An integrated steering approach to improve a phosphate supply chain efficiency

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Abstract – This paper presents and illustrates an original application of the redesign in the real context of a mining supply chain producing phosphate rock. One of the major challenges is to successfully produce the final products required by the customers, from raw materials whose chemical composition and availability depend on the extraction program and method. Redesign of the mining supply chain consists of considering the impact of extraction, processing, and blending stages in achieving target objectives. The proposed approach, based on a mixed integer linear programming model, allows moving from fixed production flows to dynamic ones by adopting a flexible and reactive management mode that fully satisfies customer requirements at minimum production costs. Numerical results obtained using real data, corresponding to the infrastructure and order books, illustrate (*i*) the flexibility, quality, and vertical alignment ensured by our approach and (*ii*) the impact of the extraction method on the ability of the SC to fulfill the orders book with more efficiency.

Keywords: Redesign, alternative routings, blending, mining supply chain, steering.

1 Introduction

The main objective of agriculture is to feed a growing world population while preserving the right of future generations to be able to feed themselves. In this context, the phosphate mining industries, the main suppliers of raw materials for chemical fertilizers, are facing new challenges, combining the preservation of natural resources and responding to the increasingly diversified demands of the market (Zeng et al., 2021).

To address these challenges, the companies can proceed to various possible strategic actions linked to the redesign of the supply chain (**SC**): methods of extraction, production lines, transportation, improvements of manufacturing recipes, new products designed, supply optimisation, etc. Structural and material changes in the SC require large investments, whether financial or organizational, whose benefits are obtained slowly. One alternative solution remains to redesign the current production system while considering the current infrastructure. This concept consists of integrating a decision that changes or modifies the current steering mode and evaluating its impact on specific objectives. It generally takes into account: productivity of the company, performance, customer satisfaction, production and transport costs, inventory management, production time management, and provision of products to customers (Person 1995) as well as environmental aspects (Martins et al. 2017).

The present work addresses a redesign applied to one of the phosphate mining and processing sites of OCP Group (Khouribga's site) which is the international leader in the phosphate and its derivatives markets. This work results from an industrial project and is focused on the export orders fulfilled by this SC and transported by train to the port. This research is then a clinical one whose structuring is based on empirical analysis and recurrent dialogues with the industrial partner (Schein 1995).

The studied SC is a classical mining chain (Attaran, 2020) considered as a production network composed of five sequential entities (nodes): extraction of the ores (from five mines), three enrichment (or treatment/washing) ones, and one drying entity. These entities are linked to each other via conveyors, to transport products of different natures (raw and transformed). **S**ource **O**res (**SOs**) are extracted and identified with their chemical characteristics and transformed by different processes in **M**erchantable **O**res (**MOs**). MOs orders are fulfilled by respecting the three famous triplet quantity, cost/quality, and delivery time. The requirements in terms of quality are reflected in a **Q**uality **C**harter (**QC**) established by value ranges with lower and upper limits of several chemical elements.

Upstream of the chain, the tactical extraction steering is based on one of three possible extraction methods. Each method differs in the number of phosphate layers extracted simultaneously, which generates a different feeding in terms of SOs quality, quantity, and availability date. In the SC's heart, five washing plants may enrich those SOs to provide intermediate products called **W**ashed **S**ource **O**res (**WSOs**) through one of three existing routings. Downstream of the chain, the blends of ingredients (a set of SO and/or WSO) are performed in the drying plant to constitute MOs based on orders book. Thus, the specificity of the studied industrial context is related to the features of the SOs: (*i*) the intrinsic structures and availability dates of SO depend on the extraction method in the mine (heterogeneity), (*ii*) these extracted products may not satisfy the chemical characteristics respecting the MOs quality charter.

MOs' production is currently based on a predefined set of manufacturing recipes and routings that have been determined empirically over time. Each recipe is defined by a blend of SOs and/or WSOs provided by specific mines and each routing is defined by enriching (or not) the chosen SOs/WSOs), depending on the stocks availability, intrinsic chemical quality of available products (SOs and WSOs), and washing plants capacity. Moreover, regarding the QC, these couples recipe/routing focus on the verification of only one chemical component, BPL[1], the other chemical components[2] are measured *ex-post*.

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[1] **B**one **P**hosphate of **L**ime: the chemical component characterising the richness of phosphate rock in P_2O_5.

[2] The quality charter is classically based on several components: BPL, SiO_2, MgO, Cd, Al_2O_5, Fe_2O_5, CO_2, etc.

This steering organisation generates two main difficulties: (*i*) the rigidity of the manufacturing recipes threatens the satisfaction of the consumer either in the quality charter (lack of the necessary SOs/WSOs) and/or in time delivery (unavailability of the equipment usually), *(ii)* the extraction mode acts as a tactical push system and is not considered in the tactical planning of the MOs production.

Our goal is then to redesign the steering of this mining SC focusing on the planning activities (Genin et al. 2007; Bachouch et al. 2011; Chahed et al. 2011; Genin et al. 2015), to improve customer satisfaction, mobilise fewer resources and reduce production costs while taking into account the extraction method, treatment and blending in the production planning and keeping the same infrastructure. Integrating the extraction methods allowes highlighting their impact on the processing program, and consequently on the ability of the SC to fulfill the orders book with more efficiency.

The paper is organised as follows: Section 2 is devoted to a literature review concerning the redesign of supply chains. Section 3 describes the features of the SC and retained assumptions. The mathematical model, belonging to the MILP[3] class, is explained in section 4. A case study is presented in Section 5. and management insights are discussed in Section 6. We end with some conclusions, possible extensions of this work into other industries and perspectives.

2 Literature review

The redesign of a logistics chain has been the subject of a lot of research for over twenty years (Persson 1995), carried out theoretically or by studying real cases. It consists of assuming an existing SC, taking into account its current infrastructure, and integrating decisions to reconfigure production activities or management mode for specific objectives (Razmi et al. 2013). The redesign is integrated generally at a strategic/tactical level and evaluated at the operational one (Martins et al. 2017).

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[3] Mixed-Integer Linear Programming model

Redesigning a SC consists of considering the sources of decision-making uncertainties and the corresponding possible redesign variables, either physical or organizational (Van der Vorst and Beulens 2002) such as making decisions about production flow allocation, distribution flows, resources (transport) selection, investments, disinvestments, facility location, storage facilities, (Feitó-Cespón et al. 2017). This should be chosen to achieve the target objective, as reducing lead time, reducing or adapting to uncertainties, eliminating or adapting to the expected pattern of demand, and simplifying structures, systems, processes, etc. (Persson 1995).

Over the previous 25 years (Berry and Naim 1996), the concept of redesign has been applied through the development of mathematical programs and tools, or by proposing the most pertinent strategies and methodologies to do so. For example, Serrano et al (2008) studied the importance of Value stream mapping (VSM) as a technique of redesigning manufacturing systems. The redesign has been studied in different industries: food (Van der Vorst et al. 2009), cement (Jahani et al. 2018), agriculture (Pissonnier et al. 2019), automotive (Hammami and Frein, 2014), plastics (Feitó-Cespón et al. 2017), pharmaceutical/medical industries (Lim et al. 2019). The analysis of these works leads to a classification based on the following criteria:

- **Supply chain level**: *i*) supply, through the redesign of reception areas for supplied products by reassigning suppliers to the docks and the storage of raw materials received to the different storage spaces (Saez-Mas et al. 2020) *ii*) production network, while deciding about production flows, the necessary transportation between different entities (Berry and Naim 1996) *iii*) the distribution network, through the definition of optimal distribution paths/ routes from plants, to the customer (Martins et al. 2019; El Mokrini et al. 2018). Other authors have treated the three levels of the SC simultaneously, as Naraharisetti and Karimi (2010) who proposed a solution for multi-purpose plants).
- **Nature of product:** Some researchers had considered only raw (Saez-Mas et al. 2020), or intermediate and final products (Krishnan et al. 2020).
- **Type of decision**: It is used to integrate improvements or modifications, over *i)* a medium and long term, as treated by Melo et al. (2012), and the impact of the redesign is often evaluated

over *ii)* the short term to verify the degree of robustness and the relevance of the decision taken on the operational level (Martins et al. 2019).

- **Resolution method**: Redesign issues are solved using different methods by discussing strategies and practices that may be used (Persson, 1995) and Van der Vorst and Beulens (2002), or generally by case studies with the following methods: optimisation: linear programming (Ivanic et al. 2013), MILP (Fattahi et al. 2018), simulation (Pissonnier et al. 2019), combination of optimisation and simulation methods (Martins et al. 2017), personalised frameworks (Krishnan et al .2020).
- **Modeling objective:** Lim et al. (2019) minimised the operating costs; Fattahhi et al. (2017), maximised the net income and the unspent budget; Hammami and Frein (2014) maximised the global after-tax profit; Jahani et al. (2018) maximized the total profit, Naraharisetti and Karimi (2010) focused on satisfying customer requirements, Yan et al. (2002) on stock management, and Razmi et al. (2013) environmental, social impacts, or a combination of objectives.

