Managing Environmental Risks with Flexibility: Case of Phosphate Fertilizer Industry in Morocco

by

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Abstract

This thesis develops and demonstrates, in the context of environmental uncertainties, a process to 1. Quantitatively assess the effects of uncertainties on long-term enterprise performance, 2. Open the design space of strategic planning using real options to mitigate risks and take advantage of positive opportunities. Global warming, which is producing more frequent extreme weather events and driving in-depth societal transformations, increases the need to change usual habits of grounding strategic planning on deterministic forecasts, and pushes for realistic evaluation of potential results under uncertainties.

We use a screening model to reproduce enterprise cash-flows and evaluate its net present value under thousands of scenarios (Monte Carlo simulation). This high-level evaluation enables us to test different strategies and compare the distribution of potential outcomes. Overall, we can realistically explore a larger design space for strategic planning, and intentionally integrate flexibility in design with an understanding of potential gains and required preparation.

We apply the analysis to a case study inspired by OCP Group, the Moroccan major phosphate mining and fertilizer manufacturer. We examine the fluctuations of commodity markets, and the transformations led by environmental concerns. We recognize that environmental constraints can regionally change the systems of production, the demand, and could deeply impact global fertilizer markets.

We especially focus on the risks of an international over-supply, caused by potential drastic decrease in East Asian consumption, and a regional change in the requirements for phosphate rock (e.g., limitation in heavy metals concentration). These could create parallel markets and change the flow of production.

Our quantitative analysis indicates the desirability of exploring strategic drivers to complement the traditional price/volume approach. Flexible capacity expansion, in terms of both volume and type of products, coupled with a systemic allocation of production to markets across the industrial bandwidth (instead of a sales strategy by product line), could improve expected NPV significantly.

Thesis Supervisor: Richard de Neufville, Professor of Engineering Systems

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The (too short!) trip to Morocco last year was for me a great glimpse at OCP's activities, and the team I met there has been incredibly helpful for this work. The quality of our discussion during this whole journey has been remarkable, as well as the team's ability to question with us the different ways to approach strategical choices, markets dynamics, and uncertainties. I couldn't have had a better introduction to the research project and to the industry. I especially want to thank my direct contacts who welcomed us during our visit, at OCP: Nabil, Adil, Mohamed, Kassem, Ghada, and, at the EMINES - University Mohammed VI Polytechnique, Nicolas, and Imane, whom we were lucky to have with us during one semester at MIT.

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1. Introduction

As intensely illustrated at the time this thesis is being finished, under the global COVID-19 pandemic: *things happen*.

The example of a pandemic hitting the global economy and social systems with an unprecedented (and, at this point, still not entirely identified) magnitude might seem very extreme. Yet, in-depth incremental transformations in the long run also occur. Global warming has been an example of such transformation in the past century – now converting into a more disruptive trend, with an increasing frequency of extreme weather events. There is a need to recognize that the world as we know and describe it at a given time is perpetually already transforming into something different and unknown, carrying promises, and risks.

Recognizing those in-depth uncertainties is especially critical for large industrial companies, which have to plan heavy investments in long-lasting assets. What could be the major changes susceptible to transform a given business? When, with what intensity could those changes occur? How would the business react? And furthermore, what flexibility would the business possibly need to navigate those changes?

The motivation to think about flexible planning is first grounded in the existence of uncertainties in itself. Acknowledging uncertainty is a powerful step to evaluate a strategy more realistically, accounting for the inevitable changes of context that might happen, and to intentionally introduce flexibility in strategic design to mitigate risks and to be prepared to make the best of potential opportunities.

With this motivation, environmental concerns provide a ground for multiple, intertangled uncertainties, susceptible to deeply reshape industrial activities.

The notion of environmental concern is by itself unstable. The perception of environmental risks has been constantly evolving during the last century, and arguably more, going back at least to the premises of industrial development in the XIXst century[1]. Societal priorities are constantly evolving and, at a given period of time, produce different approaches to the articulation of the "environment" with human activities. However, the past decades have seen a broader consensus around the scientific analysis of global warming and its potential feedback on human activities, which has materialized progressively with the adoption, step-by-step and by pieces, of environmental protection goals in international and local institutions' agendas.

If the understanding of environmental concerns and the alignment with other strategic objectives is very variable from one institution to the other, the trend moving-forward seems to be an increasing scrutiny of the environmental impacts of human activities.

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[1] Historical example, see INERIS, 'Décret Impérial Du 15/10/1810 Relatif Aux Manufactures et Ateliers Qui Répandent Une Odeur Insalubre Ou Incommode. (Abrogé)', 2019 <https://aida.ineris.fr/consultation_document/3377> [accessed 1 May 2020]., (literally, « Act concerning unhealthy or unpleasant smells from manufactories and workshops »)

Coupled with this top-down transformation, driven by various institutions, environmental concerns are also shifting citizens / consumers practices and expectations, producing at the same time a bottom-up transformation. Uncertainties associated with environmental concerns are therefore particularly interesting to explore, resulting from the intersection of different trends in regulation, resource availability, economic considerations, and societal evolutions.

The resulting risks are distributed unevenly in different parts of the globe – with a dynamic of repartition that could totally change in the near term. The consequences in terms of demand or regulations are unknown by their scope, magnitude, and timeline of occurrence. These transformations, which can be viewed as the greatest challenge of the XXIst century, might very well restructure industrial activities at a global scale, in a not-so-far horizon.

Having set this perspective, the phosphate-fertilizers industry appears to be right at the intersection of many of the transformational forces in place.

Phosphate rock, and phosphate-based fertilizers are traded on global markets mostly as commodities, yet with a breakdown of local markets and international trade, and with some level of product differentiation specific to industrial mineral valued for their physical and chemical properties with a wide range of possible specifications. These global markets are highly exposed to environmental concerns: mineral fertilizers are seen today as strategic goods to achieve sufficient agricultural productivity. Agricultural systems are essential to increase food security while global population keeps growing[2], and in the United Nations' perspective, could do so by evolving toward "*resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality*."[3] The use and production of fertilizers seem to be potentially at the intersection of a sustainable transformation of the agricultural system, that could fundamentally change the demand and the market's structure, with emerging requirements to prevent pollution and negative externalities on the natural ecosystems (from mineral fertilizer's production or use).

Overall, this industry appears as a concentrate of industrial transformation, markets' evolution, and increasing levels of regulation worldwide, which makes it specifically adapted for our exploration. Scoping down to OCP Group, which inspires our case study's context, we furthermore observe those transformations, that have been complemented with an ambitious effort initiated in 2006 to rethink and shift the group's global position. From a pure mining industry posture, pushing the products to the market, the group has been transitioning to significantly increase its market share in the international phosphate-based-fertilizers markets. This transformation implies a more diversified production pulled from the demand, in addition to maintaining the historical strength in the phosphate rock international trade. This ongoing effort provides us with an opportunity to reflect about the industrial planning and suggest potentially new frameworks to quantitatively evaluate uncertainties and flexible strategies.

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[2] "World population projected to reach 9.8 billion in 2050, and 11.2 billion in 2100", The World Population Prospects: The 2017 Revision, published by the UN Department of Economic and Social Affairs.

[3] United Nations, 'UN Sustainable Development Goals', p. Goal 2: Zero Hunger <https://www.un.org/sustainabledevelopment/> [accessed 29 April 2020].

With the motivation to develop a realistic approach to strategic planning in the context of environmental risks, we use a case-study inspired by OCP group, major phosphate rock and phosphate-based fertilizer producer. What are the effects of uncertainties on the enterprise's long-term performance? What would be the promising options to manage the risks identified, based on the exploration of a wide-ranging strategic space?

We first reiterate with more depth the challenge and potential value that represents the acknowledgement of uncertainties in strategic planning, which is a mindset that might shake some of the existing practices (section 2). We then illustrate the type of uncertainties and range of variation that exist in commodity markets (section 3). A scope-down to OCP group is made to more precisely describe the system we want to consider, its boundaries and main value creating processes (section 4). We then explore comprehensively what are the environmental risks to this system, from the production side to the demand side, to finally synthetize the varied list of punctual areas of impact in four main structural uncertainties, and takeaway two specific risks susceptible to impact our system in the near term (section 5). Building on this framing of the context and of the system, we move to the case study (section 6), with the elaboration of the particular screening model designed to explore and answer our research question, providing a quantitative evaluation of the system's performance under thousands of scenarios (Monte Carlo simulation). Our conclusions, the limitation of the work done and recommendations for next steps are finally discussed (section 7).

2. The challenge and value of acknowledging uncertainties in strategic planning

> *"It is difficult to make predictions, especially about the future"*- unknown
>
> *"We like to think that we are constant … that we as human being, have a constancy […] we are constant item in a shifting world"* - Donella Meadows[4]

The idea that reality rarely meets the forecasts and the acceptance of a variation around any prediction seem broadly accepted. However, oftentimes, the practice of anchoring strategy in deterministic forecasts persists, and can be misleading.

It is usually well identified that models of prediction have margins of error, first because they intrinsically have to simplify the world they aim to reproduce. Moreover, input data have flaws, lack of accuracy or homogeneity, and might add an additional layer of error. Finally, unpredicted events and unknown recursive effects happen, changing the overall behavior of the system in a way not easily – if even possibly - predictable.

