{m',m'}$ is the cash invested at period m maturing at period m'. MSsale$_{m',m}$ is the security sold at period m maturing at period m' All marketable securities can be sold prior to maturity at a discount or loss for the firm. Revenues and costs associated with the transactions in marketable securities are given by technical coefficients $d_{m,m'}$ and $e_{m,m'}$ where $d_{m,m'} > 1$ and $e_{m,m'} > 1$. Also, a financing source is represented by a constrained open line of credit (loan_net$_m$). Under an agreement with the bank, loans can be obtained at the beginning of any period and are due after one year at a monthly interest rate depending on the bank agreement (i.e., ≈1%). Equations 33 connect detailed budgeting variables with the rough cut ones.

Objective Function. While the more common objectives used by the process systems engineering community are minimum makespan, due date fulfillment, maximum profit, net present value (NPV), rate of return (RR), and payout time, the finance community has been for years making financial business decisions taking into account other indicators: market to book value, liquidity ratios, leverage, capital structure ratios, return on equity, sales margin, turnover ratios, stock security ratios, etc.

However, the direct enhancement of shareholder value seems to be today's priority since the relationship between investments and the cash flow generates the

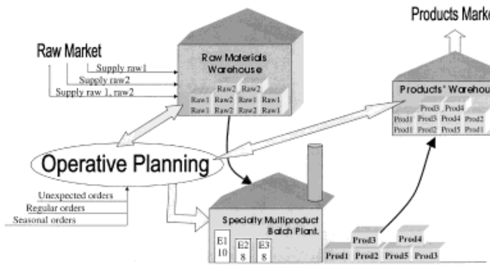

Figure 5. Case study scheme.

major influence on shareholder value. Thus, the cash position and the overall spread of cash earnings through time are optimal when the objective function used is cash flow of dividends, that is, the amount of cash that can be withdrawn from the company at a given instant of time. This is the approach taken in this work. Therefore, for $m = l1/ln$, cash is withdrawn from the system in form of enterprise earnings, that might by employed as shareholder dividends or reinvested.

$$\text{others}_{m=3,6,9,12} = -\text{div}_l \quad l = 1,2,3,4$$

$$\text{objective\_function} = \max \sum_l \alpha_l \cdot \text{div}_l \qquad (34)$$

4. Two-Step Sequential Scheduling−Planning and Budgeting Approach

The case study, used to show the proposed framework, consists of a batch specialty chemical plant. Figure 5 gives a graphical description of the case study.

The plant product portfolio is assumed to be around five different products using two different raw substances. Production times are assumed to range from 13 to 22 h. Product switch-over basically depends on the nature of both substances involved in the precedent and following batch. Cleaning time ranges from 0 up to 6 h till not permitted sequences. The different recipes of products, cleaning times as a function of product sequence, cost of raw materials, sale price of final products, the set of customer demands (amount to be delivered at a specific due dates and type of order), and initial stock of raw materials and final products are shown in the Appendix. In general, orders are never manufactured at less than one-week lead-time from receipt of an order, and due-dates have a weekly frequency.

A scheduling and planning horizon of 3 months is considered (i.e., H2 = 13 weeks or about 3 months). The first scheduling period of the model considers a one-week horizon; meanwhile, the second set is divided into 13 periods of one week.

In the two-step sequential scheduling−planning and budgeting approach, first the scheduling−planning model is solved. This corresponds to solving eqs 1−20 considering the objective function of eq 21 for maximization. The model proposed has been implemented and solved using GAMS/CPLEX. The scheduling−planning model consists of 977 single equations, 732 continuous variables, and 463 discrete variables. The model is solved in 0.8 CPU seconds at a 1.6 GHz machine.

