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Supply Chain Modelling and Production Planning: A Case Study in The Phosphate Industry

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Abstract

The present paper discusses the problem of short-term supply chain planning for production and logistics operations in the chemical industry.
Our contribution is threefold. First, we designed a model of a real-world production site, translating the constraints and realities of the field into a mathematical model that is simple enough to be tractable but sufficiently rich to support decision-making. Secondly, we formulated and solved this problem as a MILP using the CPLEX solver.
Finally, we applied this model to the OCP Safi plant, a chemical industry site of OCP Group. Using the model, we performed a sensitivity analysis on a real-life data instance, in order to detect the bottlenecks and determine the production boundaries.
The results revealed that increasing the capacity of some specific production units, but not all, is required to increase the volume that can be produced and delivered. Identifying these bottlenecks will help OCP Group make informed decisions on how to distribute the investment effort, in order to increase the performance of the whole supply chain.

Keywords
Supply chain management, Production planning, Mixed Integer Linear programming, Chemical industry, Sensitivity analysis.

1. Introduction
Efficient supply chain management (SCM) has emerged as a major challenge and a key lever for today's manufacturing companies to increase their performance and create value. SCM has become increasingly sophisticated as the supply chains today are more and more complicated, even complex, due to their globalization, their inclusion of various stakeholders, of a high number of products, and their customization to client requirements.

Successful supply chain management relies on maintaining solid procedures, receiving the correct information at the right time, making accurate forecasting as well as right trade-offs, implementing a clear strategy in a transparent manner, and digitizing the various supply chain functions. To reflect this shift, a new term "Value Network," has even been introduced, which refers to the set of connections between people, companies, or departments that benefit to value creation (Fender 2020); (Peppard and Rylander 2006); (Ferrary and Granovetter 2009). Responding to this complexity and high associated stakes, decision support tools are crucial to optimally design this value network on a strategic horizon, then plan, schedule, and execute operations on tactical and operational horizons.

In this paper, we address the planning problem of one production site of the OCP group (formerly Office Cherifien des Phosphates), an industrial company specialized in the extraction, valuation, and commercialization of phosphate in Morocco.

Over the last decade, OCP Group has been a leading exporter of phosphate and its derivatives all around the world. The group operates throughout the whole value chain, from rock mining to chemical processing of phosphoric acid and phosphate fertilizers. It plays a key role in the Moroccan economy by contributing strongly to its GDP, with a revenue of US$ 11.28 billion, and a Gross profit of US$ 6.93 billion in 2022 (OCP Group 2023).

OCP's activities are spread over five production sites: three of them are dedicated to the extraction and treatment of phosphate rock, and the other two are chemical complexes devoted to the production of phosphoric acid and fertilizers. Several grades of phosphate ore can be produced from the three mining sites, which can be transformed into seven qualities of phosphoric acid or forty-two types of fertilizers in more than seventeen plants spread over both chemical sites. Managing the group's operations is a challenging task due to its size and the necessity to constantly adapt to a volatile environment. The tactical and operational plans are the responsibility of the production sites, by taking the sales plan as an input.

In this study, we focus on the planning exercise for one of the two chemical sites, namely the site of Safi. This production site converts the phosphate rock into phosphoric acid, which is in turn transformed into phosphate fertilizer (Triple Super Phosphate TSP) and animal feeds (Monocalcium phosphate MCP and dicalcium phosphate DCP). In addition to phosphate rock, the production of those products requires additional raw materials such as sulfur, and Calcium carbonate (CACO3) that are imported from external suppliers. The studied chemical site consists of three independent operational entities. Each entity is composed of several production units to produce intermediate and finish product. A production unit comprises several production lines and one storage unit. In addition to these three independent entities, some resources are shared, such as connections that allow products to be exchanged between storage units, or transportation means (such as trucks and trains) that carry the finished products from the entities to the port where they are stored before being loaded on vessels and delivered to customers.

In the OCP Safi site, a specific team oversees the managing of these operations. More specifically, its mission consists of:

- Managing the planning of raw material and phosphate rock supplies for the various entities.
- Planning the production rate of the factories according to customer orders and the available stocks.
- Planning the transportation of the different products between the factory and the port.
- Ensuring the delivery of finished products according to the request of the shipping agency.

To support this mission, we propose in this paper an appropriate model that determine the optimal planning of production and logistics operations, while possibly pursuing several objectives (maximizing production, minimizing total costs, …).

It is indeed widely known that supply chain modeling has multiple benefits. First and foremost, it brings transparency and efficiency to decision making. It is a valuable tool to identify inefficiencies in the supply chain and therefore improve the overall performance. It is also an effective way to communicate about supply chain processes and flows to the different stakeholders, which can improve collaboration between chain partners.
Second, models are helpful in anticipating the impact of potential disruptions and evaluating the consequences of different scenarios on the supply chain, allowing organizations to proactively mitigate risks and optimize their investments. Finally, models can be used to compute a variety of metrics that describe the system's performance, including its limitations. This can help identify bottlenecks, inefficiencies, and choke points in the supply chain, inform strategic decision-making, and help organizations stay competitive in a rapidly changing environment (Min and Zhou 2002).