Overall, any forecast comes with a range of error, and with a necessarily limited vision of what could actually happen. The further is the time horizon, the wilder is usually the range of error. In addition, because systems are rarely linear, variations around the expected forecasts might not produce a comparable variation in the expected output: "average inputs" oftentimes do not lead to "average outcome", hence relying on an average input is not only unrealistic but also potentially misleading.

Future is by nature uncertain, and there is a need to deal with it: if the first part of this statement seems obvious, the second one is not and will require "*a new forecasting paradigm that focuses on understanding the range of circumstances that might occur*."[5] We illustrate in this first section the challenge it can be to acknowledge uncertainties in planning and to move the practice from trying to produce "the best possible forecast", which will always be unrealistic, to depicting and embracing the range of potential events.

We first present a common tool used to understand the competitive advantage of a producer of commodity goods compared to its competitors, however we underline the limitations of this tool when it comes to trying to anticipate market prices. Indeed, we list potential reasons that lead to a distortion of the theoretical demand / supply equilibrium. The take-away is finally to plant the idea that acknowledging uncertainties in strategical planning does require a deep change of common

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[4] Donella Meadows, 'Nature in Balance: A Vision', in *29th Annual Nobel Conference* (Audio record, 1993) <http://donellameadows.org/1993-nobel-conference-gustavus-adolphus-college/>.

[5] Richard de Neufville and Stefan Scholtes, *Flexibility in Engineering Design* (Cambridge, Massachusetts: MIT Press, 2011).

practices. Yet, this change is needed to achieve more realistic understanding of the potential outcomes of a strategic plan.

2.1. The Cost-curve, a “classic for understanding pricing” in the commodity markets

Commodities are basic resources such as raw material (e.g., crude oil, urea, aluminum, copper, phosphate rock) primary agricultural product (e.g., wheat, soybeans) or mass-produced unspecialized goods (e.g., chemicals, DAP fertilizer) that are roughly interchangeable across producing firms and can be bought and sold. The price is thus the most determinant market signal; the brand or provenance, being indifferent for the good’s use, have usually a lower importance - if any.

This section 2.1 presents the concept of a cost-curve, which can provide insightful information in the context of commodities and is broadly used to base capacity planning decision. Like any useful framework for analysis and assessment, it’s always important to remember that these instruments are simplifications of the real world, and to keep these limitations in mind when making use of them. We first present basically the theoretical constructs underlying the cost-curve and its potential practical application.

Brief overview of the formal constructs underlying a cost-curve

A cost-curve refers to the classification and representation of all producers {A, B, …, N}, in a given commodity market where goods are fungible, by their individual capacity of production (X-axis) and ranked by order of increasing cost of production per unit (Y-axis). A generic example is provided in Figure 1.

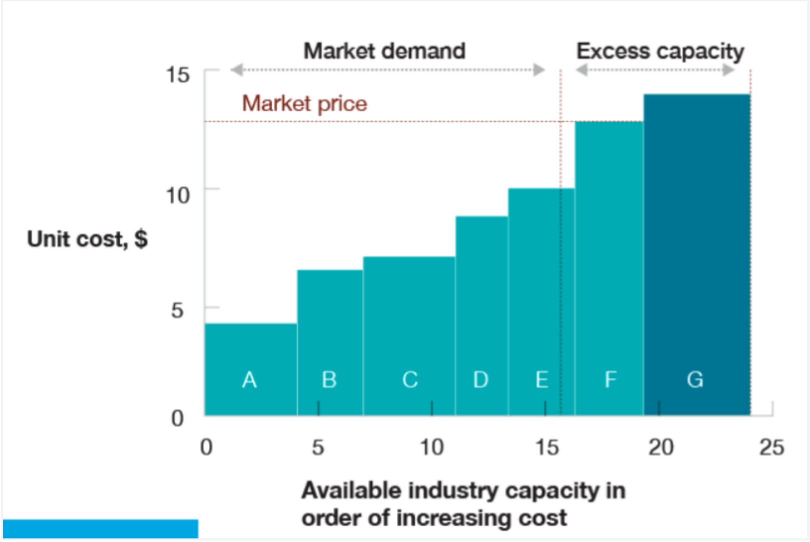

Figure 1: The industry Cost-curve, “a business school classic for understanding pricing” as represented in McKinsey Quarterly (screenshot, source Mc Kinsey[6])

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[6] Mc Kinsey, ‘Enduring Ideas: The Industry Cost Curve’, *McKinsey Quarterly*, 2009 <https://www.mckinsey.com/business-functions/strategy-and-corporate-finance/our-insights/enduring-ideas-the-industry-cost-curve#> [accessed 22 April 2020].

Identifying the consumption of the good (labelled on Figure 1 as “Market demand”) on the X-axis divides the producers: the left-side shows potential market suppliers, the right-side shows the excess capacity of production. The very strong underlying assumption is that the market price, which balances total supply and demand, will lie somewhere between the cost of the “marginal producer” (producer F in Figure 1) and the cost of the last potential market supplier (producer E in Figure 1) because, in an idealized competitive market, producers in excess capacity would not offer their production for a market-price lower than their production cost.

Potential applications

Figure 1 shows a generic example of a cost-curve picked in a McKinsey Quarterly’s article that explains further why this representation can be useful, highlighting also the limitations:

> *“Under many conditions, the level of demand for a product and the cost of the next available supplier’s capacity determine the market price. In theory, the industry cost curve allows companies to predict the impact that capacity, shifts in demand, and input costs have on market prices. In practice, however, a multitude of questions can muddy the waters. Do competitors have access to a number of markets? Will reinvesting profits in a product shift the market’s economics? Does the product’s real or perceived value differ among user segments? Faced with such complexities, before the 1980s many businesses relied on a gut-level approach to pricing.”*[7]

The production of cost-curve has become, since the 1980’s, a service offered by many consultancy groups, including CRU, Wood-Mackenzie, and S&P Global. The cost-curve can aggregate a considerable amount of detailed information, describing the competitive landscape in a given mining industries, at a specific time. For example, CRU on its website details the service that can be provided for the phosphate industry:

> *“Phosphate Rock Cost Service:*
> *Provides cost estimates 2008-19 at a plant and country level. This is accompanied by detailed analysis of the drivers of costs for benchmarking; global cost curves for site and business costs for business strategy and analysis of product premia & discounts for sales (based on products quality and distance to market).*
> *Granular data is downloadable over 100 mines covered producing phosphate rock (including generic profile regions in China), with detailed profiles and cost sheets for each plant. Up to 95% of the industry is covered”*[8]

Such information, organized in a cost-curve, can be a powerful tool to understand and represent the competitive position of a firm amongst its competitor at a given time: when it comes to evaluate the immediate decision of opening new capacities, a producer ideally wants to lie on the first

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[7] Mc Kinsey.

[8] CRU, ‘Cost Services’, *CRU Group Website*, 2020 <https://www.crugroup.com/analysis/cost-services/> [accessed 22 April 2020].

quartile of firms on the curve, which should provide a good reliability on the possibility to sell the production at a price higher than the production cost.

A very tempting step is then to link the cost-curve, which provides a market price setting mechanism as presented in Figure 1 above, to the actual price observed in the markets[9], and moreover to use this concept to ground or discuss short-term or long-term forecasts of this price.

However, we illustrate in appendix 9.9 page 95 the difficulty to actually link a market price with the industry cost-curve, based on two representations extracted from a presentation made by Phosagro. The first graphic ("Fertilizer price performance", Figure 38) provides a selection of different events susceptible to impact market price: those events illustrate individual decisions that make sense for each stakeholder at a given time with a given strategy, but might not match the "rational behavior" as expected in a pure economic sense. We then see on the example of a DAP cost-curve that only placing the market price on the cost curve, including the range of variation due to transportation, produces a wide variation on the supply-axis, even before considering the range of uncertainty existing for each firm's actual production and cost.

We discuss in the next paragraph different reasons why using the cost-curve requires caution when used to explain, and moreover to forecast, market prices.[10]

2.2. Structural disturbances of theoretical price-setting market mechanisms

Limitations of a cost-curve when it comes to understand market prices at a given time

There is first a need to disconnect different notions that are intertangled when the cost-curve is used to explain market prices.

- The industry cost-curve describes the estimated cost of producing a specific quantity of product (production) under a specific set of circumstances, given the breakdown of costs of production, per available capacities of production.
  The production is the amount that a firm or a set of firms generate and put on the marketplace.
  On the other side on the marketplace, the consumption is the amount that the market consumes or has demonstrably purchased, at some point in time.
  Both production and consumption are measurable notions that happen in the real world.
- The notion of supply curve, in economics, represents the relationship between the product price and the quantity of product that a firm or a set of firms is willing to supply, in a competitive market, to reach a cost-minimizing output.
  The notion of market equilibrium then links supply and demand through the price mechanism.
  In the supply curve perspective, supply is a dynamic function of price that gives the optimal amount of product that an industry should produce. Demand is a dynamic function of price that gives the optimal amount of a good that a market will want. Both supply and demand

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[9] Pierre-Noël Giraud, *Economie Des Phosphates* (Paris: Presse des Mines, 2017).