Once the scheduling-planning model is solved, the budgeting model consisting of eqs 22−33 maximizing the objective of eq 34 is solved. Here, the variable satisfaction_i of eq 26 and $rb_{r,k}$, $nw_{p,k,e}$, and $\text{ext}N_{p,k}$ of eq 28 are considered as parameters, these parameters

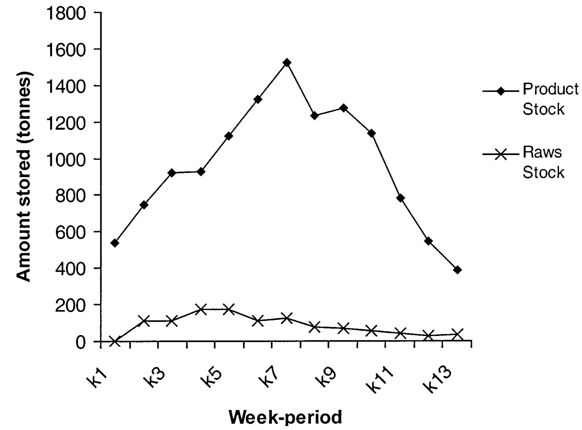

Figure 6. Case study planning results.

Table 1. Number of Batches of Each Product (*p*1−*p*5) to Be Produced at Every Week-Period (*k*1−*k*13)

product	*k*1	*k*2	*k*3	*k*4	*k*5	*k*6	*k*7	*k*8	*k*9	*k*10	*k*11	*k*12	*k*13
*p*1	6	0	2	4	2	2	6	6	2	0	0	0	0
*p*2	5	5	5	5	5	5	5	5	5	5	5	5	5
*p*3	0	11	2	2	2	2	2	2	8	8	11	11	0
*p*4	7	7	0	6	10	10	10	10	10	10	10	10	10
*p*5	0	0	11	5	4	4	0	0	0	2	0	0	7

being the output solution of the scheduling−planning model. This situation corresponds to a typical nowadays-optimized industrial routine where first operations are decided to then try to fit the finances. It is assumed that the firm has no marketable securities investments at the beginning of the period. The initial cash is equal to the minimum cash (60 000 mu). Under an agreement with a bank, the firm has an open line of credit at a 10% annual interest with a maximum debt allowed of 300 000 mu. The set of marketable securities that the firm has agreed to purchase when cash exceeds has a 5% annual interest. Receivables may be pledged at 85% of face value if they mature in less than 4 week-periods and at 80% if they mature later. Within the 12-month horizon, it is assumed that cash is withdrawn at 4, 8, and 12 periods (months). The implementation in GAMS of this budgeting model consists of 164 single equations, 590 continuous variables, and 234 discrete variables. The model is solved in 0.3 CPU seconds at a 1.6 GHz machine. The objective function, that is, the year-earnings of the sequential approach, is of 242 912 mu.

Table 1 shows the optimal number of batches of each product to be produced at every week-period. Figure 6 shows stock of raw materials and the final products profile during the three-month planning period. The cash flows given by the scheduling and planning model are summarized in Table 2. These cash flows are then used for solving the budgeting model. Optimal budget results are shown in Figure 7. Here, overall marketable securities, cash borrowed during the first 3 months, and receivables being pledged (accumulated amount of cash having been pledged) are shown.

5. Integrated Scheduling−Planning and Budgeting Approach

To achieve the integration, the production liabilities and exogenous cash at every week-period are calculated as a function of production planning variables. The scheduling−planning variables are integrated into the budgeting model. This means solving eqs 1−20 and 22−

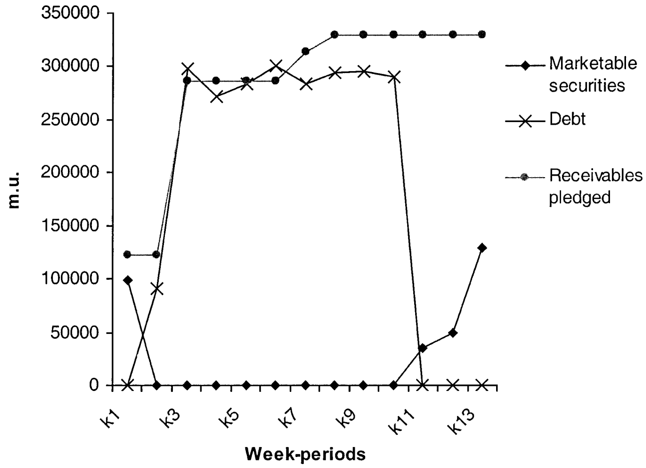

Figure 7. Case study sequential approach budget results: debt incurred, marketable securities, and amount accumulated of pledged receivables at every week period.