The above is the purpose of the present paper. We focus on a real-world case study of OCP Safi production site. The developed model is then presented using a Mixed-Integer Linear Program (MILP) model, with an objective of maximizing the delivered production.

The rest of the paper is organized as follows. Our next section discusses previous works addressing similar planning problems. Then we proceed to the description of the problem in section 3 and the mathematical model is detailed in section 4. Section 5 presents the results and insights derived from a sensitivity analysis conducted on the analyzed production site. Finally, some conclusions are drawn in section 6, which also includes some perspectives on future work.

2. Literature Review

Leveraging optimization to support the production planning exercise is a classical and well-studied approach. We could even say that production planning is one of the key applications of operations research, as shown by the high number of publications pertaining to this subject.

The first surveys related to production planning appeared at the end of the 1980s (Thomas and McClain 1993). However, for a review of recent literature related to the topic, we recommend and refer the reader to (Haaze 2012) and (Diaz-Madronero et al. 2014). Not surprisingly, in order to accompany economic development, globalization, and sustainability considerations, supply chain management has become increasingly important and complicated, especially due to the diversity and complexity of the new products on the market. Combined with the increased availability of data, this has resulted in a boom in this type of planning exercise and associated tools, resulting in an end-to-end integration of all operations, including production and logistics.

Initially applied to manufacturing sectors like sawmills, wood and furniture, automobiles, semiconductors, and electronic devices (Diaz-Madronero et al. 2014), it has since been extended to other sectors such as the chemical and pharmaceutical industries. Crama (2001) discusses and underlines the distinctive features of process industries as they relate to production planning issues and compare to discrete manufacturing. A comprehensive state-of-the-art report on planning and scheduling in the chemical process industry (Kallrath 2002). Floudas and Lin (2004) reviewed the continuous-time versus discrete-time approaches for scheduling chemical processes. Shahinidis et al. (1989) propose a multi-period MILP model to select and plan expansions of processes given time-varying forecasts for the demands and prices of chemicals over a long-range horizon. Papageorgiou et al. (2001) describes an optimization-based approach for selecting both a product development and introduction strategy and a capacity planning and investment strategy. Susarla and Karimi (2012) develop a mathematical model for the integrated problem of production planning, procurement, distribution, and inventory management in a multinational pharmaceutical enterprise. Related to the same sector of the chemical industry, Grossmann (2012) addresses some of the major issues involved in the modeling and solution of problems encountered in the area of enterprise-wide optimization for process industries. It should be noted that initially, the researchers focused on a generalization of the lot-sizing problems by taking into account and integrating aspects of practice and the real world, for example, energy constraints, carbon tax policy, multi-products, multi-sites, and multi-objectives, making the problems rich and hard to solve. Real-world case studies can be found in: (Brandenburg and Tolle 2009); (Berning et al. 2002); (Berning et al. 2004). For more details, we refer the reader to (Timpe and Kallralh 2000); (Chern and Hsieh 2007); (Torabi and Hassini 2008); (Safaei et al. 2010); (Zanoni et al. 2012); (Giglio et al. 2017) and (Vaziri et al. 2018).

Considering the breadth of the subject, we will restrain our work to deterministic planning, meaning that we will neither consider uncertainties nor scheduling. Thus, we split the time horizon into a finite number of time steps (also called periods), and we will plan what happens in our system at each time step. Furthermore, we will not consider strategic planning, limiting ourselves to tactical and operational exercises, similar to the majority of work in the field.

3. Problem description

This study addresses the problem of planning the operations of a supply chain in the chemical sector. To this end, an optimization model has been designed, implemented, and numerically experimented with. As illustrated in Figure 1, the considered value chain covers suppliers, production and logistics units, and customers. More details and information about the specific production site of Safi are provided in the following subsections.