[10] presentation largely grounded in a work-in-progress from and discussion with Dr. Frank R. Field, Materials Systems Laboratory, MIT (ongoing in April 2020). See also appendix

> are formal constructs, coming with a specific context of assumptions and simplifications, especially the simplified notion of pure rationality, to demonstrate the mechanisms of market equilibrium.

We list and briefly describe thereafter three major flaws that might come with using the cost-curve to depict theoretical market mechanisms and a supply at a price.

The notion of cost, in which is grounded each individual decision to produce as assumed in the cost-curve perspective, is in itself complex. There is a cautious step to be made before linking it to theoretical price as described in the supply-curve approach (1/). In addition, market-players have very tangible reasons to decide their actual production based on broader considerations than the pure economic "rationality". The production in reality differs from the theoretical supply resulting from a cost-minimizing optimality (2/). Last, competitive markets are not perfect (3/), which adds to the potential distortion of price setting mechanisms in reality.

1/ "Cost" is not as simple at it might look...

The first difficulty is to define the notion of cost, and to model it consistently across different firms with various contexts and systems of production. Cost, in reality, is more complex that its theorization in the supply-curve approach, as a simple function of the quantity of output assuming a cost-minimizing allocation of factors of production.

There are many different ways to define a production cost, all equally valid: based on net operating cost, cash cost, or economic cost, which illustrate the range of industrial objectives (profitability, or potentially cost coverage, or even firm survival only) that can be implied in a cost analysis, beyond only the physical cost of production[11]. In fact, cost can be seen as not only a simple intrinsic property of a good, but as an emergent property that requires to consider the good in its broader context, especially the ways the product is produced and the market that it operates within[12].

2/ Market players have more complex agendas than the simple economic "rationality"

The underlying notion in the industry cost-curve that a firm would stop production at a market price lower that its operating cost is commonly challenged in reality.

A very recent example is the crude oil price amid the COVID-19 pandemic (Figure 2 below): various forces (including but not limited to geopolitics, trade mechanisms and supply contracts, delayed feedbacks between demand drops and production adjustment) drive individual decisions. Firms have to operate under considerably more complex conditions than in the theoretical context of "rational" economic agents.

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[11] Robin G. Adams, 'Managing Cyclical Businesses', *Resources Policy*, 17.2 (1991), 100–113 <https://doi.org/10.1016/0301-4207(91)90034-S>.

[12] Frank Field, Randolph Kirchain, and Richard Roth, 'Process Cost Modeling: Strategic Engineering and Economic Evaluation of Materials Technologies', *JOM*, 59.10 (2007), 21–32.

WTI crude, adjusted for inflation, plotted weekly • Source: Refinitiv • By The New York Times

Figure 2: WTI crude oil went briefly negative: illustration of geopolitical forces, trade mechanisms (contracts) or delayed feedbacks undermining a "rational" adaptation of production.[13]

At any given time, many different reasons can jointly or partly explain apparently "non-rational" decision making (in the economic sense of "rational") from producers in markets and deepen the gap between the theoretical perspective of a supply curve and the actual production.

For example, a low-cost producer with important volume of production and market-share could be willing to maintain a high level of production, driving lower cost, to prevent new competitors from entering the market. In a more fragile situation, with higher cost of production and / or lower volume, a given firm can nevertheless not shut-down its production when prices fall: the need to keep amortizing an asset, retain the workforce, or even governmental strategies, might support temporarily their activity amid low prices. Besides, contractual obligations, either to labor or to suppliers, rents, royalties, create "semi-fixed" cost that can also come into play. On the other hand, when prices rise, each firm is tempted to increase its production compared to the theoretical cost-minimizing output, overall creating extra-supply compared to the cost-curve and instability on price (drawn down).

Introducing the uncertainties related to the choices of production at the firm's level on a cost-curve illustrates the impact those individual decisions, not necessarily fitting the theoretical behavior of firms from the pure economic standpoint, have on the level of potential price. A simple example is provided in appendix 9.10 Illustration of the possible fuzziness of a cost-curve.

3/ And competitive markets are not so perfect…

Last, at the economic market's level, the notion of perfectly competitive markets, relying on assumptions that include perfect information, no information asymmetries, no transaction costs, have well-established limits: specifically, the field of Industrial Economics offers different

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[13] Stanley Reed and Clifford Kraus, 'Too Much Oil: How a Barrel Came to Be Worth Less Than Nothing', *The New York Times* (New-York, 20 April 2020).

approaches[14] to understand theoretically and empirically the markets and price theory and develop analytical frameworks of market behaviors[15].

In the more specific context of extractive industries, a closer study[16] of the demand and prices patterns for industrial minerals compared to metals, also suggest that different dynamics in marketing (market fragmentation) and different price behaviors make the industrial minerals standing apart from a pure commodity market.

Overall, those different aspects relative to cost analysis, drivers of decision, and market imperfection, deepen the gap between actual market price and the theoretical price resulting from the supply cost perspective, where the cost of the marginal producer is the result of a mathematical optimization designed to provide the least expensive combination of resources (suppliers) required to produce a total quantity of output (demand).

Commodity markets dynamics: delayed feedbacks

On top of the fuzziness existing around the theoretical market mechanisms, delays in the supply-chain feedbacks also produce chronic instability in some commodity goods' price and availability. Systemic characteristics of a given commodity market tend to amplify, or not, these oscillations, with known uncertainties about the amplitude and frequency.

> *"Most commodities, whether animal, vegetable, or mineral, experience cycles in prices and production with characteristic periods, amplitudes, and phases. Industries with long construction delays and long asset lifetime such as shipbuilding, paper, chemicals, and real estate likewise exhibit characteristic cycles in price, profitability, and investment. The diversity of these cycles suggests they arise endogenously within each industry. In these markets the negative feedbacks through which price seeks to equilibrate supply and demand often involve long-time delays, leading to oscillation."* [17]

Commodity markets have structural delayed feedbacks that shakes the theoretical equilibrium: delay between price, profitability signal, and the adjustment of the capacity of production for a given commodity (with time to build or to retire assets of production). Figure 3 illustrates this instability in price for two examples of commodities: Natural gas in the US, and Soybeans.

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[14] Bill Gerrard, 'Industrial Economics: A Survey of Textbooks', *Bulletin of Economic Research*, 42 (1990), 311–24.

[15] Jean Tirole, *The Theory of Industrial Organization* (The MIT Press, 1988).

[16] David Humphreys, 'Similarities and Differences in the Economics of Metals and Industrial Minerals', *Resources Policy*, September, 1991, 185–95.

[17] John D. Sterman, 'The Invisible Hand Sometimes Shakes: Commodity Cycles', in *Business Dynamics: Systems Thinking and Modeling for a Complex World*, McGraw-Hil, 2000, pp. 791–841.

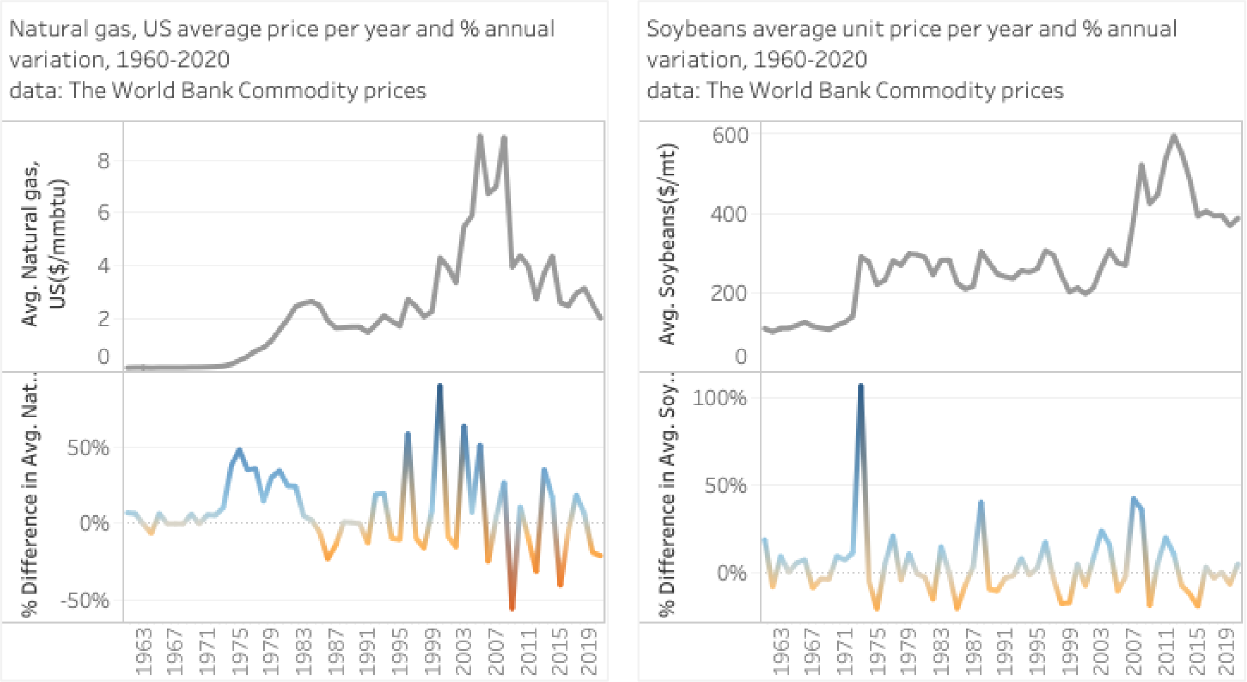

Figure 3: Examples of price instability in two commodity markets: Natural gas (left) and Soybeans (right), from 1960 to 2020. Bottom graphs with colors show the year-to-year percentage of variation with up and down oscillations. Source data: The World Bank.