Table 2. Raw Materials Liabilities and Product Sales Incomes Cash Flows Given by the Scheduling and Planning Model

week period	liabilites (mu)	incomes for sales (mu)
*k*1	23 698	0
*k*2	18 994	0
*k*3	370 166	0
*k*4	15 624	86 500
*k*5	10 646	0
*k*6	15 746	0
*k*7	10 570	0
*k*8	15 670	107 420
*k*9	16 108	57 840
*k*10	16 146	50 600
*k*11	16 327	376 480
*k*12	16 327	64 240
*k*13	10 370	272 700

Table 3. Number of Batches of Each Product (*p*1−*p*5) To Be Produced at Every Week-Period (*k*1−*k*13)[a]

product	*k*1	*k*2	*k*3	*k*4	*k*5	*k*6	*k*7	*k*8	*k*9	*k*10	*k*11	*k*12	*k*13
*p*1	5	1	0	0	5	5	5	5	4	0	0	0	0
*p*2	5	5	5	5	5	5	5	5	5	5	5	5	5
*p*3	0	9	11	11	3	2	2	0	0	8	9	3	0
*p*4	7	10	10	10	8	10	10	10	4	7	10	6	8
*p*5	0	0	0	0	1	1	1	2	7	4	1	8	8

[a] Integrated approach.

33 maximizing the objective of eq 34. The model implemented in GAMS/CPLEX has 1017 single equations, 1254 continuous variables, and 684 discrete variables.

Table 3 shows the optimal number of batches of each product to be produced at every week-period. The corresponding budgeting results are shown in Figure 8. The cash withdrawn in a year, year-earnings, is 328 882 mu, incrementing earnings at almost 35.4% from the sequential results.

Comparing Table 1 versus Table 3, it can be observed that the scheduling and planning results vary substantially when considering the integrated model. Figure 7 versus Figure 8 shows that the integrated solution incurs less debt and avoids having to pledge receivables (financial transaction of high cost for the firm). The sequential approach is pledging around 400 000 mu, and this means a cost of around 72 000 mu for the firm.

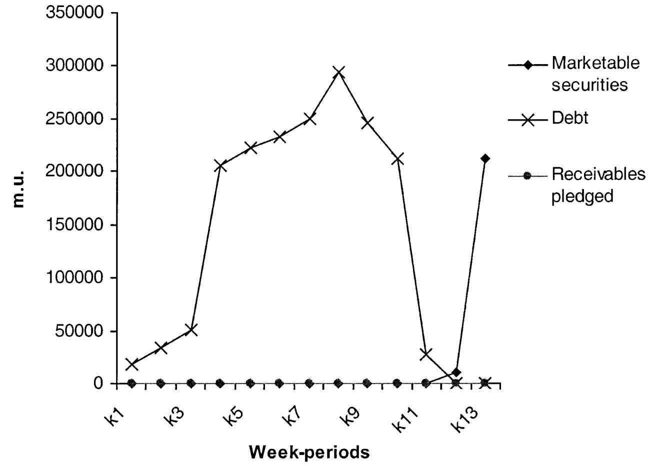

Figure 8. Case study integrated approach budget results: debt incurred, marketable securities, and amount accumulated of pledged receivables at every week period.

6. Conclusions

This paper has addressed the importance of integrating scheduling−planning and budgeting models. This work presents a more desired measure of the effectiveness of a schedule, based on an economic one as an alternative to the commonly used makespan or sum of tardiness objectives. When due-date policy is set as the unique objective, many potential capacity improvements are shutdown. Regardless of approximations and misconceptions, the impact of introducing scheduling systems in plant operation is clear. They generate, in the first place, capacity improvements, as well as better forecasts of stock levels, personnel reductions, and many other benefits that make system payback often within the first year of application.[18] However, the scope of this work permits us to remove from common practice the economic blindness when just due-date policy application is used. This policy occasionally results in production paths involving important capacity losses and dangerous operating expenses with negative impacts in short-term cash flow planning.[19,20] In the framework presented in this work, the negative impacts of due-date fulfilment are proactively explicit and directly shown in economic figures, therefore transparent to all managers. With joint financial and operation schedules/plans, the impact of improvement goes beyond those achieved by operative schedules, specifically adding the benefits of an optimized financial capacity to the benefits of an optimized use of production capacity, the latter already undertaken in routine practice by today's scheduling and planning tools.