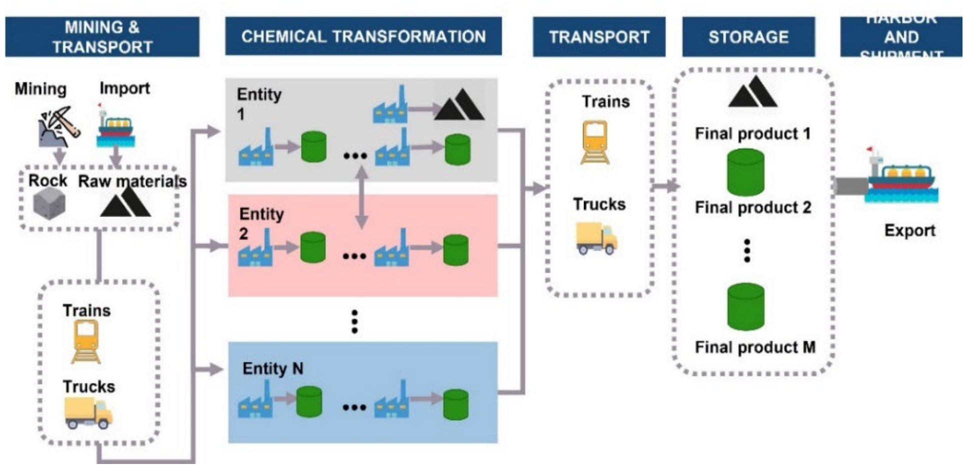


Figure 1: The studied supply chain structure

3.1 Products and production units

Naturally, the supply chain juggles multiple products that can be grouped into 3 groups: Raw materials (two types of rocks, CACO3 and solid sulfur), intermediate products (liquid sulfur SL, ACS, ACP30, steam MP, steam LP and steam HP) and finished products (ACP54, ACP54 BG, ACP54 Feed, TSP, MCP and DCP).
The two types of rocks are imported and exported. However, in the context of this paper, rock will be considered only for its role as an imported raw material. This choice is justified by the fact that there are no coupling constraints between the export of rock and the rest of the export.

As explained in the introduction, the considered production site is organized in three levels:

- It is divided into three legal entities.
- Each entity is composed of several production units, following the different stages of the chemical process.
- Each production unit comprises several production lines and associated with its own storage unit.

These production lines operate on the same principle: taking a set of products as inputs and transforming them into a single output product. The only units that can produce multiple products are the ACS units; they produce ACS product and steam as a result of the exothermic transformation; the steam is then used in other production processes, essentially the concentration of ACP30. The quantity of inputs required to produce one unit of output is specified by the Bill of Materials (BOM) of the production lines. Some production lines can alternate between different production schemes, characterized by a set of inputs and the resulting output product. One of the key decision variables of the optimization model relates to this choice: which production schemes should be operated at each period and in what quantity?
Along the chemical process, the outputs of a stage are used as inputs for the following stages, as illustrated in Figure 2.

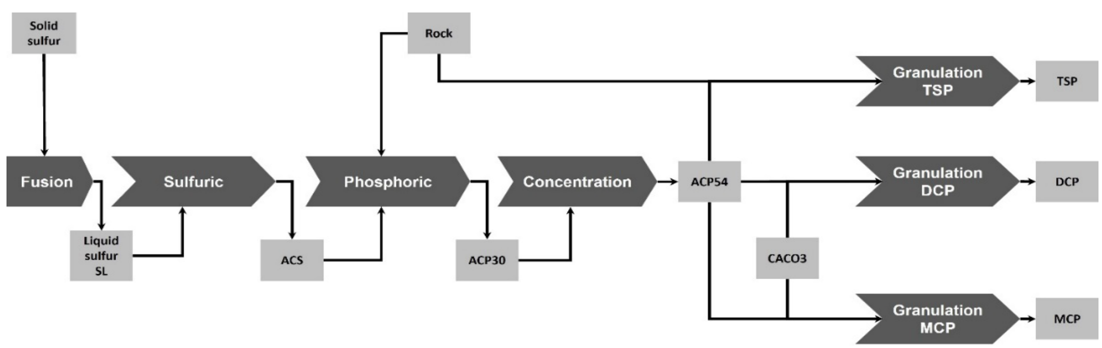


Figure 2: Production stages

The production lines are considered to have a limited, time-varying production capacity per period, calculated by considering historical performance and maintenance plans. Usually, if production lines are going to produce during the period, they are required to satisfy a minimal level of production per period. Finally, changeovers between production schemes are not considered here, but at most one production scheme can be operated during each period.

3.2 Storage units

Storage units can be of two types: tanks or hangars, depending on whether the product is liquid (acid) or solid (fertilizers or feeds). But the underlying structure, and therefore the resulting model, are the same, as described as follows:

- Each storage unit is dedicated to a single product.
- Each storage unit is characterized by a capacity (a maximum filling level) and a minimum filling level.
- The initial stock level is given as an input to the model.

3.3 Transportation units

Transportation is required to transport products from one production unit to another and from production entities to the port. The transportation network consists of three modes:

- Pipelines to link production units together.
- Trains connect production entities to the port, where products are loaded onto ships.

- Trucks also connect the production entities to the port; they are used to transport feeds and are complementary to trains for the transport of ACP54 acid.

Among the trains, some are dedicated to the transportation of phosphoric acid as a finished good (from production units to port) and sulfur as a raw material (from port to production units) simultaneously, while others are carrying TSP products from the entity to the port. It is nonetheless impossible to independently consider these transportation capacities since these trains share one single railroad connecting the port to the production units. In our model, we simplified this transportation system in the following ways:

- The transfer of products between entities shall respect the minimum and maximum capacities for each period in the whole horizon.
- The proposed model does not provide a transportation schedule but instead considers each transportation mode as a flow that links entities to the port.
- For each transportation unit, the planner may assign a lot size value: the amount of an item transported in a single trip; the transferred value must be a multiple of the specified value; this assumption is related to the trains since planners prefer the trains to be completely filled.