Table 1 summarises this literature's analysis based on 21 articles and puts forward the originality of our work.

Contributions:

To the best of our knowledge, the redesign of productive SC has received less attention in the mining sector. A new combination of structural aspects of the mining SC is developed in this paper. The redesign is generally associated with distribution networks and the production plants are considered as « black boxes » with specific capacities. In our case, we consider the details related to producing MOs, with the definition of product flows to forward between plants, routings to use, resources to mobilise, after choosing between several mines (as internal suppliers), and the extraction method to adopt. Unlike other works such as those by Azzamouri et al (2021) or Hilali et al. (2023), the blends are made from SO and/or WSO. Moreover, three objectives are combined: improving customer satisfaction, minimizing resources mobilisation, and production costs.

Author(s)	Year	Sector														Type of study		Type of Problem			Type of decision			Time					Variables		Supply chain										Adopted approach							Objective						
																								Horizon			Period				Number of products		Nature of products			Output		Supply chain stage				Optimisation												
		Automobile industry	Food industry	Cement industry	Agriculture	Chemical industry	Pharmaceutical/medical industry	Personal computers industry	Electronics industry	Mining industry	Plastics industry	Aquaculture	Steel industry	Renewable energies	Not-defined	Descriptive	Prescriptive	Design	Solving	Case study	Strategic	Tactic	Operational	Long term	Middle term	Short term	Single-period	Multi-period	Single-variable	Multi-variables	Single product	Multi-products	Raw material	Intermediate	Final product	For stock	On demand	Supply	Production	Distribution	Linear programming	Mixed Integer Linear	multi-objective mixed integer linear Program	Mixed Integer Quadratically Constrained Program	Simulation	Personalised framwork	Discussing strategies, methodologies, and tools to implement redesign	Economic	Customer satisfaction	Social	Lead time	Reactivity and responsiveness	Environmental	Stock level
Göran Persson	**1995**														X	X		X	X		X		X	X																							X	X	X		X			X
Berry and Naim	**1996**							X									X	X		X	X		X						X		X		X	X	X	X			X	X					X				X					
Van der Vorst and Beulens	**2002**		X													X				X	X		X																								X							
Yan et al	**2002**								X								X	X			X	X		X	X																													X
Serrano et al	**2008**														X	X		X		X																											X							
Van der Vorst et al	**2009**		X														X	X		X	X		X	X		X			X		X				X	X				X					X			X	X				X	
Naraharisetti and Karimi	**2010**					X											X	X		X	X	X	X	X	X	X		X		X		X	X	X	X		X	X	X	X		X			X				X					
Melo et al	**2012**														X		X	X	X		X		X	X				X												X		X						X						
Razmi et al	**2013**						X										X	X		X	X		X				X				X				X					X		X						X	X					
Hammami and Frein	**2014**	X															X	X		X	X		X	X				X		X		X		X	X				X	X		X						X						
Feitó-Cespón et al	**2017**										X						X	X		X	X		X	X				X		X	X		X	X	X			X	X	X		X						X	X				X	
Martins et al	**2017**						X										X	X			X		X							X									X						X			X	X					X
El Mokrini et al	**2018**						X									X	X	X		X	X			X								X			X					X							X	X				X		
Jahani et al	**2018**			X													X	X		X	X	X		X	X			X		X		X			X		X			X		X						X						
Fattahi et al	**2018**														X			X			X	X		X	X			X		X		X			X					X		X						X						
Martins et al	**2019**		X														X	X		X	X		X	X				X		X		X				X				X		X						X		X			X	
Pissonnier et al	**2019**				X												X	X		X	X	X		X	X			X		X		X			X				X	X		X			X			X					X	
Lim et al	**2019**						X										X	X		X	X	X	X	X	X	X		X	X			X			X		X			X		X						X						
Krishnan et al	**2020**				X												X	X			X		X							X	X		X	X	X			X	X	X						X		X					X	
Saez-Mas et al	**2020**	X															X	X			X		X							X		X	X			X		X			X										X			
Our article	**2023**									X							X	X		X		X	X		X	X		X		X		X	X	X	X		X	X	X			X						X	X					

Table 1. Article analysis grid

3 Main features of the mining supply chain

In this section, the different features and assumptions adopted are presented since this work concerns a real industrial context. Figure 1 illustrates the general scheme of the SC (index *r* is assigned to a resource).

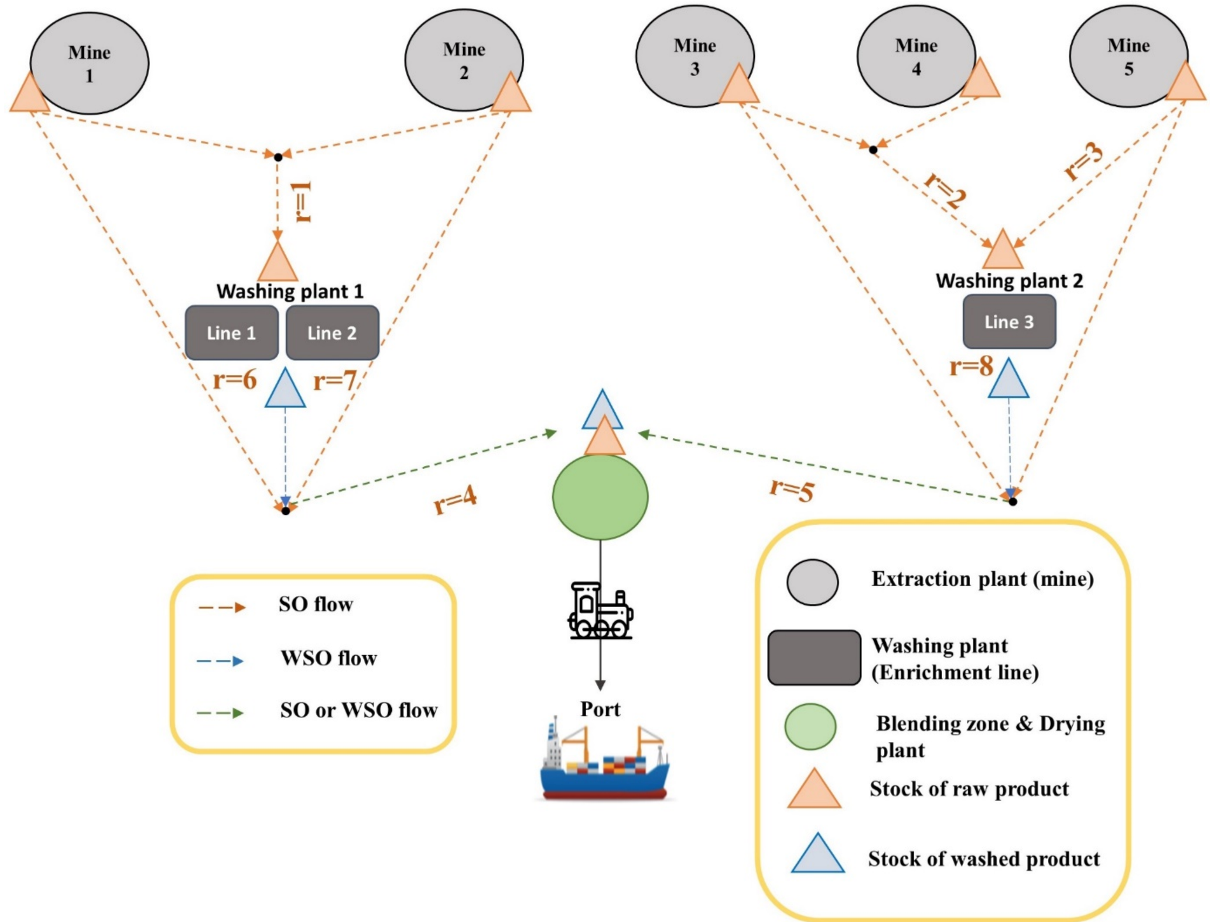

Figure 1. General scheme of the mining SC

3.1 Extraction methods

Phosphate rock takes the form of several superimposed layers separated by non-phosphate (sterile) layers, which should be extracted in such a way as to obtain the quality and quantity desired at the delivery time corresponding to the order's one to satisfy. To extract phosphate layers, there is a need to go through several successive and obligatory extraction operations before accessing phosphate layers while mobilising specialised machines (Azzamouri and al.

2018). There exist three extraction methods (illustrated in Figure 2) that may be used to satisfy customer's needs, but three ones are generally used at Khouribga's site:

- Selective method: consists of extracting phosphate layer independently from sterile ones, and for each phosphate layer, the underlays are extracted independently from each other;
- Semi-global method: consists of combining the extraction of some phosphate layers with each other, or with some sterile layers;
- Global method: which consists of combining the extraction of all the phosphate and sterile layers at the same time.

