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Production-storage and transport integrated planning for a multi-site mining industry

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Abstract. Assuming that local planning usually leads to sub-optimal solutions, this work aims to solve an integrated production, storage and distribution problem as part of a global supply chain system. The problem we address combines a lot sizing and distribution problem in a multi-level, multi-product, multi-period production network. To solve it, we propose a MILP (Mix Integer Linear Program) taking into consideration the local constraints of the different subsystems, but also the global ones that express the interactions between subsystems. This model proposes simultaneously a production, storage and transport plan that satisfies a known demand while minimizing total production, storage and distribution costs. Finally, the solutions found within this approach have the advantage of considering the system's overall decisional cohesion as well as the constraints propagation in the various links of the chain. The originality of the work comes from the fact that we have addressed a multi-level lot-sizing problem, combined with a single rail transport problem. This integrated problem, to the best of our knowledge, has not been previously addressed. The model is tested and validated on a real mining industry, it proposes an integrated solution for simultaneous production, storage and distribution planning.

Keywords: Integrated lot sizing · Transportation · Linear optimisation · Mining industry.

1 Introduction

This work takes place at OCP group, one of the world's leading companies in the phosphate market. OCP has a complex supply chain structure that starts with the mining phosphate deposits and reaches customers all over the world. The present study concerns Youssoufia site, located in the central axis, one of the three independent parallel axes of OCP's supply chain. This site produces three products (P1, P2, P3) delivered for two types of customers: local customers who refer to chemical transformation sites where acids and fertilizers are produced, and international ones from around the world. Youssoufia site is composed of three plants (laundry, calcining, and drying plant) that are interconnected by conveyors and separated by stocks upstream and downstream of each transformation process. This research focuses on supply chain planning problems as a

whole. It considers an integrated planning approach where production, inventory, and transportation decisions are integrated. It adopts a global approach aiming to achieve an integrated flow planning that considers all the supply chain components including their respective constraints and specifications. The aim is to propose a single optimisation model taking into consideration (i) the characteristics of each subsystem composing the global production system, but also (ii) the different interactions that interconnect these subsystems in order to guarantee their synergy in the global logistics system. Classical models address supply chain planning problems sequentially or independently. The most classical approach starts with production and storage planning decisions, and establishes later transport decisions in an independent way. Though, it is now demonstrated that production and distribution decisions are mutually related problems and need to be dealt with simultaneously in an integrated manner [9]. According to [3], integrating these decisions lead definitely to a considerable increase in efficiency and effectiveness.

In addition, this paper addresses a real industrial problem posed by OCP. The studied system is a complex mining industrial system consisting of a multi-level, multi-product supply chain. This supply chain is composed by a multi-site production system, several storage sites and a train transport system within a single railway. This railway is used sequentially for passengers transport and for finite products transport, which imposes fixed time windows for finite products transport. This said, this paper addresses a capacitated lot sizing problem, combined with a hybrid transport problem using conveyors (for inter-site transport) and a single rail with time windows (for finished product delivery). All the production, storage and transport resources are limited by finite capacities. The remainder of this paper is organized as follows: section 2 presents a literature review of the main themes addressed by this work. The proposed MILP to answer the problem is detailed in section 3 before illustrating it with a practical case study in section 4. Finally, some conclusions are addressed in section 5.

2 Literature review

Many researchers have been interested in production and stock planning using the lot sizing problem which has led to a literature proposing diverse and varied models to solve this kind of problems. The main objective of these models is determining the quantities of products to be manufactured in order to meet the demand while minimizing production, set up and storage costs [8]. Other costs may be added such as stock shortage cost. One of the reasons for interest in these models is their wide scope. Indeed, these models can be applied for the uncapacitated lot sizing [5], scheduling and lot sizing (small bucket) [12], and flow control [15]. They can also be associated with other supply chain planning problems [2] such as distribution problems to form the Integrated lot sizing with direct shipment models class, or to routing problems to form the class of models called Inventory Routing Problem (IRP), or even include all supply chain planning problems (production, storage, distribution, and routing) to cre-

ate the Production Routing Problem (PRP) class. The extension of lot sizing models to multi-level supply chain structure is called multi-level lot sizing problem (MLLSP). The basic multi-level model, called the Multi-Level Capacitated Lot Sizing Problem (MLCLSP), was proposed by [6]. Its purpose is to link the end-products demand with the needs for internal components using the Gozinto matrix. This matrix is composed of the coefficients $a_{i,j}$ which represent the number of products i necessary to produce a product j , where i is the immediate predecessor of j in the product bill of material.