3.4 Suppliers
Suppliers supply raw materials to the production units. Two types of suppliers are considered: global suppliers and local suppliers. Local raw materials are transported by truck to the production units; the quantity supplied can be considered unlimited, while global raw materials are stored in the port before being transported by train or truck to the entities. Furthermore, suppliers are modeled as production units that don't need any input products.

3.5 Demands
The demand is represented as a set of orders and assumed to be deterministic. Each order is characterized by:

- The product.
- The quantity.
- The range between the estimated arrival time and the estimated departure time of the vessel during which the order shall be served.

3.6 Port and loading
We consider two types of customers: international and local clients. Local customers' products are delivered by truck, while international orders are loaded at the port. Several storage units are available in the port to store finished products delivered by entities and waiting to be loaded. Once the train or trucks arrive to the port, the product is unloaded into the port's warehouses, carried to the docks through conveyors, and finally loaded onto the vessel.

3.7 Utility
Utilities ensure the functioning of production lines with water, electrical energy, compressed air, or steam.
Steam is one of the most important products in our study because it is used as an input product in certain manufacturing processes. It is produced at the sulfuric stage. The underlying chemical reaction is very exothermic, and the heat produced by this reaction is used to generate high-pressure (HP) steam, which can in turn be converted into medium-pressure (MP) steam, low-pressure (LP) steam, and electricity. The steam conversion is realized using turbo generators. It has the purpose of generating low or medium pressure steam from the high-pressure steam generated by the sulfuric units. The resulting steam products are then used in the other production processes (concentration, granulation, and fusion) and required amount of steam must be condensed.

4. Mathematical model
In this section, we present the MILP formulation of the studied problem. The developed MILP model can be formulated as shown in the following subsections.

4.1 Sets, parameters, and decision variables
Tables 1 and 2 represent a list of notations considered to model the problem.

Table 1. Sets and indexes

P	Set of products	$p \in P$	Product index.
S	Set of utilities (steam, water) with $S \subset P$.	$s \in S$	Utilities product index.
H	Planning horizon	$t \in H$	Time index.
E	Set of entities	$e, e' \in E$	Entity index.
$U_{p,e}$	Set of production lines associated with product p and related to entity e.	$l \in U_{p,e}$	Production line index.
$T_{p,e,e'}$	Set of transportation units that can transport product p from entity e to entity e'; $e \neq e'$	$i \in T_{p,e,e'}$	Transportation unit index.
A_p	Set of types of product p	$a \in A_p$	Type product index.
O	Set of orders	$o \in O$	Order index.
R_p	Set of products needed to produce product p	$r \in R_p$	Product recipe index
Q_p	Set of products that use product P in their recipe	$q \in Q_p$	Index of products in Q_p

Considering that among the products and units there are some that have special features that must be taken into account while modeling, we included additional notations related to utilities: hps, lps, mps, wr and gta for high pressure steam, low pressure steam, medium pressure steam, condensed water, and turbogenerator units respectively.

Table 2. Table of parameters and decision variables considered in the model.

Parameters	
$\boldsymbol{\zeta_p}$	$\in R$, product margin.
$\gamma_{t,l}^{min,p,e}(\gamma_{t,l}^{max,p,e})$	$\in R$, minimum respectively maximum capacity of production line l producing product p during period t.
$\alpha_t^{min,p,e}(\alpha_t^{min,p,e})$	$\in R$, minimum respectively maximum storage capacity of product p in the entity e.
$\theta_t^{min,p,e,e'}\left(\theta_t^{max,p,e,e'}\right)$	$\in R$, minimum respectively maximum quantity of product p transferred or delivered by a transport unit (pipeline, train...) from entity e to entity e' during period t.
$\mu_l^e(p', p)$	$\in R$, the quantity of product p' needed to produce one unit of product p.
η_l^e	$\in R$, lot size assigned to production line l of the entity e.
$\iota_i^{e,e'}$	$\in R$, lot size of the transportation unit used to deliver products from the entity e.
$\beta_o^{p,e}$	$\begin{cases} 1 \text{ if the order o can be served from the stock of the product p in entity e.} \\ 0 \text{ otherwise} \end{cases}$
ω_o	$\in R$, volume related to order o.
χ_o	$\in R$, estimated arrival time of the vessel requesting the order o.
ψ_o	$\in R$, estimated departure time of the vessel requesting the order o.
Decision variables	
$x_{t,l}^{p,e}$	$\in R$, quantity of product p produced in the production line l of entity e during period t.
$l_{t,l}^{p,e}$	$\in$ N, number of lots of product p produced by the production line l of the entity e, during period t.
$a_{t,l}^{p,e}$	$\begin{cases} 1 \text{ if the line l of the entity e will produce the product p at the period t} \\ 0 \text{ otherwise} \end{cases}$
$y_{t,i}^{p,e,e'}$	$\in R$, quantity of product p transferred from entity e to entity e' by using transport unit i during period t.
$b_{t,i}^{p,e,e'}$	$\in$ N, number of lots of product p delivered by the transportation unit i from entity e to entity e' during period t.
$r_{t,i}^{p,e,e'}$	$\begin{cases} 1 \text{ if the transportation unit i will be used during the period t} \\ 0 \text{ otherwise} \end{cases}$
$s_{o,t}$	$\in R$, amount of quantity satisfied from order o during period t.