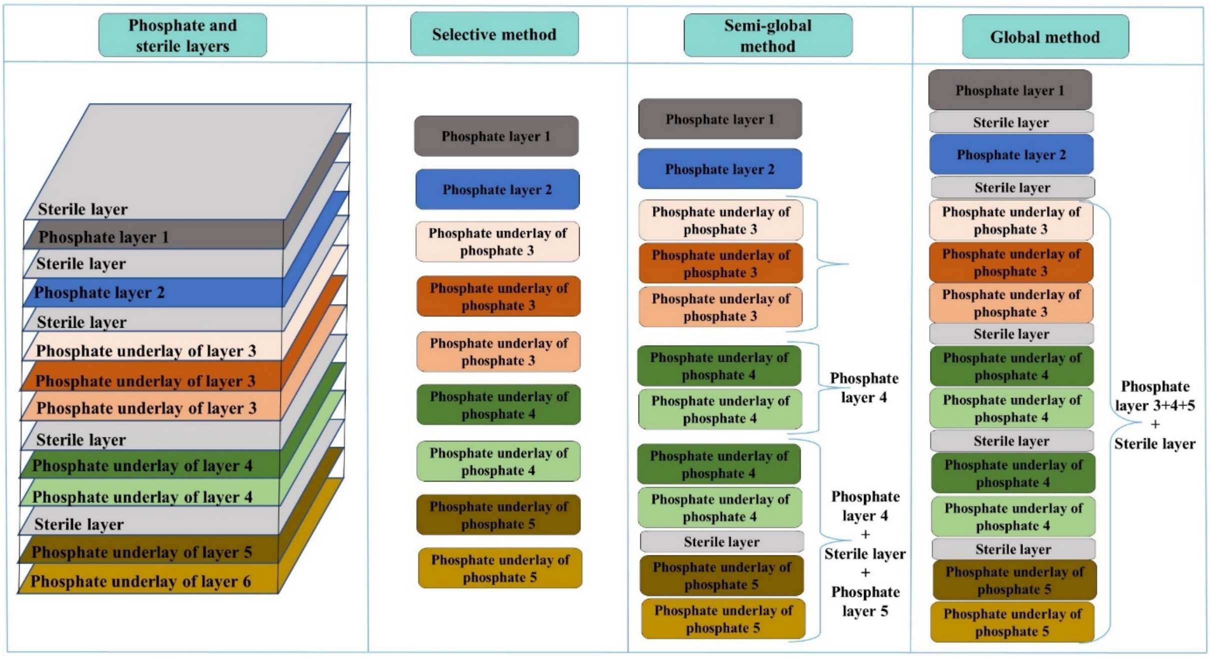

Figure 2. Illustration of extraction methods

The choice between those methods in the mine is linked to several parameters, as quantities, quality (chemical characteristics), availability date of phosphate rock obtained, and extraction costs.

3.2 Technical resources

Each conveyor is used to forward products from specific stocks or plants and each washing plant is allowed to enrich raw phosphate coming from dedicated stocks (*i.e.* mines). This SC consists of eight resources (indexed on figure 1), five critical conveyors (bottlenecks) forwarding either raw products and/or washed ones $(r \in \{1,2,3,4,5\})$, and three enrichment lines of washing plants $(r \in \{6,7,8\})$.

Non-critical conveyors appear on the scheme but have no capacity impact on the mathematical model. Critical conveyors can either forward SO if they link mines to enrichment lines of washing plants $(r \in \{1,3,4\})$ or SO/WSO if they link mines or washing plants to the drying plant $(r \in \{2,5\})$.

3.3 Alternative routings

Some SOs need a wash treatment to increase their phosphate content (BPL component), generating modifications either related to the WSOs quantities which results from a reduction of the used SOs quantities, due to the enrichment process based on eliminating impurities, or concerns the chemical components which should increase for BPL and decrease for the other chemical elements. All SOs and WSOs have to pass through the drying unit to reduce the humidity rates of ingredients after blending and before loading the final product on the train. Four routings can be adopted: no enrichment, simple washing, washing-flotation, washing-grinding-flotation.

Routing 2,3 and 4, consist of transforming SOs into WSOs while routing 1 consists of transporting directly the selected SOs/WSOs from the stock to the drying unit for blending, without any enrichment.

3.4 Production configurations

Five production paths/configurations are possible, illustrated in Figure 3, and represented by the couple (input, routing):

- Usually, if the SO doesn't require enrichment, it is forwarded directly to the drying unit (configuration 1).
- "Poor BPL" SO must pass through the washing plant (configurations 2 and 3).
- Some stocks of WSO (washed SO) exist downstream washing plant and/or SO upstream drying plant and have to be forward to the blending zone (configurations 4 and 5). In this case,

the decision about enriching the products was already applied (routing 1). At the drying unit, the necessary blending is carried out to satisfy customers in terms of quantity and quality and dried before loading the trains with the final product.

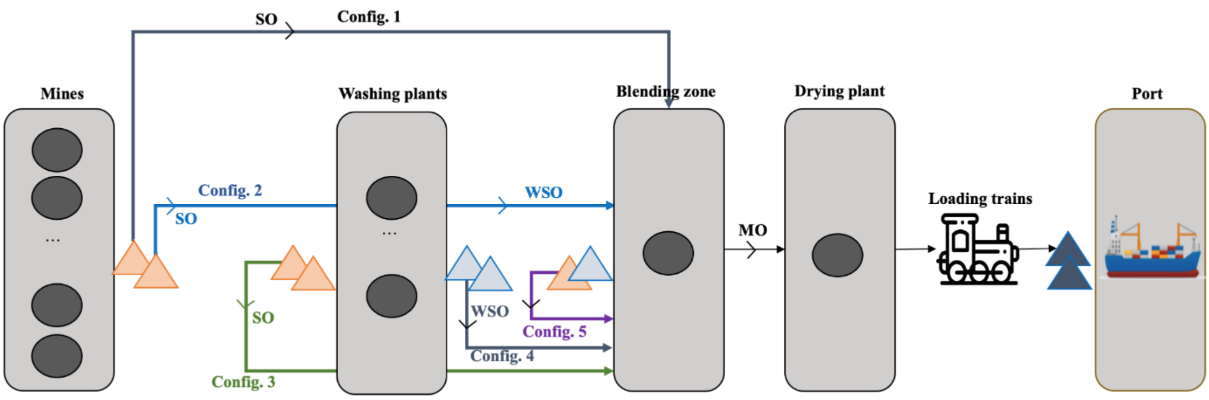

Figure 3. Illustration of production configurations

3.5 Operating time by configuration

Each configuration is characterised by its operating time. During its preparation, the product goes generally through three main operations: processing, transport, and storage. Each operation duration varies between a few minutes, a few hours, and a few days. It is, therefore, necessary to find the exact unit of time to adopt when modeling the SC and which agrees with the times required for each operation. Also, the earliest and latest delivery times of the various MOs may overlap, resulting in an overlap in the periods over which those MOs must be prepared. It is therefore judicious to set up simplifying assumptions to determine the periods over which the inputs will be processed.

We thus assume that each of the production operations is carried out over different but successive periods and respect the constraint related to the maximum capacity of the resources mobilised. This is illustrated in Table 2.

Configuration 2			
Operations	Forwarding SOs from mines to washing plants	Washing SOs+ storage	Forwarding WSOs from washing units to the drying plant
Mobilised resources	Conveyor	Washing unit	Conveyor
Periods of mobilising resources	t	t+1	t+2

Table 2. Assumptions and features related to mobilising resources (configuration 2)

4 Mathematical model

We propose a linear programming model to address the problem of redesigning the studied SC. First, notations are described in a table; then, the objective function is proposed followed by all constraints.

Notations:

Index	**Description**
t	Time index $t = \{1,...,T\}$.
i	Inputs index $i = \{1,...,I\}$.
j	Outputs index $j = \{1,...,J\}$.
k	Orders index $k = \{1,...,K\}$.
c	Chemical components index $c = \{1,...,C\}$.
h	Routings index $h = \{1,...,H\}$.
r	Resources index $r = \{1,...,R\}$.

Parameters	**Description**
General parameters	
λ_k	The output *j* of order *k* such as $j = \lambda_k$.
D_k	Requested quantity belonging to order *k*.

N	Minimal input quantity to use (if input *i* is chosen).
M	Maximal input quantity to use (if input *i* is chosen).
$SO_{extraction\_plant}$	Set of source ores available in the stocks of all extraction plants.
$SO_{upstream\_washing\_plant}$	Set of source ores available in the upstream stocks of all washing plants.
$WSO_{downstream\_washing\_plant}$	Set of washed source ores available in the downstream stocks of all washing plants.
$SO\_WSO_{drying\_plant}$	Set of source ores and washed source ores available in the drying plant stock.
I_r	Set of inputs forwarded or enriched by resource *r*.

<u>Technical parameters</u>

$\beta_{cj}^{\min}$	The lower bound of component *c* of output *j*.
$\beta_{cj}^{\max}$	The upper bound of component *c* of output *j*.
τ_{cj}	The target value of component *c* of output *j*.
α_{ic}	Percentage of the weight of chemical component *c* in the total weight of input *i*.
ω_{hci}	Enrichment rate, defined for each chemical component *c* of input *i*, passing through the routing *h*.
η_{ih}	Reduction weight rate of input *i*, when using treatment routing *h*. For $h=1$, $\eta_{i,h=1}=1$.
U_{ih}	Binary parameter equal to 1 is the input *i* can be treated using the routing *h*.