From a systems dynamics perspective[18], structural feedbacks are responsible for the oscillatory regimes, each feedback having a different weight given the specific context of each commodity and system of production. Overall, as in many markets beyond commodities, the adaptation of demand and supply to price is slowed by:

- Physical delays in production:
  There is a structural delay in the adjustment of the capacity utilization and production rate to match the demand, caused both by the time to get the information about consumption and then by the manufacturing delay itself.
- Time to adjust the total capacity of production:
  In a greater timescale, the time and willingness to acquire new capacity of production, or to retire old ones, based on the actors' bounded rationality, differences in preferences and expected profitability or costs, also generates delayed feedback loops.

<u>*Takeaway: impact on the immediate and long-term understanding of market price*</u>

Commodity markets exhibit fluctuations, and we have seen different reason why the cost-curve might not produce an accurate understanding of price setting mechanism at a given time (firms' behaviors cannot be only explained through recourse to simple models of rational behavior), nor of its dynamics (the cost-curve does not fully capture the dynamics of price evolution with delayed feedbacks).

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[18] Sterman.

These fluctuations can be harmful, to individual investors as well as to larger institutions (countries) that might rely on commodity exports to ensure their currency's stability or rely on commodity imports to supply their internal production or food industry.

2.3. Introducing flexibility in industrial planning: "*mobilis in mobili*"[19]

We have observed that reality is uncertain, does (thankfully) not occur always accordingly to mental or numerical models: decisions at the firms' level are much more complex than pure economic decisions, and aggregated properties of commodity markets, furthermore of industrial mineral markets, distort the theoretical price-setting mechanisms with uncertain effects. Those uncertainties have unintended consequences for investors and firms, and the "flaw of average" concept reminds us that the resulting average output differ from the output with average inputs.

There is therefore a need to focus on understanding how uncertainties might impact the system, in order to be in a position to intentionally mitigate the risk and take advantage of the possible better contexts of operation. Introducing flexibility in design[20] provides a standard method to navigate uncertainties, realistically assess the profitability of a project, and evaluate alternative flexible designs.

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[19] Captain Nemo's Nautilus motto can be translated as "*moving within the moving element*". Jules Verne, *Twenty Thousand Leagues Under the Sea*, 1871.

[20] de Neufville and Scholtes.

3. Commodity markets: scope down to the phosphate-industry

3.1. Overview of the global industry of phosphate

As they grow, plants take from the soil three types of nutrients derived from Nitrogen (N), Phosphate (P_2O_5) and Potassium (K_2O). Those nutrients can be added to the soil as mineral fertilizers, to increase the soil's productivity. The world fertilizer demand in 2014 was estimated to reach 180 Million tons of nutrient, including 40 Million tons of phosphate (P_2O_5)[21].

World's reserves in phosphate is plentiful however unevenly distributed. Phosphate reserves naturally occurred as sedimentary deposits (larger in Morocco, ~70% of the world's total reserves, but also reserves in Florida, US, China, the middle East) or as igneous occurrences (such as reserves in Brazil, Russia, Finland, South Africa)[22] .

Globally, the fertilizers consumption is growing, driven by the agricultural production, but varies widely across region (e.g., Africa, very low rate of fertilizers use per acre of agricultural land compared to world average[23]) and with different N:P:K demand ratios per crops and per region, depending on practice.

Value chain, from phosphate mining to the farmers

We focus on mineral fertilizers based on phosphate. The industry is traditionally divided into different segments from the mining activities to the farmers, as represented in Figure 4 below :

- mining and beneficiation processes, to extract phosphate ore from the soil, wash and sort out the rock according to its chemical properties (concentration, …). Phosphate rock can be traded or re-used in the following processes.
- acid production: using sulfur to make sulfuric acid, which can transform phosphate rock into phosphoric acid. Phosphoric acid can be traded or re-used in the following processes
- chemical fertilizers manufacturing: lastly, phosphoric acid can be used to produce P-fertilizers such as TSP (triple super phosphate) or mixed with ammonia that provides nitrogen, to get N-P fertilizers such as MAP (Monoammonium phosphate) or DAP (Diammonium phosphate).
- Distribution to the farmers, can be made directly from the chemical fertilizer producer or by distributors. This activity requires to handle transportation (maritime and last mile) and potentially storage. The farmers are the end-consumers of the crop nutrients. Their demand varies depending of the type of crop they intent to grow, the specificities of the soil, and

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[21] Patrick (IFA) Heffer, Armelle (IFA) Gruère, and Terry (IPNI) Roberts, *Assessment of Fertilizer Use by Crop at the Global Level, International Fertilizer Industry Association and International Plant Nutrition Institute*, 2017 <www. fertilizer. org/ifa/Home-Page/LIBRARY/Publication-database>.

[22] Source: US Geological Survey, Mineral Commodity Summaries, February 2019. See Appendix 9.1 page 70

[23] Source: The World Bank, data. See also appendix 9.2, page 71

the usual practices and behaviors. They can consult environmental studies offices, or consulting services directly provided by the distributors or manufacturers.

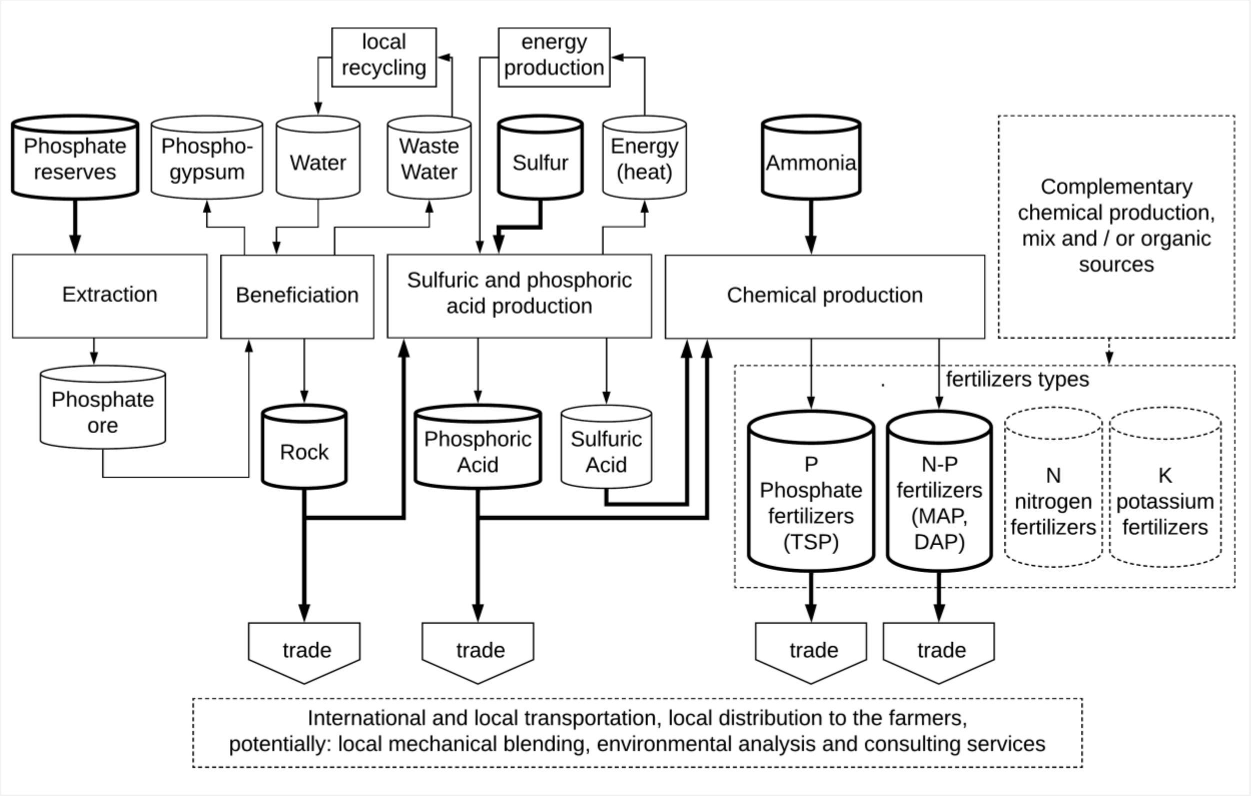


Figure 4: Overview of the chain of activities, inputs and outputs of the phosphate mining and phosphate fertilizer manufacturing industry

Different levels of integration and segments of operation:

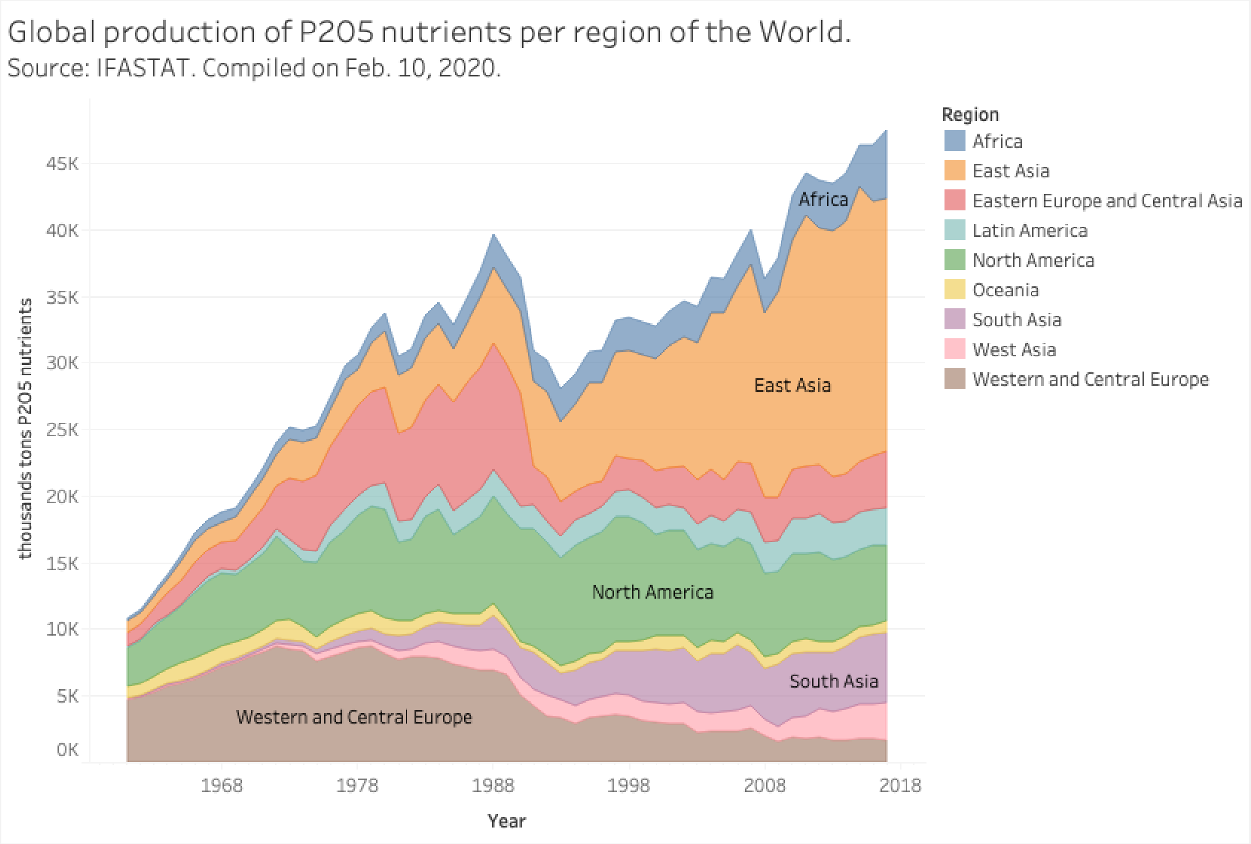
The phosphate-fertilizer industry is thus dependent of upstream supply of raw materials, such as sulfur and ammonia, and of downstream activities closer to the end-customer: distribution to the farmer, mix with complementary sources of nutrients, environmental services.

Different stakeholders of the industry operate across different segments. OCP group was historically leaning towards mining activities and has now reinforced its presence on the chemical transformation and chemical production of phosphate (P and N-P) fertilizers. The Florida-based Mosaic company is an example of another historical mining company, yet also extracting complementary nutrients (potash) for its production of potassium fertilizers, in addition to the main production of phosphate-based fertilizers. Both OCP Group and Mosaic, with different approaches, have experimented upstream or downstream integration of activities: either securing raw material supply (sulfur from natural gas production) or distribution activities. At the other end of the spectrum, a global major company such as YARA International, a Norwegian chemical company, is an example that leans towards the chemical production activities of a broader mix of various fertilizers, coupled with distribution and environmental services capabilities. Last, "non-integrated" stakeholder also exist, and can be specialized in chemical transformation (acid production) or chemical production, thus relying on the international trade of phosphate rock and raw materials.

Overview of the global market: world's production per region and consumption per product

Being an industry tightly dependent of the mineral extraction and raw material supply, the global production per region of the world is distributed and heavily present in the regions where the reserves are located. Figure 5 below provides a break-down of P2O5 nutrients per region of the world according to the IFA's classification of countries (given in appendix 9.7, page 93). Though the heaviest producer of phosphate nutrients, all type of products together, is also the heaviest consumer: East Asia (including China), concentrates 40% of the world's production, most of it being so far used on the local market, which has the highest rate of fertilizers use per acre of arable land in the world (due to practices and higher harvests frequency). North America, South Asia and Africa are each producing about 10%, with different level of presence on the international vs local markets.

This is important to note that those figures describe the global production, without a distinction between local markets and international trade. East Asia massive production is for example quasi-entirely absorbed by its internal consumption (see appendix 9.5).



Global production of P2O5 nutrients per region of the World.

Source: IFASTAT. Compiled on Feb. 10, 2020.

Figure 5: World's production of P2O5 nutrients, shows an overall rising trend despite the recent short drop in 2008. Source data: IFASTAT.

At a global level, the consumption of phosphate-based nutrients (Figure 6) shows a declining trend in phosphate-only products (rock, SSP, TSP) while ammonium phosphate containing N and P (DAP, MAP) has taken off in the past 30 years, reaching almost 50% of the current global production. The mixed fertilizers, NPK compounds, stay steadily around 25% of the global consumption.

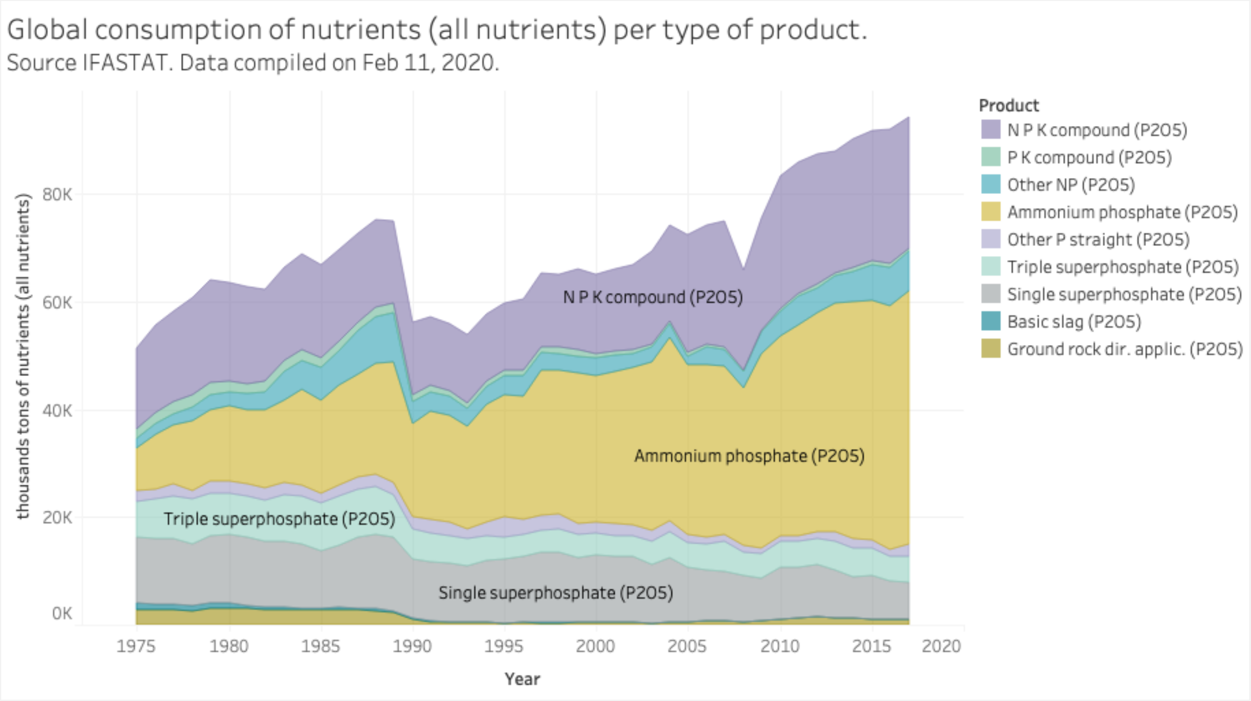


Figure 6: Global consumption of nutrients per type of products that include P2O5. Source data: IFASTAT.

Overall, the phosphate-fertilizer industry is distributed per region of the world and across different segments of operations, with different strategies from firm to focus or extend their spectrum of activities, secure raw material supply and / or internal markets or shares of the international trade. This industry is recognized as strategical for the global food safety, yet it is still subject to uncertainties about the future demand (both volume and nature) and profitability that we explore in the next two sections.

3.2. Existing volatility of demand and drivers of future trends

Long-term uncertainty

If historical trend on mineral fertilizers shows solid growth, driven by the overall increased use of fertilizers per hectare of arable land coupled with the growth of agricultural production, forecasting the trend for fertilizers use still relies on many unknown.