u_o	$\in R$, slack of order o, which represent the volume that is not satisfied at the end of the horizon.
$i_t^{p,e}$	$\in R$, quantity of product p stored at entity e during period t.
$x_{t,l}^{p',p,e}$	$\in R$, quantity of product p' used to produce product p during period t in the production line l of entity e.

4.2 Model formulation

Demand satisfaction is the primary objective of our model. The expression (1) indicates that the amount volume that is not satisfied for each order must be minimized.

$$\mathrm{Min}\ \sum_{(d\in D)} \rho_o * u_o \tag{1}$$

S.t

$$\gamma_{t,l}^{min,p,e} * a_{t,l}^{p,e} \le x_{t,l}^{p,e} \le \gamma_{t,l}^{max,p,e} * a_{t,l}^{p,e}\ \forall t \in H, \forall p \in P, \forall l \in U_{p,e}, \forall e \in E \tag{2}$$

$$x_{t,l}^{p,e} = \eta_l^e * l_{t,l}^{p,e}\ \forall t \in H, \forall p \in P, \forall l \in U_{p,e}, \forall e \in E \tag{3}$$

$$x_{t,l}^{p,e} = \frac{x_{t,e}^{r,p,e}}{\mu_l^e(r,p)} \forall t \in H, \forall e \in E, \forall l \in U_{p,e}, \forall r \in R_p \tag{4}$$

$$\sum_{(p\in A_p)} a_{t,l}^{p,e} = 1\ \forall t \in H, \forall l \in U_{p,e}, \forall e \in E, p \notin S \tag{5}$$

$$x_{t,gta}^{hps,e} = x_{t,gta}^{mps,e} + x_{t,gta}^{wr,e}\ \forall e \in E, \forall t \in H \tag{6}$$

$$\alpha_t^{min,p,e} \le i_t^{p,e} \le \alpha_t^{max,p,e}\ \forall t \in H, \forall e \in E, \forall p \in P \tag{7}$$

$$i_t^{p,e} = i_{t-1}^{p,e} + \sum_{(l\in U_{p,e})} x_{t,l}^{p,e} + \sum_{(e'\in E\backslash e)} \sum_{(i\in T_{p,e',e})} y_{t,i}^{p,e',e} - \sum_{(e'\in E\backslash e)} \sum_{(i\in T_{p,e,e'})} y_{t,i}^{p,e,e'} - \sum_{(p'\in Q_p)} \sum_{(l\in U_{p,e})} i_{t,l}^{p,p',e}$$

$$-\sum_{(o\in O)} s_{o,t} * \beta_o^{p,e}\ \forall t \in H, \forall e \in E, \forall p \in P \tag{8}$$

$$i_t^{s,e} = \sum_{(l\in U_{s,e})} x_{t,l}^{s,e} + \sum_{(e'\in E\backslash e)} \sum_{(i\in T_{s,e',e})} y_{t,i}^{s,e',e} - \sum_{(e'\in E\backslash e)} \sum_{(i\in T_{s,e',e})} y_{t,i}^{s,e,e'} - \sum_{(q\in Q_S)} \sum_{(l\in U_{s,e})} i_{t,l}^{s,q,e}$$

$$\forall t \in H, \forall e \in E, \forall s \in S \tag{9}$$

$$\theta_{t,i}^{min,p,e} * r_{t,i}^{p,e,e'} \le y_{t,i}^{p,e,e'} \le \theta_{t,i}^{max,p,e} * r_{t,i}^{p,e,e'}\ \forall p \in P, \forall t \in H, \forall e, e' \in E, \forall i \in T_{p,e,e'}, e' \ne e \tag{10}$$

$$y_{t,i}^{p,e,e'} = \iota_i^{e,e'} * b_{t,i}^{p,e,e'} \forall p \in P, \forall t \in H, \forall e, e' \in E, \forall i \in T_{p,e,e'}, e' \ne e \tag{11}$$