Inventory parameters

S_i^{init}	The initial quantity of input *i* in stock at period $t = 0$.
A_{it}	Supply quantity of input *i* at period *t*. Each input is assigned to one and only one storage area.
ρ_r	Daily flow capacity defined for each resource *r*.
ϕ_{rt}	Daily availability rate defined for each resource *r* per period *t*.

Time parameters

E_k	Earliest date to prepare order *k*.
L_k	Latest date to prepare order *k*.
ϑ_{ih}	Average operating time to treat input *i* with routing *h*, *i.e.* configuration (*i,h*).
ϑ'_{ihr}	Transit time from the stock of input *i* to resource *r* if routing *h* is involved, *i.e.* configuration (*i,h*).

Cost parameters

σ_c	Penalty cost for the gap between the required weight of component *c* in the output $j = \lambda_k$ (target value) and the weight obtained by the blend.
σ'_{ih}	Penalty cost for prioritising the use of production configuration based on operating time.
σ''_h	Cost related to the use of the routing *h*.
σ'''_{em}	Cost related to the use of a specific extraction method "*em*" (global, semi-global, or selective).

Variables	**Description**
Decision variables	
x_{ihkt}	Decision variable- quantity of input *i*, treated by routing *h*, to produce order *k* during period *t*.
o_{ihkt}	Binary decision variable- equal to 1 if the input *i* is treated by routing *h*, to produce order *k*, during period *t*.
y_{ihkt}	Intermediate variable- used to impose a maximum value M to x_{ihkt}.
z_{ihkt}	Intermediate variable- used to impose a minimum value N to x_{ihkt} if $x_{ihkt} > 0$.
Auxiliary variables	
S_{it}	Intermediate variable- represents the level of stock of input *i* at the end of period *t*.
ϖ_{ck}	Intermediate variable- defines the intermediate weight of the chemical component *c* of the output $j = \lambda_k$ (order *k*).
λ_{ck}	Intermediate variable- represents the weight of the chemical component *c* of the output $j = \lambda_k$ (order *k*).
Δ_{ck}	Intermediate variable- defines, for each component *c* of the output $j = \lambda_k$ (order *k*), the absolute gap between the weight of chemical component *c* of the optimal blend and a target value requested for order *k*.

In the following, some constraints are restricted by predicates, logical expressions which generally define the condition of the existence of a decision variable. A predicate, defined with operator " | ", serves to a pre-treatment of data and reduces drastically the number of constraints and variables and therefore the size of the mathematical problem and the necessary execution time. In our model, predicates concern either a technical constraint "$\mathrm{U}_{ih} = 1$" (possibility of using routing *h* for input *i*) or the available routings concerned by the constraint itself ($h \in \{...\}$). Predicate $t - \vartheta'_{ihr} \geq 1$ allows considering only the periods $t - \vartheta'_{ihr}$ belonging to the horizon T. Some variables or indices are restricted by a combination of predicates.

The model is formulazed as follow:

$$\mathrm{Min}(\mathrm{P}_1 + \mathrm{P}_2 + \mathrm{P}_3)$$

$$\text{with : } \begin{cases} \mathrm{P}_1 = \sum_{c,k} \sigma_c \cdot \Delta_{ck} \\ \mathrm{P}_2 = \sum_{i,h,k,t|\mathrm{U}_{ih}=1} \sigma'_{ih} \cdot \vartheta'_{ih} \cdot o_{ihkt} \\ \mathrm{P}_3 = \sum_{i,h,k,t|\mathrm{U}_{ih}=1} (\sigma''_h + \sigma'''_{em}) \cdot x_{ihkt} \end{cases} \qquad (1)$$

- P_1 focuses on the quality of the finished product, through the minimisation of a penalty related to the gap Δ_{ck}.
- P_2 concerns the mobilisation of resources through the prioritisation of the use of some configurations among others. For example, if the head manager wants first to prioritise emptying stocks downstream washing plants, coefficients σ'_{ih}, such that (*i,h*) corresponds to configurations 4 or 5, take higher values. This part of the objective function and specifically the penalty σ'_{ih} allows managing resources mobilisation, managing/ prioritising the consumption of inputs, prioritising the use of stocks, and the use of routings.

  We attribute some arbitrary high or low penalties for $\sigma_c, \forall c$ and $\sigma'_{ih}, \forall i, h$ depending on the importance giving by managers to each component *c* of each order *k* or for each production configuration (*i,h*).

- P_3 is related to managing costs related to the use of routings h, σ''_h and the cost σ'''_{em} of the adopted extraction method.

Subject to:

$$D_k = \sum_{i,h,t|U_{ih}=1} x_{ihkt} \cdot \eta_{ih}, \forall k \quad (2)$$

Each order k is satisfied in terms of quantities thanks to relation (2). The initial quantity x_{ihkt} of input i is reduced to $x_{ihkt}.\eta_{ih}$ if routing $h>1$ is used.

$$\varpi_{ck} = \sum_{i,h,t|U_{ih}=1} x_{ihkt} \cdot \eta_{ih} \cdot \alpha_{ic} \cdot \omega_{hci}, \forall c,k \quad (3)$$

The composition in each chemical component is calculated in relation (3). The weight of component c in the order k depends on the quantities of inputs to use, the chemical characteristics of each chosen input α_{ic}, the weight reduction rate η_{ih} as well as the chemical enrichment rate ω_{hci} related to the routing h. Note that the variable x_{ihkt} exists only if routing h can be used for input i.

$$\beta^{\min}_{c\lambda_k} \cdot D_k \le \varpi_{ck} \le \beta^{\max}_{c\lambda_k} \cdot D_k, \forall c,k \quad (4)$$

Relation (4) represents the quality charter constraint for each order k. The chemical weight ϖ_{ck} of component c in the blend has to respect the quality constraint defined by intervals $\left[\beta^{\min}_{c\lambda_k};\beta^{\max}_{c\lambda_k}\right]$.

$$\sum_{h|U_{ih}=1} o_{ihkt} \le 1, \forall i,k,t \quad (5)$$

Relation (5) prevents the use of more than one routing for one given input i used to produce order k in period t.

$$\begin{cases} 0 \le y_{ihkt} \le 1 \\ y_{ihkt} = \dfrac{x_{ihkt}}{\mathrm{M}} \quad \forall i,h,k,t \\ y_{ihkt} \le o_{ihkt} \end{cases} \tag{6}$$

$$\begin{cases} z_{ihkt} = \dfrac{x_{ihkt}}{\mathrm{N}} \quad \forall i,h,k,t \\ z_{ihkt} \ge o_{ihkt} \end{cases} \tag{7}$$

Relations (6) and (7) take into account the minimum (N) and maximum (M) quantities to use for each chosen and treated input *i* per period. Those relations reflect the two following properties: $x_{ihkt} = 0 \Leftrightarrow o_{ihkt} = 0$ and $\mathrm{N} \le x_{ihkt} \le \mathrm{M} \Leftrightarrow o_{ihkt} = 1$.

$$\mathrm{E}_k.o_{ihkt} \le (t + \vartheta_{ih}).o_{ihkt} \le \mathrm{L}_k.o_{ihkt}, \forall i,h,k,t \tag{8}$$

Each customer order *k* has to be satisfied during a specific time interval, with the earliest and latest docking dates of the ship, transporting the products to the customer, from the port (relation (8)).

$$\sum\nolimits_{i,h,k | i \in \mathrm{I}_r \wedge \mathrm{U}_{ih}=1 \wedge t-\vartheta'_{ihr} \ge 1} x_{ihk,t-\vartheta'_{ihr}} \le \rho_r \cdot \phi_{rt}, \forall t, r \mid r \in \{1,3,4\} \tag{9}$$

$$\begin{aligned} &\left(\sum\nolimits_{i,h,k | i \in \mathrm{I}_r \wedge h \in \{2,..,4\} \wedge \mathrm{U}_{ih}=1 \wedge t-\vartheta'_{ihr} \ge 1} x_{ihk,t-\vartheta'_{ihr}} \cdot \eta_{ih}\right) + \\ &\left(\sum\nolimits_{i,h,k | i \in \mathrm{I}_r \wedge h=1 \wedge \mathrm{U}_{ih}=1 \wedge t-\vartheta'_{ihr} \ge 1} x_{ihk,t-\vartheta'_{ihr}}\right) \le \rho_r \cdot \phi_{rt} \\ &\forall t, r \mid r \in \{2,5\} \end{aligned} \tag{10}$$

$$\begin{aligned} &\sum\nolimits_{i,h,k | i \in \mathrm{I}_r \wedge h \in \{2,3,4\} \wedge \mathrm{U}_{ih}=1 \wedge t-\vartheta'_{ihr} \ge 1} x_{ihk,t-\vartheta'_{ihr}} \le \rho_r \cdot \phi_{rt}, \\ &\forall t, r \mid r \in \{6,7,8\} \end{aligned} \tag{11}$$

Relations (9) to (11) prevent the use of more capacity than available for each resource *r* at each period *t*. The time index in x_{ihkt} has to take into account the transit time from the stock of input *i* to resource *r* if routing *h* is involved. Hence, an input collected at period *t* is delivered to resource *r* at period $t + \vartheta'_{ihr}$.