The example of three different projections made in 2012, cited in [Giraud, 2019][24] , can illustrate here the range of uncertainties: from a common starting point at 200Mt in 2010, the different assumptions lead to a range from 220 to 300Mt of fertilizers consumed in 2030 and the range extends from 260 to 410 Mt in 2050. These projections rely indeed on different assumptions for

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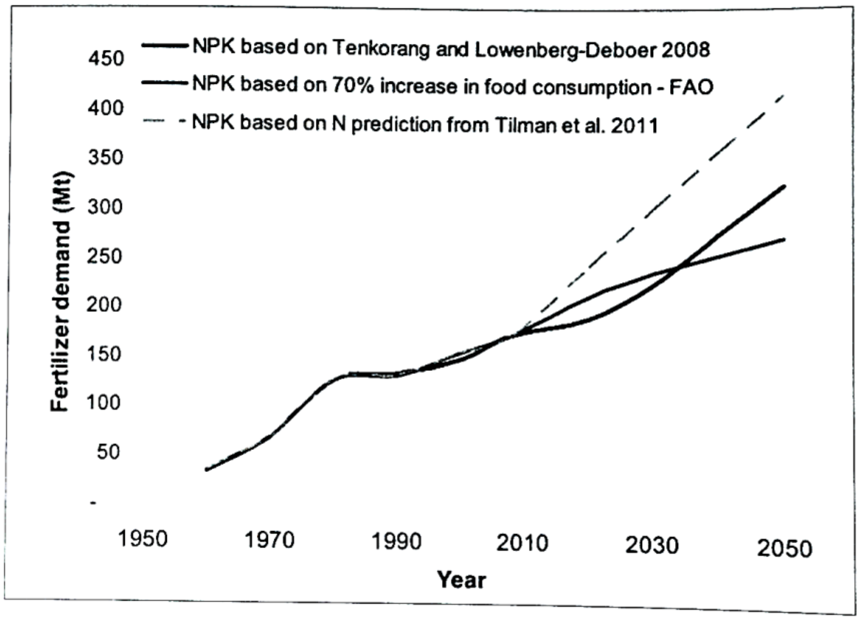
[24] Giraud.

the global population projection, the relationship to the food production (quantities and types of crops), and finally the ratio of N:P:K nutrients used per crops.

Figure 3.9. Trois projections de la consommation totale d'engrais en 2050 (Mt de $N + P_2O_5 + K_2O$)



Source : Malingreau, Eva 2012.

Figure 7: Different forecasts of fertilizers demand illustrate the range of uncertainty for the long term-demand. Source: Giraud, 2017.

Moreover, other models of prediction, with different objectives, also question the shift to different sources of fertilizers (organic) and the ability to restrain the consumption given the assumed reserve of phosphate with different scenario of scarcity / abundance. One such study is briefly shared in appendix 9.13, page 100, to illustrate that those additional structural assumptions keep broadening the range of potential long-term demand for phosphate fertilizers, including scenario of decreased demand and total substitution, or plateau.

Short-term volatility

It is also important to mention the high volatility of consumption resulting from agricultural cycles and uncertainties: the demand follows seasonal variations tailored to the type of crops and the planting and harvesting cycles. In the remaining window of opportunity for fertilizers application, the effective use then heavily depends on whether local conditions.

In that context, the supply chain from the international port of destination to the farmer is critical to make the product available at the right time of application. The product flow must adapt to a very variable demand (impacted by crops, seasons, daily weather) with a challenging dependency to external factors such as port operations, domestic transportation services, inland border crossing, and finally retail shops to avoid a product shortage caused by the "port to farm" supply chain.

3.3. Commodity prices volatility and impact on costs and profitability

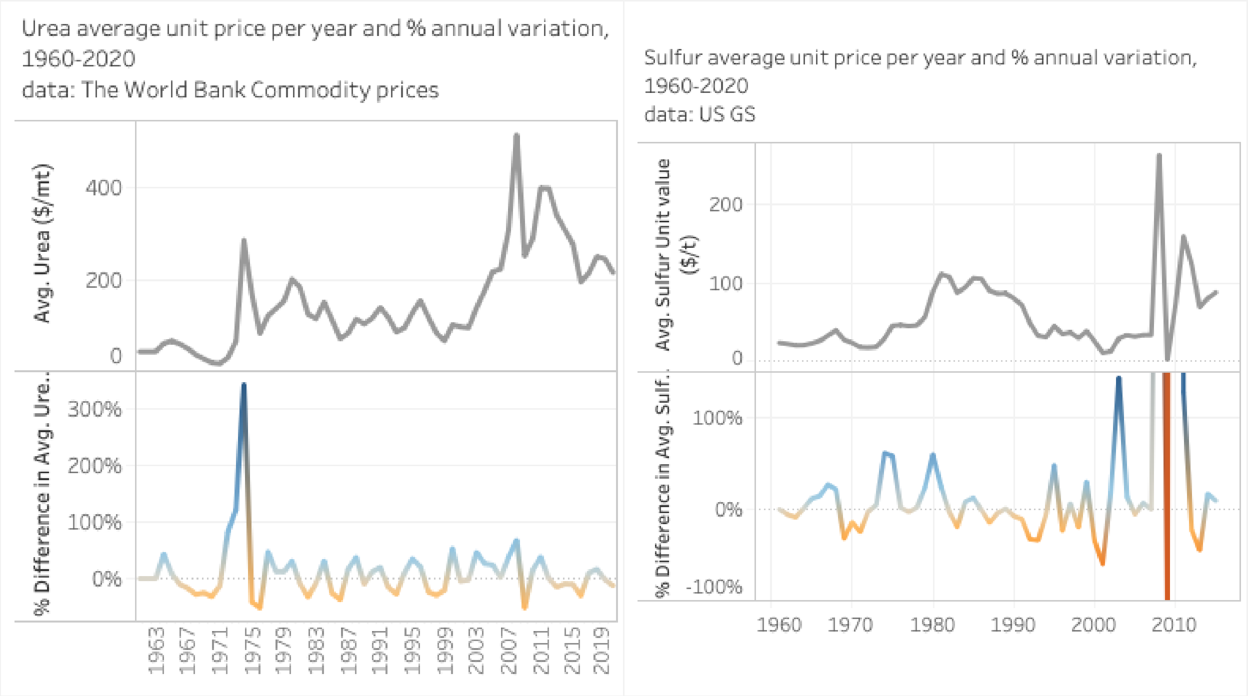
The phosphate value chain, from mining to trade, relies on the supply of raw materials, as well as the allocation of products either to trade, or to use as input in subsequent processes – as represented with Figure 4 in paragraph 3.1.

The profitability of operations therefore depends on the economic context of production: cost of supplying upstream raw materials, opportunity cost to trade or reuse the production of intermediary products (phosphate rock, phosphoric acid), given the cost of operations per product and the commodities' current sale prices.

We illustrate with the following historical data the range of variations in costs of inputs and sale prices in the phosphate industry, confirming the uncertainties and oscillations that comes with the raw materials and commodity prices.

Raw material supply

We present historical variation of the average price of urea (used for its nitrogen content) and sulfur. Further analysis of these prices' volatility is provided in appendix 9.11.



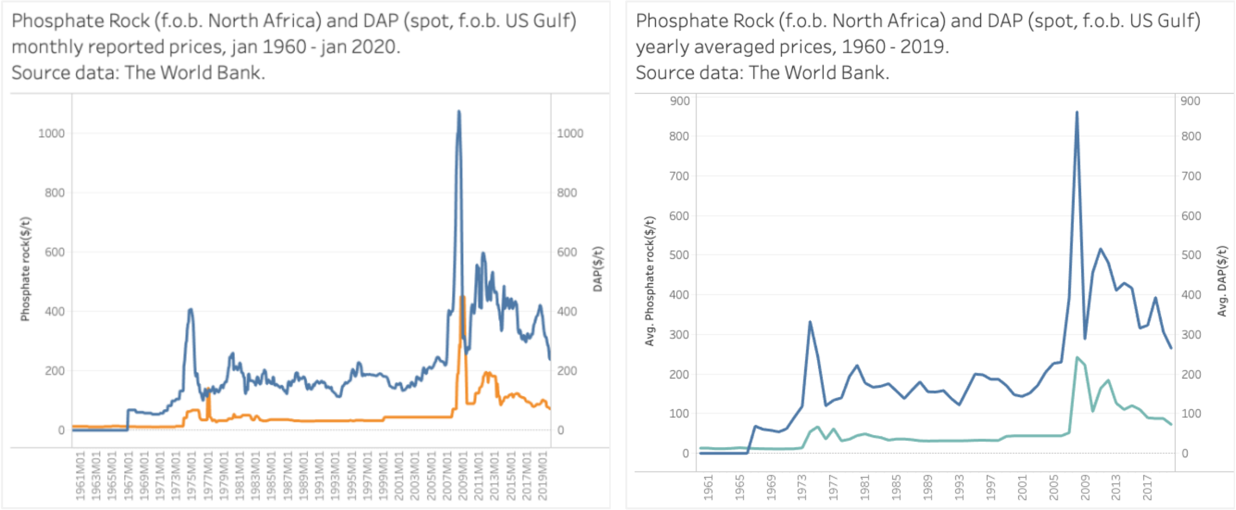
Urea average unit price per year and % annual variation, 1960-2020
data: The World Bank Commodity prices

Sulfur average unit price per year and % annual variation, 1960-2020
data: US GS

We observe a rough correlation between urea price and fertilizers (DAP, TSP) monthly prices that we present in appendix 9.12 page 99.