$$\omega_o = \sum_{(t\in H)} s_{o,t} + u_o\ \forall o \in O \tag{12}$$

$$s_{o,t} = 0\ \forall o \in O, \forall t < \chi_o \tag{13}$$

$$s_{o,t} = 0\ \forall o \in O, \forall t > \psi_o \tag{14}$$

The constraint (2) expresses the limitation of resource capacities, indicating that the produced quantity for each production line *l* must respect the minimum and maximum level; Equation (3) expresses that the quantity produced for each production line *l* must be a multiple of the specified "lot size" number. Equation (4) describes compliance with the nomenclature associated to each product. Except for turboalternator units, the equation (5) specifies that just one process must be performed for each production line in each period. Finally, constraint (6) connects the steam admission process, steam filling and steam condensation process at turboalternator units. The constraint (7) ensures that the stock level in each period respects the minimum and maximum threshold levels. Equations (8) and (9) express the flow conservation constraints. We express in the constraint (10) that for each transportation unit (pipes, loading unit, trains, and trucks), the maximum capacity and the minimum level must be respected, while constraints (11) indicates that the transport unit must transfer a multiple of the indicated lot size. The constraint (12) links the quantity demanded with the quantities satisfied during each period t and the unmet quantity of the demand. Equations (13) and (14) express that the order should be satisfied between the estimated arrival time and the estimated departer time of its related vessel.

5. Real-life case study

In this section, we will perform a sensitivity analysis of the studied supply chain by examining how in parameters, related to production lines capacities can affect the overall performance of the system. This analysis will help us comprehend the sensitivity of the supply chain and pinpoint areas that need to be improved. In the following, we provide an overview of the data structure that we used in our experiments. We describe afterwards the scenarios studied, highlighting the results obtained and their conclusions.

5.1 Data instance description

The OCP Safi plant is divided into three entities: Maroc Phosphor I, Maroc Phosphor II and Maroc Chimie. Each entity has several production units, and each unit comprises several production lines (total of 45 production lines). The MC entity produces four products: ACP54, TSP, MCP and DCP. MP1 produces ACP54 using fusion units, sulfuric units, phosphoric acid units and concentration units. MP2, created in 1981, produces ACS sulfuric acid and ACP-30, ACP54 Feed and ACP54 BG phosphoric acids.

5.2 Numerical Results

This section investigates how the model responds to different planning horizons and supply chain sizes. We considered two datasets, each consisting of four instances; the first dataset includes only the MC complex, while the second is tested on the entire SAFI plant. For each instance, we modified the capacity of the production or transport units. Then we evaluate the solution for different size horizons (H = 10, 30, 60) with a daily time step. Table 3 describes the number of instances solved, the number of instances solved to the optimum, the average computation time in seconds, and the average gap in percentage for each horizon and dataset.

Results show that the planning horizon and supply chain complexity have an impact on both execution time and solution quality. All instances of the MC complex can be solved to the optimum for all horizons. In addition, the quality of the solution decreases depending on the size of the supply chain and the planning horizon.

Table 3. Computational results

	MC Entity				OCP SAFI Plant			
Horizon	Resolved Instances	Instances solved at optimum	Average time (s)	Average gap	Resolved Instances	Instances solved at optimum	Average time (s)	Average gap
10	4	4	0,275	0	4	4	4,25	0
30	4	4	0,95	0	4	2	6,5	0,0075
60	4	4	3,5	0	4	1	19,75	0,1725

5.3 sensitivity analysis

The purpose of the following tests is to study the resources of the supply chain and to calculate the optimal production plan. This allows us to determine the maximum demand volume that the site can possibly address and to identify the limits of our resources. By analyzing the shadow price of each constraint, we identify the production lines or transportation units with the greatest potential for increasing the outcome of the production system. To this end, we start by running the model with the objective of maximizing the delivered volume. We assume that for each exportable product, the demand is unlimited, and products margin are all equals.

5.3.1 Analyzing dual price

We analyze the dual prices associated with all capacity constraints for each production and transportation unit. We notice that the dual prices related to capacity constraints of all transportation units are equal zero. However, the dual prices associated with certain production units are positive as shown in Table 4.

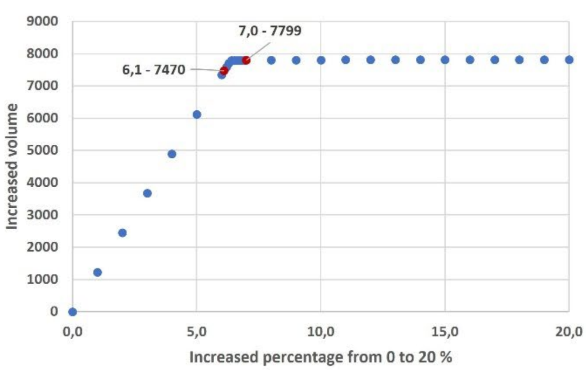
Table 4. Table of total shadow prices related to production lines capacity constraints

	Total shadow price for each entity		
Units/Entity	MC	MP1	MP2
Sulfuric	0	0	0
Phosphoric	89,88	120	90
Concentration	0	0	0
Granulation MCP	14	-	-
Granulation DCP	16	-	-
Granulation TSP	37	-	-
GTA	0	0	0
Fusion	0	0	0

We suppose now that we can invest in production lines and increase their capacity, and we analyze the impact of capacity changes on demand satisfaction.