Relation (9) (resp. relation (10)) concerns conveyors $r \in \{1,3,4\}$ (resp. $r \in \{2,5\}$). The total quantity treated in each enrichment line of the washing plants should not exceed its maximum daily capacity, which is reflected by relation (11) for $r \in \{6,7,8\}$.

$$\mathrm{S}_{i,0} = \mathrm{S}_i^{init}, \forall i \tag{12}$$

Relation (12), considers the initial stock related to each input i at period t=0.

$$\begin{aligned} &\mathrm{S}_{it} = \mathrm{S}_{i,t-1} + \mathrm{A}_{it} - \sum\nolimits_{h,k|\mathrm{U}_{ih}=1} x_{ihkt}, \\ &\forall t, i \,|\, i \in \{\mathrm{SO}_{\text{extraction\_plant}}\} \end{aligned} \tag{13}$$

$$\begin{aligned} &\mathrm{S}_{it} = \mathrm{S}_{i,t-1} - \sum\nolimits_{h,k|\mathrm{U}_{ih}=1 \wedge h\in\{2,3,4\}} x_{ihkt}, \\ &\forall t, i \,|\, i \in \{\mathrm{SO}_{\text{upstream\_washing\_plant}}\} \end{aligned} \tag{14}$$

$$\begin{aligned} &\mathrm{S}_{it} = \mathrm{S}_{i,t-1} - \sum\nolimits_{h,k|\mathrm{U}_{ih}=1 \wedge h=1} x_{ihkt}, \\ &\forall t, i \,|\, i \in \{\mathrm{WSO}_{\text{downstream\_washing\_plant}}\} \end{aligned} \tag{15}$$

$$\begin{aligned} &\mathrm{S}_{it} = \mathrm{S}_{i,t-1} - \sum\nolimits_{h,k|\mathrm{U}_{ih}=1 \wedge h=1} x_{ihkt}, \\ &\forall t, i \,|\, i \in \{\mathrm{SO\_WSO}_{\text{drying\_plant}}\} \end{aligned} \tag{16}$$

Relations (13) to (16) describe the behavior of each stock. It takes into account the state of stock over the previous period as well as the quantities consumed during the same period t, using the routing h. The expected supply program (provisional production program) A_{it} impacts the upstream stock of input i (SO) in relation (13).

Relations (14) to (16) take into account the state of the different stocks of the chain, apart from the ones belonging to the extraction plants.

$$\mathrm{S}_{it} \geq 0, \forall i, t \tag{17}$$

Relation (17) ensure that the stock of input i at each period t is positive (no shortage).

$$\left| \begin{aligned} &\Delta_{ck} \geq \varpi_{ck} - \mathrm{D}_k \times \tau_{c\lambda_k}, \forall c, k \\ &\Delta_{ck} \leq \varpi_{ck} - \mathrm{D}_k \times \tau_{c\lambda_k} \end{aligned} \right. \tag{18}$$

Relation (18) reflects, for each order k and each component c, the absolute gap Δ_{ck} between a target component weight and the weight of component proposed by the model.

5 Numerical illustration

To evaluate the impact of the mining supply chain redesign, a mathematical model (MILP class) for planning production activities is developed.

In this section, we present the general framework in sub-section 5.1 and the settings and technical data used in subsection 5.2. We discuss the results obtained and the contributions of this paper in the last subsection 5.3.

5.1 General framework

The main goal is to assess the impact of steering the SC from mines to loading final products on trains while considering the behavior of several chemical components characterising it.

We focus on the use of a provisional production program resulting from the use of a unique extraction method for all mines, and apply the same technique for all the existing extraction methods, to point out the impact on the obtained results.

As explained before, planning production activities depends on the supply of SO stocks which is directly linked to the extraction process (Figure 1). The deposit is organised into parcels, exploited to obtain a volume of phosphate rock with specific chemical characteristics belonging to one of seven input families. Those volumes and specific chemical characteristics depend on the extraction method used. The necessary time to access each phosphate layer depends on the necessary time to access all layers above. Based on those hypotheses, the parameter A_{it} is calculated for each extraction method (in tons of SO i supplied in period t).

The model determines, for a specific extraction method, the flows of products required at each period by order (each order concerning one MO). Each flow is characterised by the quantities of ingredients (SO or WSO) and a production path defined by the passage or not through washing plants. The followed procedure is represented in Table 3:

Steps	Actions
Step 1	A_{it} Calculation based on the chosen extraction method
Step 2	Initialisation of all parameters
Step 3	MILP optimisation
Step 4	Results
Step 5	Applying steps 1 to 4 to each extraction method
Step 6	Comparing results

Table 3. The followed procedure

5.2 Settings and technical data

Technical data were collected from the operational staff, considering five mines, two washing plants, a drying plant, 88 SOs (inputs, *i*), 6 orders (index *k* related to output *j*), 4 chemical components (index *c* linked to BPL, SiO_2, MgO, Cd) over 31 periods (days). Each order is characterised by a quality charter, a quantity, and a delivery period (Table 4 and Table 5).

Order k	Order 1	Order 2	Order 3	Order 4	Order 5	Order 6
Ordered output $j=\lambda_k$	1	7	5	7	5	2
Order quantity D_k	5000	5000	4800	4000	4800	3000
Latest delivery date L_k	12	9	18	22	25	23

Table 4. Specificities of orders

	$j=1$	$j=2$	$j=5$	$j=7$
$c=1$: BPL	65 < ... < 66	66.5 < ... < 67.7	69.38< ... < 71.04	69.92 < ... < 70.72
$c=2$: SiO_2	2.2 < ... < 3.9	2.8 < ... < 3.5	2 < ... < 3.5	1.7 < ... < 2.1
$c=3$: MgO	0.45 < ... < 0.65	0.45< ... < 0.65	0.38 < ... < 0.44	0.38 < ... < 0.48
$c=4$: Cd	18 < ... < 25	19 < ... < 25	17 < ... < 20	20 < ... < 22

Table 5. Chemical characteristics of MO

We consider that no storage capacity constraints exist, so we attribute to 0 the earliest date of order *k*, to broaden the interval of preparing MO. For a matter of confidentiality, reduction weight ,and enrichment rates, extraction, and enrichment costs are not presented.

5.3 Main results and analysis

The mathematical model is formulated with FICO's Xpress-IVE AML (Algebraic Modeling Language) and run on a Windows (R) server-12 vCPU, 64 Gb RAM, with an average execution time of less than 30 minutes. Recall that the objective function (cost minimisation) is composed of three parts: P_1: management of product quality, P_2: mobilisation of resources, P_3: extraction and enrichment costs.

The results obtained by the use of each extraction method are presented in Table 6. To avoid confusion, the input numbers are not listed in the table. Indeed, the same index *i* can correspond to inputs with different chemical compositions depending on the extraction method used. Table 7 resumes the obtained chemical composition of the 6 orders in the three extraction configurations.