Trade price of rock and DAP and extreme events

Historical trends for DAP and phosphate rock prices are presented in detail in appendix 9.8 for the past decade. We present below the historical variations from 1960 to 2020, with a special focus on the greater variations that are present in the monthly data, as opposed to looking only at the average price per year. This reinforces the monthly variations and potential effects of demand volatility across the year.


Phosphate Rock (f.o.b. North Africa) and DAP (spot, f.o.b. US Gulf) monthly reported prices, jan 1960 - jan 2020.
Source data: The World Bank.

Phosphate Rock (f.o.b. North Africa) and DAP (spot, f.o.b. US Gulf) yearly averaged prices, 1960 - 2019.
Source data: The World Bank.

Figure 8: Phosphate Rock and DAP prices, monthly (on the left) and yearly (on the right) averaged.

We observe a relatively recent Major fly-up in 2008 (suddenly +366% from 2007 to 2008 averaged price). In the past, a major fly-up happened in 1974 (297%), and historical data show regular peaks such as in 1980 (+26%), 1999 (+32%), based on the annual average prices.

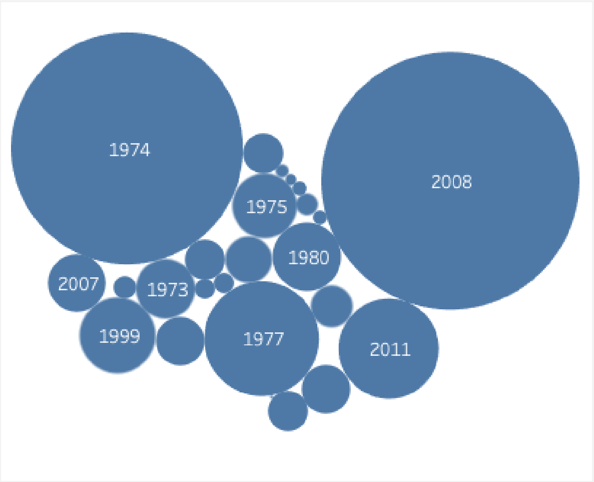


Figure 9: years of greatest percentage of increase, annual DAP prices

The most recent peak in 2011 (+55% compared to the previous year) seems to be still the tail of the 2008 fly-up, which would be an unprecedented rebound.

The 2008 peak was unprecedented by its magnitude and aftermaths: we observe a peak at $1,065/t for the DAP and $450/t for the rock at the 2008 peak for the monthly prices. On average in 2008, DAP price reached $860/t and rock price reached $240/t.

As of January 2020, DAP price reaches $265/t and rock price $73/t. The average value in 2019 was $306/t for the DAP and $88/t for the rock, which represents respectively +79% and +106% compared to the 1999 prices, 20 years ago (i.e. rock price doubled in that period).

However, the new long-term trends remain uncertain, as the tail of the 2008 fly-up seem to not be fully dissipated yet. We provide an example of successive forecasts of DAP prices made by the World Bank that had to be reconsidered its prediction year after year in appendix 9.8 page 94.

4. Defining the system: OCP group, Phosphate and Phosphate-based fertilizers producer

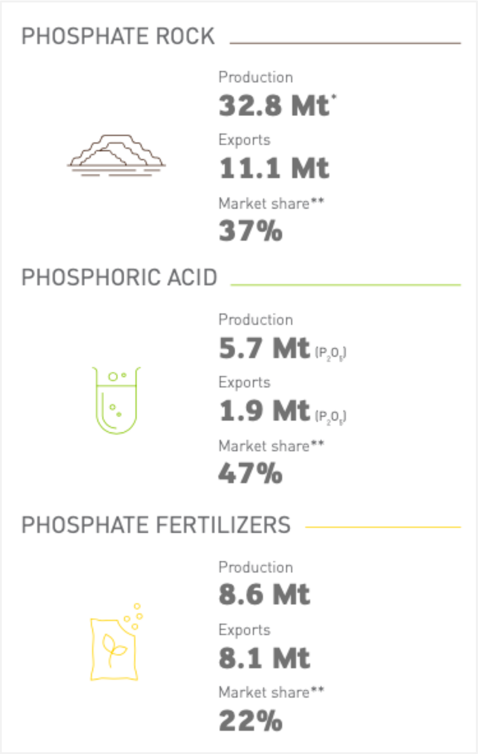
As a general reminder: the description and analysis presented below are solely the author's perspective, none of this content should be taken as representative of OCP group's perspective or orientation.

4.1. Value creation processes of OCP group

OCP group was created in 1920 and is a major player both in the phosphate industry and in Morocco's economy.

The group today highlights on its website 21,000 employees, and about US $5.4 billion in revenues, with a massive investment program[25] going-on. The group produces phosphate rock, phosphoric acid, and phosphate-based fertilizer, with significant market-shares on the international markets: respectively 37%, 47% and 22% as represented in the screenshot on the right[26]. Overall, the annual report highlights a breakdown of its revenue by product: 19% from phosphate rock, 24% of phosphoric acid, 57% from phosphate fertilizers.

The group's mining activities are based in Morocco, where are the world's largest reserves of phosphate (see the distribution of phosphate reserve globally in appendix 9.1). Industrial activities are mostly based in Morocco, and commercial activities extend worldwide. An increasing number of joint ventures distribute parts of the industrial and commercial presence internationally in Africa, or South America (see industrial capabilities and global footprint in appendix 9.15). We dive into the value chain of industrial and commercial activities performed by OCP group, as synthetized in the DSM representation (Figure 11) or with the more extensive OPD representation (Figure 12) presented below.



PHOSPHATE ROCK

Production
32.8 Mt*
Exports
11.1 Mt
Market share**
37%

PHOSPHORIC ACID

Production
5.7 Mt (P_2O_5)
Exports
1.9 Mt (P_2O_5)
Market share**
47%

PHOSPHATE FERTILIZERS

Production
8.6 Mt
Exports
8.1 Mt
Market share**
22%

Figure 10: Screenshot from OCP Group's annual report 2017: substantial market-shares on international trade.

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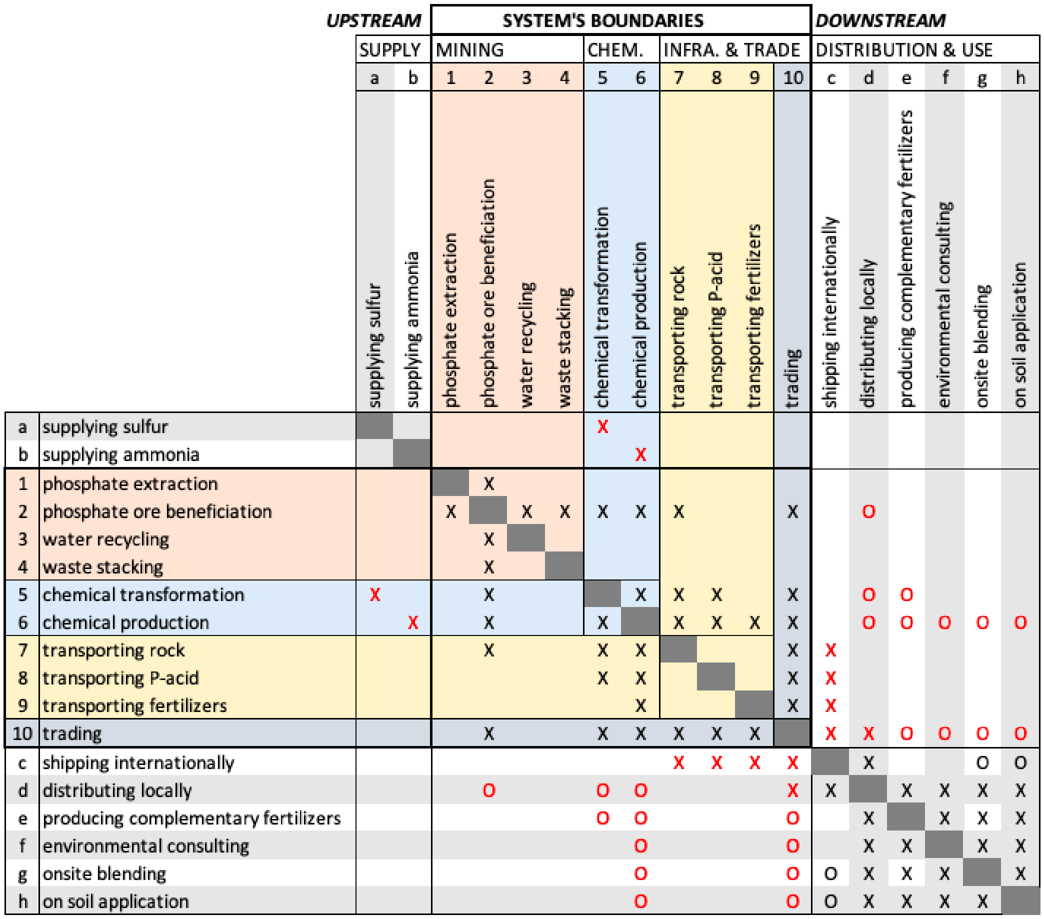
[25] OCP, 'OCP Group Webpage', 2019 <https://www.ocpgroup.ma/en> [accessed 26 April 2020].