5.3.2 Increasing ACP30 production

In the following tests, we increase the capacity of the ACP30 production lines and analyze the impact on demand satisfaction. As the margins are equal, we analyze the impact of this increase on the total volume produced and delivered. The results introduced in Figures 3 show that the maximum demand volume that can be gained by increasing the capacity of ACP30 production lines is 7797 with a percentage of 6,37%.



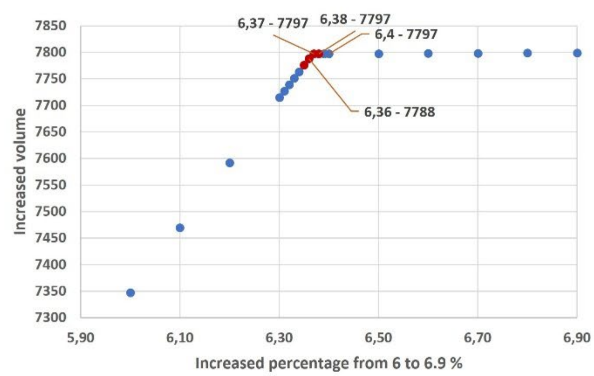


Figure 3. Increasing the capacity of phosphoric production lines from 0% to 20% and from 6% to 6.9%

5.3.3 Increasing TSP production Lines Capacity

As in the previous section, in the following tests we try to investigate the impact of increasing the capacity of the TSP Granulation lines, and to what extent this will help us increasing the volume delivered. Results introduced in Figure 4 shows that by increasing the production capacity by 17.82%, we can increase the total volume produced by 8938.

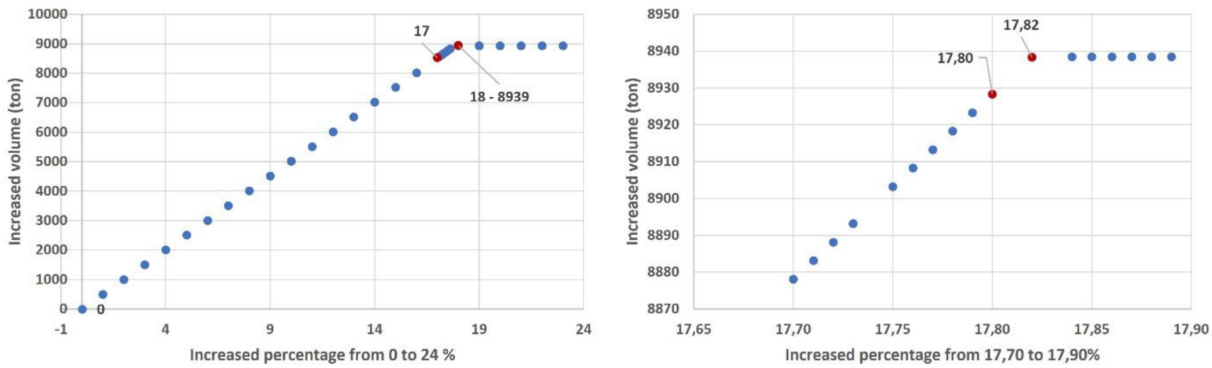


Figure 4. Increasing the capacity of granulation TSP production lines from 0% to 23% and from 17.8% to 17.9%

5.3.4 Increasing Granulation MCP production Lines Capacity

Similar to what we experienced in the previous sections. Figure 5 shows the results obtained by increasing the capacities of the Granulation MCP production lines. As shown in the figures, increasing the total capacity by 7.54% enables to increase the production by 514 tons.