By means of a comparison using a case study, it has been shown that significant improvements are possible as compared to the use of scheduling models followed by budgeting models. The case study presented in this work is a very specific situation where two types of raw materials with very different prices (3000 mu vs 85 mu) are purchased. Figure 9 shows that the sequential approach is buying expensive products at early periods. However, the integrated approach leaves this expensive purchase for later periods, when the firm starts receiving some income of cash from sales of products that are used for the expensive product purchase. This, plus the fact of having a limited line of credit for the firm and the only alternative of having to pledge receivables, is why for this case study the integrated approach is given such extra revenues.

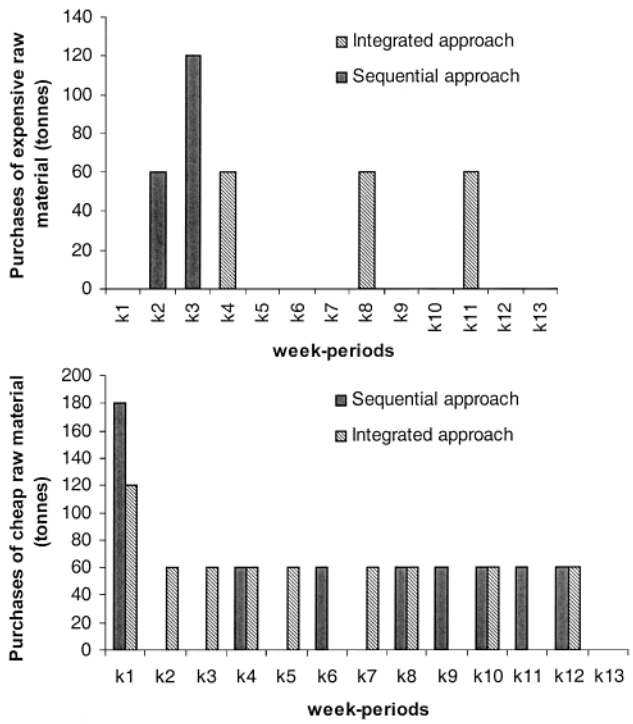

Figure 9. Purchases of raw materials.

Besides the decrease of costs or increment of revenues and the benefits of cash flow synchronization by load rearrangement to flatten peaks balancing firm's financial liquidity, there is an internal benefit in companies that rarely is possible to be measured with something else than intuitive reasoning. It is the opportunity cost ignored by not optimizing the quality of management decisions, and very especially in the resource assignment to functional areas that create value. Undoubtedly, it would be extremely useful to be able to manage simultaneously and globally with transparent and forward looking information their operations, knowing previously what contributions to shareholders' value those areas receiving the assigned limited resources would make.

Because of space, the next work will argue more about these scopes making full use of the advantages that lineal programming offers by marginal costs and shadow prices, also considering parametric optimization approaches and uncertainty.