Orders (k)	Selective method							Global method							Semi-global method						
	Input name and type	Source	h	t1	t2	Quantities (in ton)	$x_{ik} / \sum_i x_{ik}$ (%)	Input name and type	Source	h	t1	t2	Quantities (in ton)	$x_{ik} / \sum_i x_{ik}$ (%)	Input name and type	Source	h	t1	t2	Quantities (in ton)	$x_{ik} / \sum_i x_{ik}$ (%)
1	raw HTM	mine 2	2	6	9	1488,44	24,46%	raw TBT	mine 1	2	9	12	703,58	10,91%	raw TBT	mine 1	2	2	5	636,54	10,03%
	raw HTM	mine 2	2	8	11	3448,30	56,68%	raw BTR	mine 2	2	2	5	5489,17	85,12%	raw BTR	mine 2	2	2	5	5408,90	85,21%
	raw TBT	mine 3	2	9	12	210,18	3,45%	raw TBT	mine 5	2	7	10	155,75	2,42%	raw MT	mine 2	1	10	11	102,57	1,62%
	raw BT	mine 5	2	1	4	353,67	5,81%	raw BT	drying plant	1	2	2	100,00	1,55%	raw HTN	mine 2	1	10	11	100,00	1,58%
	raw BT	mine 5	2	6	9	483,54	7,95%								raw BT	drying plant	1	5	6	100,00	1,58%
	Washed TBT	drying plant	1	5	5	100,00	1,64%														
2	raw HTM	mine 1	2	5	8	2412,78	39,20%	raw BTR	mine 2	2	5	8	2975,28	48,00%	raw BTR	mine 2	2	6	9	2975,28	48,00%
	raw BT	mine 5	2	3	6	340,89	5,54%	raw THT	mine 2	1	7	8	100,00	1,61%	raw THT	mine 2	1	7	8	100,00	1,61%
	raw HTM	washing plant 1	2	4	7	3401,82	55,26%	raw HTM	washing plant 1	2	4	7	2823,07	45,55%	raw HTM	washing plant 1	2	1	4	2823,07	45,55%
								Washed HTM	drying plant	1	1	1	100,00	1,61%	Washed HTM	washing plant 2	1	1	1	100,00	1,61%
								Washed TBT	drying plant	1	2	2	100,00	1,61%	Washed TBT	drying plant	1	5	5	100,00	1,61%
								Washed BT	drying plant	1	9	9	100,00	1,61%	Washed BT	drying plant	1	1	1	100,00	1,61%
3	raw HTM	mine 1	2	6	9	2195,56	42,13%	raw HTM	mine 1	2	15	18	2195,56	42,13%	raw HTM	mine 1	1	16	17	738,78	14,54%
	raw THT	mine 1	1	1	4	1952,72	37,47%	raw THT	mine 1	1	14	15	1952,72	37,47%	raw HTM	mine 1	2	13	16	2004,47	39,45%
	raw MT	mine 3	1	2	3	804,66	15,44%	raw MT	mine 3	1	14	15	804,66	15,44%	raw THT	mine 1	1	13	14	2159,11	42,50%
	raw BT	mine 5	2	9	12	258,64	4,96%	raw TBT	mine 5	2	5	8	258,64	4,96%	raw HTN	mine 2	1	17	18	178,27	3,51%
4	raw HTM	mine 1	2	16	19	3605,75	78,36%	raw HTM	mine 1	2	14	17	3254,85	69,33%	raw HTM	mine 1	2	17	20	3254,85	70,90%
	raw HTN	mine 3	1	21	22	656,31	14,26%	raw HTN	mine 3	1	8	9	505,52	10,77%	raw HTN	mine 2	1	20	21	153,76	3,35%
	raw BT	mine 5	2	1	4	239,31	5,20%	raw TBT	mine 5	2	16	19	257,51	5,48%	raw HTN	mine 3	1	16	17	505,52	11,01%
	Washed BT	drying plant	1	22	22	100,00	2,17%	raw HTM	washing plant 1	2	21	24	676,93	14,42%	raw HTM	washing plant 1	2	5	8	676,93	14,74%
5	raw HTM	mine 1	2	9	12	2195,56	42,13%	raw HTM	mine 1	2	22	25	2195,56	42,13%	raw HTM	mine 1	1	23	24	738,78	14,54%
	raw THT	mine 1	1	18	19	1952,72	37,47%	raw THT	mine 1	1	13	14	1952,72	37,47%	raw HTM	mine 1	2	19	22	2004,47	39,45%
	raw MT	mine 3	1	7	8	804,66	15,44%	raw MT	mine 3	1	1	2	804,66	15,44%	raw THT	mine 1	1	23	24	2159,11	42,50%
	raw BT	mine 5	2	11	14	258,64	4,96%	raw BT	mine 5	2	22	25	258,64	4,96%	raw HTN	mine 2	1	24	25	178,27	3,51%
6	raw HTM	mine 2	2	4	7	2651,51	72,72%	raw HTM	mine 2	2	20	23	2862,62	76,11%	raw HTM	mine 2	2	11	14	2862,62	78,88%
	raw TBT	mine 3	2	5	8	432,02	11,85%	raw BT	mine 5	2	15	18	327,62	8,71%	raw HTN	mine 2	1	21	22	195,46	5,39%
	raw TBT	mine 3	2	6	9	195,38	5,36%	raw HTM	washing plant 2	3	1	4	571,13	15,18%	raw HTM	washing plant 2	3	15	18	571,13	15,74%
	raw BT	mine 5	2	18	21	267,34	7,33%														
	raw BT	drying plant	1	23	23	100,00	2,74%														

t1: Period of consuming inputs from stocks

t2: Period of arrivage of inputs in the drying plant

Table 6. The obtained solutions

Selective method	c=1: BPL	c=2: SiO2	c=3: MgO	c=4: Cd
Order 1	65.00	2.20	0.55	21.67
Order 2	70.00	1.78	0.41	21.00
Order 3	70.00	2.80	0.42	19.00
Order 4	70.00	2.09	0.42	21.00
Order 5	70.00	2.80	0.42	19.00
Order 6	67.00	2.80	0.64	21.68
Global method	c=1: BPL	c=2: SiO2	c=3: MgO	c=4: Cd
Order 1	65.00	2.48	0.45	20.50
Order 2	70.00	1.98	0.38	20.85
Order 3	70.00	2.80	0.42	19.00
Order 4	70.00	2.01	0.41	21.00
Order 5	70.00	2.80	0.42	19.00
Order 6	67.00	2.80	0.57	21.46
Semi-global method	c=1: BPL	c=2: SiO2	c=3: MgO	c=4: Cd
Order 1	65.00	2.51	0.45	20.43
Order 2	70.00	1.98	0.38	20.85
Order 3	70.00	2.80	0.43	19.00
Order 4	70.00	2.01	0.41	21.00
Order 5	70.00	2.80	0.43	19.00
Order 6	67.00	2.80	0.57	21.46

Table 7. The chemical characteristics of orders

For each extraction method, the mathematical model determines blendings that fulfill all orders in terms of the quality charter, quantity, and delivery time. In this specific case, the global method is the most accurate one with a minimum total cost of 2.06 M$ (2.16 and 2.09 respectively for the semi-global and selective methods).

As shown in Table 7 for a given order, component's weights may differ from one extraction method to another but respect anyway the quality charter. For the example of SiO_2 of order 1, the model proposes a solution with 2.20% for the selective method, 2.48% for the global method, and 2.51% for the semi-global, with a given target value of 3.20%.

Moreover, total input quantities differ from one method to another, and with the use of SO and WSO already stocked (see Table 6). The selective method consumes a lower quantity of inputs.

For this method, extracted SO don't need generally a lot of treatment in washing plants, because they were extracted separately from non-phosphate products. Lower costs of enrichment are then generated. The global and semi-global methods consume more input quantities because SO were extracted in a mixed way with non-phosphate layers and need enrichment in washing plants. Therefore, more enrichment costs are generated.

This observation highlights the necessary trade-off between mines and washing plants costs.

5.4 Sensitivity analysis

The three parts of the objective function (P_1: costs of quality, P_2: resources, and P_3: production costs) are combined to ensure satisfaction for both sides: customers, and the company itself.

To illustrate the impact of those three parts, we realise several tests, while considering null production costs in case I (P_2 and P_3 of the objective function are null), and null deviance penalties in case II (P_1 is null). Roughly speaking, case I focuses on the client's expectations (target value of each component) while case II focuses on production optimisation. All the other parameters of the previous illustrations are identical. Table 8 and Table 9 present respectively results for cases I and II, where all orders requirements are fulfilled.

Results of the case I show that the most used configurations are those mobilising washing plants, consequently requiring more time and resources. In this case, the main concern is fully satisfying customers' needs (as close as possible to component targets), without caring about the generation of production costs. In this case, the supply chain can emphasise its ability to provide a MO of homogeneous composition for several orders of this MO. The selective method is the least expansive one, that is, the optimal blends have compositions closest to the target values expected by the clients. This method requires also the least total inputs quantity.

In case II, production steering gives priority to configurations that don't require enrichment or at most, require a simple wash, because the objective function of this case is based on minimising production costs. The global method provides the best economic result.