Based on the research that we analyzed, we could not find a paper that combines the problem of multi-level lot sizing with that of transport using a single railway track with time windows. To the best of our knowledge, little attention has been given to the problem of variable transport capacity and minimum quantity to be transported. Moreover [13] indicate that the most of industrial lot sizing literature is interested on discrete production problems, which makes production planning in the process industry a promising area for new research. All of these and other differences were synthesized in Table 1 containing the comparison between our MILP model and the reviewed ones that are dealing with a multi-level modeling.

Table 1. Comparison of the proposed MILP and reviewed models[illegible]

3 Multi-level integrated planning model

The considered production network Fig. 1 is inspired by a real case industrial problem, it is composed of several manufacturing plants producing N products intended to meet two types of demand: an independent final demand known for a finite horizon, and an intermediate one of a product being a component of another downstream product in the supply chain. Shortages are not allowed and manufactured product have general type structure. The planning horizon is discrete and is composed by T periods. One product can be manufactured in several plants. Each plant is limited by a maximum production capacity and has a downstream stock in which the manufactured products can be stored. Each stock is limited by a maximum stock capacity. The different plants are interconnected by conveyors characterized by $z_{u,u'}$: which refer to time required for a product to be transferred from plant u to plant u' , u' being a downstream plant of the plant u in the supply chain structure. All finished products are transported via a single railway track to two different destinations: the port from which products are exported to international customers, and the local customers (chemical manufacturing sites). Products can be stored at the train unloading stations. Each train can ship only one product at a time and requires time to travel between production sites and destination sites. There are fixed time windows (train paths) in which the transport of finished products is possible; outside these hours, the railway is reserved for passenger transport. The delivery of the finished products must therefore respect these train paths.

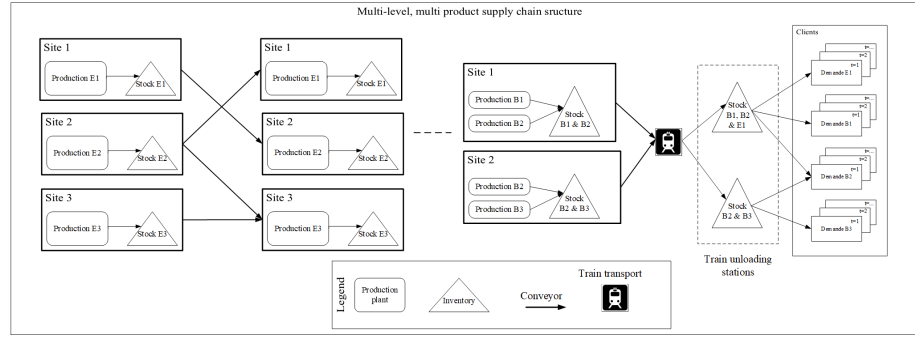


Fig. 1. Multi-level, multi product supply chain structure

In order to solve this problem, we propose a multi-level multi-product linear model where the shipment of end-products to the final stocks is provided by trains respecting the transport time windows. The objective of the model is to identify the periods in which production takes place as well as the production quantities, the amount that has to be stored and the quantity to be transported by train and the time windows to exploit. The production of each product gen-

erates a variable production cost, a set up cost and a set up time are incurred whenever a production batch starts. A holding cost is incurred per unit held in inventory per period. In addition, transport by train of a product generates a train transport cost. The considered notations of the mathematical model are detailed in Table 2. The formulation of the mathematical model is as follows:

Table 2. Parameters and variables

N	Number of products ($i = 1..N$)
T	Number of periods in the planning horizon ($t = 1..T$)
J	Number of days ($j = 1..J$) composing the planning horizon
H	Number of hours considered per days
S^p	Set of production sites
S^f	Set of final stocks
$D_{i,t}$	Final demand for product i in period t
X_u^{\max}	Maximum production capacity at the plant u
$a_{i,j,u}$	The quantity of i needed to produce a unit of j at the plant u . $a_{i,j,u} = 0$ if $j < i$ (j predecessor of i)
$db_{i,t,u}$	Hourly production rate of product i in the plant u at the period t
$I_{\max,u}$	Maximum storage capacity at the site u
Q_{\max}	Maximum train transport capacity
Q_{\min}	Minimum train transport capacity
λ_t	Binary parameter equals to 1 if train transport is possible at period t , 0 otherwise
$z_{u,u'}$	Time required for a product to be shipped from the plant u to the plant u'
ts_i	Set up time of the product i
$\beta_{i,u}$	Binary parameter equals to 1 if the product can be produced at the plant u , 0 otherwise
h_i	Unit holding cost of product i
p_i	Unit production cost of product i
s_i	Set up cost of product i
t_u	Train transport cost from the plant u
M	Large number
R	Maximum number of trains allowed per day
$X_{i,t,u}$	Quantity of product i , to be produced at plant u in period t
$I_{i,t,u}$	Inventory level of product i at the end of period t for plant u
$Q_{i,t,u}$	Quantity of product i delivered by train from site u to final stocks, at the end of period t
$\gamma_{i,t,u}$	Binary set-up variable equal to 1 if and only if $X_{i,t,u} > 0$
$\omega_{i,t,u}$	Binary transport variable equal to 1 if and only if $Q_{i,t,u} > 0$

Minimize

$$\sum_t \sum_u \sum_i (p_i \cdot X_{i,t,u} + s_i \cdot \gamma_{i,t,u} + h_i \cdot I_{i,t,u} + t_u \cdot \omega_{i,t,u}) \quad (1)$$

Subject to:

$$I_{i,t-1,u} + X_{i,t,u} - Q_{i,t,u} - \sum_j a_{i,j} \cdot X_{j,t+z_{u,u'};u'} - I_{i,t,u} = 0 \quad (\forall i, t, u \in S^p, u' \in S^f) \quad (2)$$

$$I_{i,t,u} = I_{i,t-1,u} - D_{i,t} \quad (\forall i, t < z_{u';u}, u \in S^f) \quad (3)$$

$$I_{i,t,u} = I_{i,t-1,u} + \sum_{u'} Q_{i,t-z_{i,u'};u,u'} - D_{i,t} \quad (\forall i, t \geq z_{i,u'}; u \in S^f) \quad (4)$$

$$ts_i \cdot \gamma_{i,t,u} \cdot db_{i,t,u} + X_{i,t,u} \leq X_u^{\max} \quad (\forall i, t, u) \quad (5)$$

$$\sum_i I_{i,t,u} \leq I_u^{\max} \quad (\forall t, u) \quad (6)$$

$$X_{i,t,u} < \beta_{i,u} \cdot X_u^{\max} \quad (\forall i, t, u) \quad (7)$$

$$I_{i,t,u} < \beta_{i,u} \cdot I_u^{\max} \quad (\forall i, t, u) \quad (8)$$

$$Q_{i,t,u} \leq Q^{\max} \cdot \lambda_t \quad (\forall i, t, u) \quad (9)$$

$$Q_{i,t,u} \geq Q^{\min} \cdot \omega_{i,t,u} \quad (\forall i, t, u) \quad (10)$$

$$\sum_{t \in H} \omega_{i,t+((j-1) \cdot H),u} \leq R \quad (\forall i, j \in J, u) \quad (11)$$