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Nomenclature

TOP_p = processing time required for producing product p
TPfw_e = production time available for every equipment unit e in the first stage
$\mathrm{CT}_{o,e}$ = required cleaning time after sequence o at equipment unit e
$\mathrm{CL}_{p,p'}$ = required cleaning time between two products, p and p'
$x_{p,o,e}$ = binary variable that defines the assignment of product p to sequence o within the first scheduling week at equipment unit e.
$nx_{p,o,e}$ = integer variable that defines the number of batches of product p produced at sequence o within the first scheduling week at equipment unit e.
H2 = planning horizon
H3 = planning horizon H2 divided into n periods
$\mathrm{TP}_{k,e}$ = production time for every equipment unit e in each period k
θ_k = idle time introduced at every week period to account for the required setup times not contemplated in the planning part
$w_{p,o,e}$ = binary variable assigning products p to periods k and equipment units e within the planning part
$nw_{p,k,e}$ = integer variable assigning the number of batches of product p to periods k and equipment units e within the planning part
$\mathrm{satisfaction}_i$ = binary variable determining if an order i will be fulfilled (accepted)
$P\_\mathrm{stock}_{p,k}$ = amount of product p being stored at period k
D_i = due-date week for order i
δ_i = delay in order i delivery
prod_i = product to be produced at order i
B_e = batch size of equipment unit e
qp_i = amount (tonnes) to be delivered at order i
$\mathrm{ext}N_{p,k}$ = amount of product p purchased from other suppliers or another plant and received at period k
$R\_\mathrm{stock}_{r,k}$ = amount of raw material r being stored at period k
qr_i = amount of raw material R_i consumed for producing a batch of product i
R_p = raw material r for producing product p
qb_r = amount of raw material r in a purchased lot
$rb_{r,k}$ = integer variable representing the number of lots of raw material r to be received at period k
$\mathrm{sale}P_i$ = unitary sale prize of order i
$\mathrm{PriceRaw}_r$ = purchasing cost of a lot of raw material r
$\mathrm{cost\_batch\_hour}_{p,e}$ = cost of running product p at equipment unit e
$(1 + \alpha_p)$ = cost of buying part of the needed final product from another supplier or another plant
WCash_k = cash at period k
$\mathrm{exogenous\_cash}_k$ = exogenous cash from the sale of products, assets, pledging, or any other inflow of cash at period k
$\mathrm{liability}_k$ = production liabilities at period k
$\mathrm{loan\_net}_k$ = amount borrowed or repaid to the credit line at period k
$\mathrm{MS\_net}_k$ = sales and purchases of securities transactions at period k
debt_k = actual debt being incurred by the firm at period k
max_debt = maximum debt the firm can have in agreement with a bank
F = interest rate at which loans are obtained at the beginning of any period and are due after one year
min_cash = minimum cash the firm can have
$\mathrm{MSinv}_{k,k'}$ = is the cash invested at period k maturing at period k'
$\mathrm{MSsale}_{k,k'}$ = Is the security sold at period k maturing at period k'.
$d_{k,k'}$ and $e_{k,k'}$ = coefficients defining the yield of marketable securities
ξ_p = time span agreed with the customers in which they are paying to the firm the products purchased (receivables)
Ψ = face value of receivables being pledged
$\phi_{i,k}$ = binary variable that defines if receivable i is being pledged at period k
WCash_m = cash at period m
$\mathrm{net\_production\_\ incomes}_m$ = cash net flow at period m

$loan\_net_k$ = amount borrowed or repaid to the credit line at period *m*

MS_net_k = sales and purchases of securities transactions at period *m*

$debt_m$ = actual debt being incurred by the firm at period *m*

Appendix

In this appendix, a specific description of the case study presented in the paper is given, see Tables 4−7.

Table 4. Recipe of Products

product	processing time (h)	equipment units	type of raw required	amount of raw (tonnes)	initial stock (tonnes)
*p*1	19	1	r1	2	100
*p*2	22	3	r2	2	150
*p*3	13	1	r2	4	10
*p*4	16	2	r2	2	25
*p*5	14	1,2	r1	4	150

Table 5. Orders Received for the Three-Month Planning Period

order	amount to deliver (tonnes)	type of product	due date (week-period)	type of order	sale prize (mu/ton)
*i*1	60	1	9	regular	702
*i*2	60	4	4	regular	101
*i*3	110	5	13	seasonal	1230
*i*4	20	2	4	unexpected	150
*i*5	110	1	4	seasonal	704
*i*6	100	2	8	regular	131
*i*7	160	3	8	seasonal	140
*i*8	230	1	8	seasonal	704
*i*9	120	2	9	seasonal	131
*i*10	200	3	10	regular	145
*i*11	160	4	10	seasonal	135
*i*12	320	4	11	seasonal	104
*i*13	260	5	11	regular	1320
*i*14	260	3	12	regular	134
*i*15	210	4	12	seasonal	140
*i*16	150	4	13	seasonal	130
*i*17	90	5	13	seasonal	1310

Table 6. Raw Materials Supplied for Production

raw material	raw cost (u/ton)	lot size (tonnes)	initial stock (tonnes)
*r*1	3000	60	13
*r*2	85	60	25

Table 7. Plant Facilities Description

equipment unit	batch size (tonnes)
*e*1	10
*e*2	8
*e*3	8

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