Orders (k)	Global method			Semi-global method			Selective method		
	Input family	Production routings (h)	Quantities (in ton)	Input family	Production routings (h)	Quantities (in ton)	Input family	Production routings (h)	Quantities (in ton)
1	raw TBT	h=2: SW	6450,66	raw TBT	h=2: SW	6450,66	raw HTM	h=2: SW	6048,57
	raw TBT	h=2: SW		raw BTR	h=2: SW		raw HTM	h=2: SW	
	raw BTR	h=2: SW		raw BTR	h=2: SW		raw TBT	h=2: SW	
	raw BTR	h=2: SW		raw BTR	h=2: SW		raw BT	h=2: SW	
	raw TBT	h=2: SW		raw BT	h=2: SW		raw BT	h=2: SW	
	Washed BT	h=1:NE		Washed BT	h=1:NE		Washed TBT	h=1:NE	
	Washed TBT	h=1:NE		Washed TBT	h=1:NE				
2	raw BT	h=4: WFG	6336,59	raw BT	h=4: WFG	6336,59	raw HTM	h=2: SW	6148,2
	raw BTR	h=2: SW		raw BTR	h=2: SW		raw MT	h=3: WF	
	raw HTM	h=2: SW		raw HTM	h=2: SW		raw BT	h=2: SW	
	Washed HTM	h=1:NE			h=1:NE		raw HTM	h=2: SW	
3	raw BTR	h=2: SW	5415,73	raw HTM	h=2: SW	5790,04	raw HTM	h=2: SW	5541,71
	raw BTR	h=2: SW		raw BTR	h=2: SW		raw HTM	h=2: SW	
	raw THT	h=1:NE		raw MT	h=2: SW		raw BTR	h=2: SW	
	raw MT	h=1:NE		raw MT	h=2: SW		raw HTM	h=2: SW	
	raw MT	h=2: SW		raw HTM	h=1:NE		raw BTR	h=1:NE	
	raw HTN	h=1:NE		raw TBT	h=3: WF		raw BTR	h=2: SW	
							raw HTM	h=1:NE	
							raw TBT	h=3: WF	
							Washed HTM	h=1:NE	
4	raw HTM	h=2: SW	5672,83	raw HTM	h=2: SW	5672,83	raw HTM	h=2: SW	4870,17
	raw MT	h=3: WF		raw MT	h=3: WF		raw HTM	h=2: SW	
	raw TBT	h=4: WFG		raw MT	h=3: WF		raw MT	h=3: WF	
	raw TBT	h=4: WFG		raw TBT	h=2: SW		raw MT	h=3: WF	
	raw BT	h=2: SW		raw TBT	h=4: WFG		raw BT	h=2: SW	
	raw HTM	h=2: SW		raw TBT	h=4: WFG		raw HTM	h=2: SW	
				raw TBT	h=4: WFG				
				raw HTM	h=2: SW				
5	raw BTR	h=2: SW	5475,91	raw HTM	h=2: SW	5905,28	raw BT	h=4: WFG	5856
	raw THT	h=1:NE		raw BTR	h=2: SW		raw HTM	h=1:NE	
	raw MT	h=1:NE		raw BTR	h=3: WF		raw BTR	h=2: SW	
	raw MT	h=2: SW		raw HTM	h=2: SW		raw HTM	h=2: SW	
	raw MT	h=2: SW		raw MT	h=2: SW		raw MT	h=2: SW	
				raw MT	h=2: SW		raw MT	h=2: SW	
				raw HTM	h=1:NE		raw MT	h=2: SW	
				raw TBT	h=3: WF		raw MT	h=2: SW	
							raw TBT	h=3: WF	
6	raw HTM	h=2: SW	3761,11	raw HTM	h=2: SW	3629,21	raw HTM	h=2: SW	3646,24
	raw HTM	h=2: SW		raw HTN	h=1:NE		raw HTM	h=2: SW	
	raw TBT	h=2: SW		raw TBT	h=3: WF		raw TBT	h=2: SW	
	raw BT	h=2: SW		raw TBT	h=3: WF		raw TBT	h=2: SW	
	raw TBT	h=3: WF					raw BT	h=2: SW	
							Washed BT	h=1:NE	
	P1 = 633 089			P1 = 633 089			P1 = 496 850		

Table 8. Case I results (clients focus)

Orders (k)	Global method			Semi-global method			Selective method		
	Input family	Production routings (h)	Quantities (in ton)	Input family	Production routings (h)	Quantities (in ton)	Input family	Production routings (h)	Quantities (in ton)
1	raw BTR	h=2: SW	5443,21	raw BTR	h=2: SW	5257,22	raw HTM	h=2: SW	5378,17
	raw MT	h=1:NE		raw HTN	h=1:NE		raw HTM	h=1:NE	
	raw THT	h=1:NE		raw THT	h=1:NE		raw THT	h=1:NE	
	raw TBT	h=2: SW		raw BT	h=1:NE		raw BT	h=2: SW	
	raw BT	h=1:NE		Washed TBT	h=1:NE				
	Washed TBT	h=1:NE		Washed BT	h=1:NE				
	Washed BT	h=1:NE							
2	raw BTR	h=2: SW	6017,55	raw BTR	h=2: SW	6017,55	raw HTM	h=2: SW	5733,64
	raw THT	h=1:NE		raw THT	h=1:NE		raw HTM	h=2: SW	
	raw BT	h=2: SW		raw BT	h=2: SW		raw HTN	h=1:NE	
	raw HTM	h=2: SW		raw HTM	h=2: SW		raw BT	h=2: SW	
3	raw THT	h=1:NE	4867,75	raw THT	h=1:NE	4800	raw THT	h=1:NE	4867,75
	raw THT	h=1:NE		raw HTN	h=1:NE		raw THT	h=1:NE	
	raw MT	h=1:NE		raw THT	h=1:NE		raw MT	h=1:NE	
	raw BT	h=2: SW					raw BT	h=2: SW	
4	raw HTM	h=2: SW	4586,92	raw HTM	h=2: SW	4484,34	raw HTM	h=2: SW	4586,92
	raw HTN	h=1:NE		raw HTN	h=1:NE		raw HTN	h=1:NE	
	raw TBT	h=2: SW		raw HTN	h=1:NE		raw BT	h=2: SW	
5	raw THT	h=1:NE	4867,75	raw THT	h=1:NE	4800	raw THT	h=1:NE	4867,75
	raw THT	h=1:NE		raw HTN	h=1:NE		raw THT	h=1:NE	
	raw MT	h=1:NE		raw THT	h=1:NE		raw MT	h=1:NE	
	raw BT	h=2: SW					raw BT	h=2: SW	
6	raw HTM	h=2: SW	3246,90	raw MT	h=1:NE	3143,88	raw HTM	h=2: SW	3201,64
	raw MT	h=1:NE		raw HTM	h=2: SW		raw MT	h=1:NE	
	raw THT	h=1:NE		raw HTN	h=1:NE		raw THT	h=1:NE	
	raw BT	h=2: SW		raw THT	h=1:NE		raw BT	h=2: SW	
							raw BT	h=1:NE	
							Washed TBT	h=1:NE	
							Washed BT	h=1:NE	
	P2 = 22500 P3 = 1 270 000			P2 = 16000 P3 = 1 340 000			P2 = 22500 P3 = 1 430 000		

Table 9. Case II results (SC focus)

		TBT	BT	BTR	MT	HTN	HTM	THT
Case I	Selective method	1.59%	5.78%	13.70%	8.99%	51.20%	0.00%	0.00%
	Semi-global method	12.41%	0.97%	33.53%	5.91%	32.56%	0.58%	0.00%
	Global method	11.26%	1.38%	40.56%	7.74%	18.56%	0.72%	10.03%
Case II	Selective method	0.00%	5.79%	0.00%	7.38%	45.96%	6.86%	29.89%
	Semi-global method	0.00%	0.35%	10.46%	1.09%	26.26%	4.34%	46.06%
	Global method	1.77%	2.60%	11.59%	21.36%	26.17%	3.01%	26.32%

Table 10. Input family's analysis

A final analysis can be made on the input families used (summarised in Table 10). Depending on the weight given to the customer's target value, the optimal blends will draw more or less on rich-phosphate ores (HTN, HTM, and THT). Those ores are of considerable importance in the management of the SC. Firstly, they are relatively less found in the deposits. Secondly, they are generally reserved for the production of particular MO(s). In any case, the results show that it is possible to satisfy the orders book by using a few phosphate-rich ores, even if it degrades the total deviation penalty cost.

6 Managerial insights

The mining SC is redesigned via a new planning approach. It is based on integrating changes in extraction, enrichment, and blending logics. As mentioned previously, the current management mode of the supply chain is based on the use of a unique extraction method and fixed blending recipes to prepare each final product. The customer satisfaction becomes challenging for the site when customers become discerning in terms of product quality and their requirements may change in terms of specificities from one order to another. Our paper is the result of an original solution proposing several changes in the management mode to better satisfy customers' needs at lower production costs. The proposed solution allows a redesign of the management mode by moving from fixed and frozen production techniques to flexible ones and by comparing the impact of three existing extraction methods. The table 11 represents a summary of the redesign decisions integrated to the mining SC studied and their impact on the supply chain.

Table 11. Elements of the adopted redesign

General objectif of the redesign	Redesign decisions	Supply chain before redesign	Supply chain after redesign
Adopting an efficient and effective management mode to customer requirements at a lower cost	Flow control based on the impact of production operations on the behaviour of several chemical elements characterizing products quality	Difficulties to respect the quality charter with flow management based on BPL mainly	Quality charter perfectly respected in terms of several chemical elements
	Use of dynamic manufacturing recipes instead of frozen ones	Difficulties to respect the quality charter, with the use of predefined SO to produce efficiently	Respect of Quality charter while using flexible and dynamic recipes and preparation of orders according to the state of the chain and the orders to satisfy
	Possibility of changing extraction methods instead of using a fixed one depending on demand and mine state	Neglect of the impact of extraction methods on the satisfaction of customer requirements in terms of quality	More flexibility in customer order preparation through the testing the impact of several extraction methods

The main novelty of the paper is the consideration of the redesign concept with a new angle of attack, since it proposes changes applied to a mining context and it considers all the SC stages (extraction, treatment and blending) with specific aspects of each one in making decisions and ensuring an integrated planning of production activities. The extraction phase is crucial because it provides the raw material, which should be of specific caratertistics and basically the extraction methods/techniques can create the differences in those characteristics. The treatment and the blending phases are complementary to the extraction one, allowing through the dynamic approach proposed to prepare MOs while choosing quantities of ingredients and routings that change depending on the available raw material and customer requirements. The management of product quality is a very challenging task in the mining sector, the proposed approach helps in making decision in all the SC stages to ensure product quality requested by customers.