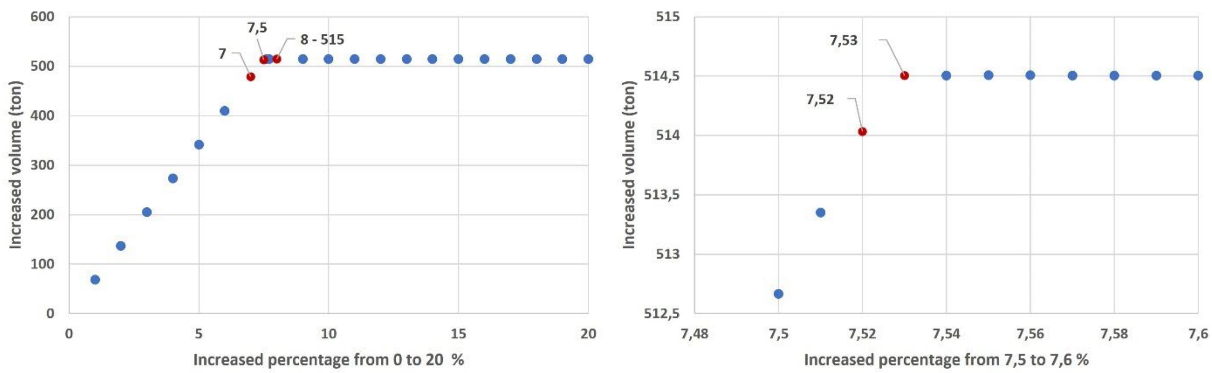


Figure 5. Increasing the capacity of granulation MCP production lines from 1% to 20% and from 7.5% to 7.6%

5.3.5 Increasing Granulation DCP production Lines Capacity

In this section, we increase the capacity of DCP granulation production lines. The results presented Figure 6 show that to increase the delivered volume by 7687, the capacity needs to be increased by 145.78%, which is more than double the current capacity.

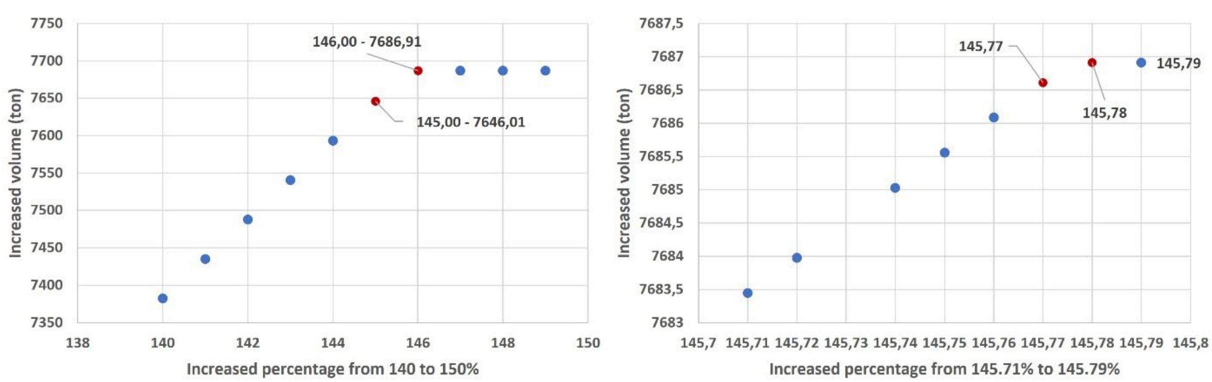


Figure 6. Increasing the capacity of granulation DCP production lines from 140% to 149% and from 145.71% to 145.79%

6. Conclusions

Setting up an advanced planning and scheduling (APS) solution in manufacturing and supply chains is key to the performance of industrial chemical complexes, allowing supply chain managers to synchronize thousands of resources including machinery, raw materials, inventories, logistics, in order to fulfill the demands of the customers. Moreover, as stated in McKinsey (2022), building a digital twin of the supply chain, and using it to run "what-if" scenarios, is an essential part of efforts to achieve structural resilience and to be able to run the business in a volatile context.

In this paper, we propose such a tool for a chemical industry site, in a deterministic context. Our contribution lies firstly in the modeling of the real-life production site, translating the constraints, and the reality of the field into a mathematical model, simple enough to be solvent and rich enough to bring value. The purpose of this model is to determine the production, transportation, and demand satisfaction plan while taking into account a variety of production, transportation, storage, and demand-related constraints. The objective function considered aims to maximize the produced and delivered volume. Although our model was designed for the Safi site of the OCP group, the model is quite generic and could be applied to other process manufacturing production systems. Second, we solved this model with a MILP solver (CPLEX). Finally, using this model, we conduct numerical experiments on a real case study to examine our studied supply chain through a sensitivity analysis and to identify its boundaries and possible improvements.

To this end, we have manipulated the function objective to maximize the delivered product, by considering an infinite demand. We ran the model and examined the dual prices linked to each resource capacity constraint (production and transportation units). In this step, we revealed that positive dual prices are only associated with the manufacture of phosphorus and granulation. Then, we investigated the associated units by raising their capacities and evaluating their effect on the delivered volume. As discussed in the previous section, an increase of 6.37% in phosphoric units' capacity results in a gain of 7,797, while doubling the capacity of the TSP production lines results in a gain of less than 7,687 in the total volume delivered. The results of our study provide valuable insights into the supply chain planning problem and support the policymakers in developing policies that support the growth of supply chain networks.

Finally, there are several ways to enrich the model developed in this study. First, by integrating the scheduling plan for trains and trucks as well as loading and unloading vessels. Second, by incorporating real-time data on traffic, weather, and resource unavailability and propose methods to adjust the schedule. Another option would be to consider the stochastic version of the problem by harnessing historical data.

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