$$X_{i,t,u} - M \cdot \gamma_{i,t,u} \leq 0 \quad (\forall i, t, u) \quad (12)$$

$$Q_{i,t,u} - M \omega_{i,t,u} \leq 0 \quad (\forall i, t, u) \quad (13)$$

$$I_{i,t,u} \cdot X_{i,t,u} \geq 0 \quad (\forall i, t, u) \quad (14)$$

$$\gamma_{i,t,u}, \omega_{i,t,u} \in 0, 1 \quad (\forall i, t, u) \quad (15)$$

Objective function (1) minimizes total costs. Constraint (2) is stock balance equation of stocks downstream the production plants. Constraints (3) and (4) are stock balance equations of final stocks. Constraints (5) and (6) ensure the respect respectively of the maximum production and inventory capacity. Constraints (7) and (8) assign the products respectively to the plant / stocks in which they are produced / stored. Constraints (9) and (10) ensure maximum and minimum quantity limitations for transport by train. Constraint (11) limits the maximum number of trains per day. Constraints (12) and (13) bind binary variables to corresponding decision variables. Constraints (14) and (15) define the domain of the decision variables.

3.1 Case study

In what follows, we illustrate the model previously described by a numerical example. The model is solved on a one week horizon with a temporal mesh of one hour (168 periods). The daily demand has been converted to hourly demand by assuming it is evenly distributed during the day. The program has been solved in few minutes using Xpress solver. The model has calculated an integrated plan of all components of the overall production system. These plans have enabled a demand satisfaction rate of 100%. For each period, product and site, the model proposes: (i) A production plan defined by the quantity to be produced per period and per product in each site where the fact that product P2 can be manufactured in two different sites has been considered. (ii) An inventory plan for the whole stock of the productive system. (iii) A transport plan, which identifies the quantity to be transported from the production sites to the final stocks. This plans respects travel time required to transport products to final stocks which is 2 hours. The results of the products P1, P2 are respectively presented in table 3, 4. These plans have enabled a demand satisfaction rate of 100%. We have found a global solution applicable in a global supply chain context.

Table 3. Production, storage and transport plans for product P1

Period	Quantity to produce	Inventory level	Quantity to transport by train	Inventory level at final stock	Demand
1	68	1068	0	0	0
2	91	1159	0	0	0
...
20	91	2803	0	0	0
21	91	519	2376	0	0
22	91	610	0	0	0
23	91	701	0	2376	0
24	91	793	0	2376	0
25	91	884	0	2268	108
26	91	975	0	2160	108
...
...
164	0	0	0	828	83
165	0	0	0	745	83
166	0	0	0	662	83
167	0	0	0	579	83
168	0	0	0	496	83

Table 4. Production, storage and transport plans for product P2

Period	Calcining plant			Drying plant			Inventory level at final stock	Demand
	Quantity to produce	Inventory level	Quantity to transport by train	Quantity to produce	Inventory level	Quantity to transport by train		
1	91	1091	0	0	0	0	4583	417
2	258	1349	0	0	0	0	4166	417
3	258	1607	0	0	0	0	3749	417
4	258	1865	0	0	0	0	3332	417
5	258	2123	0	0	0	0	2915	417
6	258	2381	0	0	0	0	2498	417
7	258	2639	0	272	272	0	2081	417
8	258	2897	0	272	545	0	1664	417
9	258	1066	2089	272	817	0	1247	417
10	258	1324	0	272	1089	0	830	417
...
167	0	0	0	0	0	0	417	417
168	0	0	0	0	0	0	0	417

4 Conclusion

In this paper, we propose a MILP to perform simultaneous planning of production, storage and transport over a finite horizon composed of discrete periods. This planning takes place in the context of a multi-level, multi-period, multi-product supply chain structure, while taking into account all the different capacities. Also, the transport of the finished products is ensured by a single railway track, with fixed time windows. This model has been tested on a mining system in order to achieve an overall flow optimization, that takes into account the characteristics of the different subsystems, their interactions and the propagation of constraints all along this chain.

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