The proposed work supports managers to easily compare scenarios and take decisions to guarantee different aspects that we illustrate with the results of the global method:

- **Flexibility:** For each MO, the optimal blend changes over time and depends on the availability of SOs and infrastructures. Since the chemical characteristics and quantities of the available SOs differ from one month to another, the ingredients used, the production configurations, and the treatment routing for each MO differ (figure 4 represents the optimal blends for two orders of the same final product, which differ in quantities and delivery time intervals).

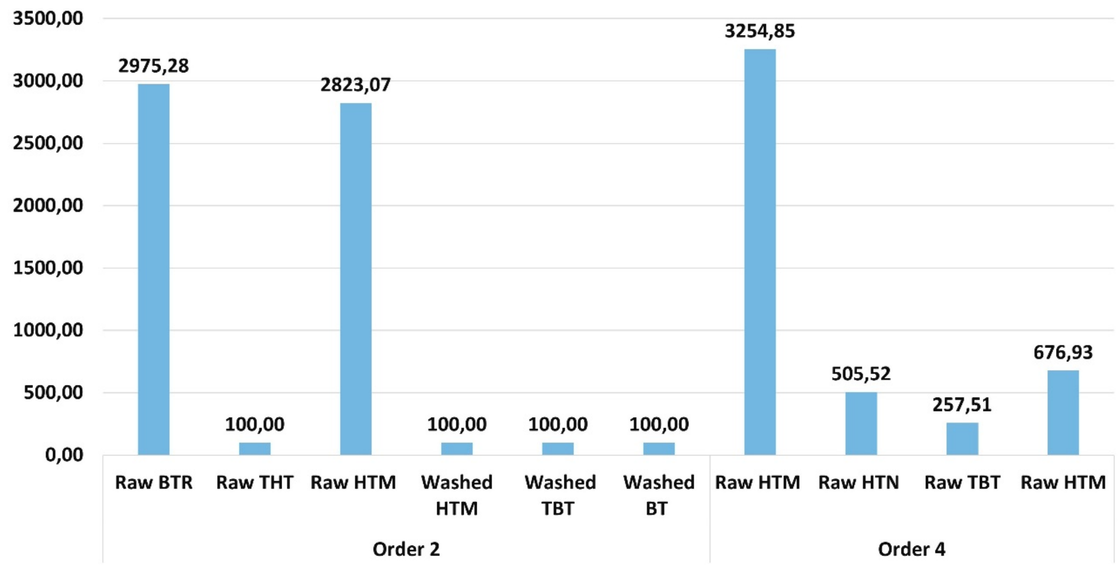

Figure 4. Dynamic blending illustration

- **Quality:** the finals products (MOs) obtained by the model fulfill all requirements in terms of chemical components for all extraction methods (quality charter). In the current organization based on fixed recipes, the planner has to reserve some "Rich BPL" SOs because this kind of SOs appears in recipes. Their unavaibility may lead somehow to a delay in delivering products or uncertainties in satisfying product quality requierements by adopting non experienced or new recipes proposed manually. Our dynamic approach has the advantage of potentially offering a blending solution depending on the ores available. One of this mining companie's strategies is the "preservation of scarce resources". In our model, with the penalty pattern adopted in the objective function, planning managers can prioritise the use of resources.
- **Efficiency:** The dynamic approach ensures satisfying customer requierements while mobilising minimum resources, by finding the possible combinations of SOs and routings, whatever the infrastructure state is. Then, our approach guarantees an efficient steering mode, through being able to propose the least expensive production programs while achieving the objective of customer satisfaction. Moreover, in case of unexpected orders (downstream the SC), unavailability of resources (process), or needed SO in the

deposit (upstream the SC), managers can test new solutions via our model with new parameters entries (especially as the calculation time is relatively short).

- **Vertical alignment**: The proposed approach highlights the interest of a vertical coordination between the different entities of the SC, in ensuring efficiency. Those entities work in complementary to each other for an objective of satisfying customers at minimum global production costs, which makes the decisions based on tradeoffs search. Currently, this SC operates as a push decision-making system. Combining extraction and processing stages at a tactical level should help managers to define the best extraction mode and production recipes, such as the global cost of the SC is minimised.

7 Conclusion and perspectives

This paper proposes the redesign of a phosphate mining SC to improve customer satisfaction while mobilising fewer resources. In this industrial case, one of the major challenges is to satisfy discerning customer requirements in particular, in terms of chemical composition of MOs. Since the current management mode of flows and planning doesn't allow so, we proposed an original redesign approach dealing with blending and enrichment techniques, and justifying the interest in considering the impact of the extraction phase in satisfying customer needs, for an integrated planning of production activities.

This redesign approach ensures a flexible and reactive management mode that fully satisfies customer requirements efficiently, through the development of a mathematical model, which takes into account decisions of extraction of the upstream chain.

Thus, the model laids the fondations of a future decision-support system for determining the tactical plan of the integrated mining supply chain. The industrial partner has approved this clinical approach and praised its relevance. Even if this study is focused on one specific supply chain, the issue of the impact of extraction methods on the downstream part of the chain, as well as of dynamic blending, arise in other mining industries. In appendix, we have added a list of some mining companies around the world having a production process composed of extraction, blending and processing raw materials to produce the final product as the one of the studied company. In this way, our approach can be a useful and adaptable basis for other SC.

Finally, perspectives are threefold: (i) a more accurate cost analysis would allow a more detailed analysis of the trade-off between upstream the SC and processing plants, (ii) consideration of other types of orders (shipped via pipeline) to allow a global vision of the studied site of OCP Group, and (iii) vertical alignment requires the development of a global information system providing reliable information at all levels of the chain: information related to extraction (composition of SO, dates of availability), processing (enrichment and yield of each routing), and forecasts generating the orders book.

8 Disclosure statement

The authors report there are no competing interests to declare.

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10 Appendix

Table 12. Examples of mining industries adopting extraction, blending and processing in their production process

Company name	Type of ore produced	Multiple routings + Blending	Sources
BHP Billiton	Copper, Metallurgical coal, Nickel, Potash, Iron ore	Multiple routings and always same: flotation, grinding, leaching concentrating	https://www.bhp.com/what-we-do/products/copper
Ma'aden	Phosphate, Gold Aluminuim,and base metals, industrial minerals	Alternative routings : flotation, refining grinding, leaching, concentrating	https://www.maaden.com.sa/en/business/
Nutrien	potash, phosphate	Alternative routings: screening, washing, floating, dewatering, calcination. For potash, routings are always the same: crushing, grinding, desliming, flotation, drying and sizing, compaction, crystallization	https://www.nutrien.com/what-we-do/our-business/
Vale S.A.	Iron, Nickel, Manganese and ferroalloys, Copper,	Alternative routings depending on the quality of the ore	https://www.vale.com/w/vale-inaugurates-pilot-plant-that-allows-for-more-sustainable-mining
Glencore	Copper, Nickel Zinc & Lead, (Cobalt, Ferroalloys Other metals & minerals)	Alternative routings: for Nickel, grinding, flotation, drying, smelting, and refining for zinc and lead ore. For copper, crushing, grinding, flotation, leaching, and melting	https://www.glencore.com/what-we-do/metals-and-minerals/
Anglo American	Copper, Steelmaking Coal (Nickel Platinum group metals, Diamonds, Iron ore Manganese, Polyhalite)	Grinding, concentration using gravity separation for coal, flotation for copper,	https://www.angloamerican.com/about-us/what-we-do
Newmont Mining Corporation	Gold, silver	Alternative processing methods, depending on the ore, heating, heap leaching, flotation, gravity circuit	https://www.newmont.com/about-us/about-mining/the-mining-process/default.aspx
First Quantum Minerals	Iron Copper Gold zinc, pyrite	Alternative routings, choosing between: crushing, grinding, leaching, flotation, filtering, depending on the type of mineral and the need	https://www.first-quantum.com/English/our-operations/
Norilsk Nickel (ee)	Nickel, Palladium, Copper Platinum, Cobalt, Rhodium,	Mandatory and successive operations: Concentration, smelting, and refining,	https://nornickel.com/business/products/
KGHM Polska Miedź	Copper, Silver and other precious metals	Alternative routings, depending on ore types, sifting and crushing, milling and classifying, flotation, thickening and filtration, and drying.	https://kghm.com/en/our-business/mining-and-enrichment
AngloGold Ashanti	Gold	Alternative routings: crushing, milling, screening, and classification processes which are common, and then they choose the cyanide leaching process or heap leach process or flotation and oxidation	https://www.aga-reports.com/11/downloads/AGA-Gold-production.pdf
Kinross Gold Corporation	Gold	Alternative routings: Milling, heap leach, or milling and gravity or Milling, gravity, heap leach	https://www.kinross.com/operations/default.aspx