[26] OCP Group, *OCP 2017 Annual Report: Switch to Digital*, 2018.



		UPSTREAM		SYSTEM'S BOUNDARIES										DOWNSTREAM					
		SUPPLY		MINING				CHEM.		INFRA. & TRADE				DISTRIBUTION & USE					
		a	b	1	2	3	4	5	6	7	8	9	10	c	d	e	f	g	h
		supplying sulfur	supplying ammonia	phosphate extraction	phosphate ore beneficiation	water recycling	waste stacking	chemical transformation	chemical production	transporting rock	transporting P-acid	transporting fertilizers	trading	shipping internationally	distributing locally	producing complementary fertilizers	environmental consulting	onsite blending	on soil application
a	supplying sulfur	■						X											
b	supplying ammonia		■						X										
1	phosphate extraction			■	X														
2	phosphate ore beneficiation			X	■	X	X	X	X	X			X		O				
3	water recycling				X	■													
4	waste stacking				X		■												
5	chemical transformation	X			X			■	X	X	X		X		O	O			
6	chemical production		X		X			X	■	X	X	X	X		O	O	O	O	O
7	transporting rock				X			X	X	■			X	X					
8	transporting P-acid							X	X		■		X	X					
9	transporting fertilizers								X			■	X	X					
10	trading				X			X	X	X	X	X	■	X	X	O	O	O	O
c	shipping internationally									X	X	X	X	■	X			O	O
d	distributing locally				O			O	O				X	X	■	X	X	X	X
e	producing complementary fertilizers							O	O				O		X	■	X	X	X
f	environmental consulting								O				O		X	X	■	X	X
g	onsite blending								O				O	O	X	X	X	■	X
h	on soil application								O				O	O	X	X	X	X	■

Figure 11: DSM representation of the system with interfaces (X strong, O soft interfaces). Main clusters of activities within the system are Mining, Chemical processing, Transportation and Trading. Upstream and downstream activities interact at the system's boundary (red crosses and dots), implying exogenous risks to the system.

Overall, the decomposition and description of OCP group industrial and commercial "system" organizes the activity in different essential clusters, with interesting interactions across the value-chain and at the system's boundaries, that ground the elaboration of the screening model that we describe in the next section.

We especially articulate the activities around:

- Clusters of production: mining, chemical transformation (acid) and production (granulation, fertilizers)
- Transversal activities: internal logistics, and trade
- Upstream critical interactions (red crosses on the DSM representation) for the supply in raw material, we select Sulphur and urea (ammonia)
- Downstream critical interactions (red crosses on the DSM representation), with international shipping and local distribution.
- Downstream soft interactions (red circles on the DSM), that might shape the long-term activities of the group, with the local practices of blending, environmental services, and finally on-soil application.

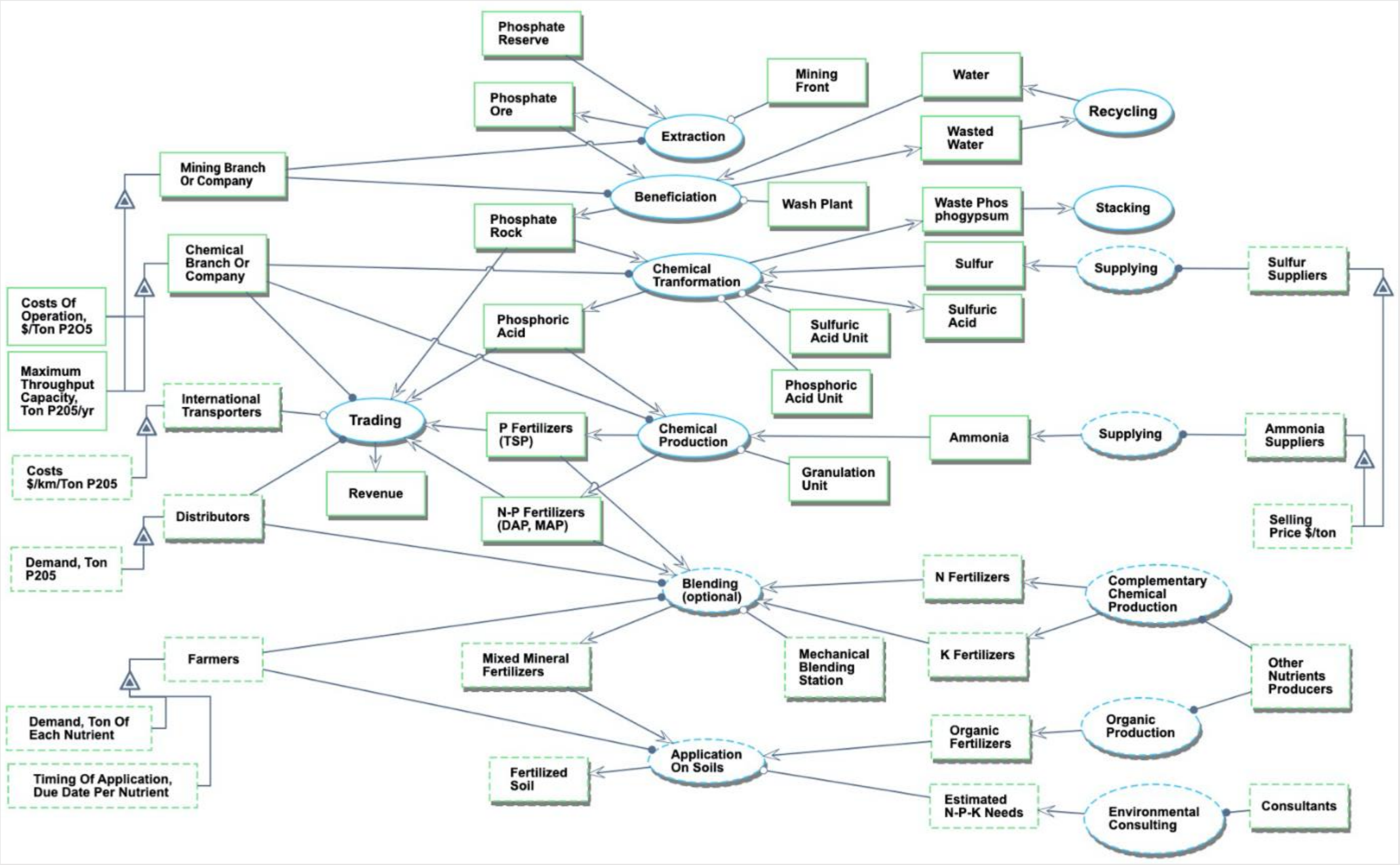


Figure 12: OPD representation of a "mining to fertilizer production" integrated system, such as OCP group. The value-generating process is " trading" " phosphate rock" , " phosphoric acid" and " fertilizers" (P or N-P). Dashed objects and processes are " environmental" to the system, i.e., out of the current system' s boundaries.

Finally, we represent OCP group as a "semi-integrated" phosphate producer, including all the activities from extraction to chemical production, with still upstream and downstream interfaces.

As presented in section 3.1 with the overview of different levels of integration possible, potential strategies could lead the company to weight more heavily on specific segments on its activity (typically, mining or fertilizers) and / or to reinforce upstream or downstream integration of activities. Especially, one strategical driver during the past decade has been to extend the capacity across the three main markets (rock, acid, fertilizers) with a special reinforcement on fertilizers markets as discussed in the next paragraph.

4.2. Competitive position: major player in the international trade, expanding

Historical strategic driver: low costs and volume, complemented with increased market-share on fertilizers

OCP Group presents on its website and annual reports its ambitious industrial program for 2008-2027, summarized as follow:

> *"Launched in 2008, this strategy will mobilize a total of nearly MAD 200 billion* [US $ 20 billion] *of investment, and aims, from rock extraction to its transport and processing into fertilizer, to promote sustainable agriculture by doubling the Group's mining capacity and tripling its processing capacity by 2027, while reducing its environmental footprint.*[27]

Overall, the industrial objectives are articulated in the 2017 annual report around "*increased industrial efficiency*", "*tripling of fertilizer capacities*", and "*enhancement of logistics capacities*".

We note, in the perspective of modelling our system's activities, the different strategic dimensions that are embedded in this program, relying on an in-depth industrial transformation and a shift on the activities' "center of gravity" with a reinforced weight of chemical activities compared to mining historical activities. The historical strategic driver of volume remains also present.

Heavy presence on the international trade-markets

A strong specificity of OCP group seems to be its heavy reliance on international trade to sale its production. If the group stands on the world's largest reserves, the African consumption of phosphate and fertilizers is not – yet – very substantial. Especially, Figure 13 below represents the size of the production, and the (export – import) balance per continent (based on a compilation of IFA data and IFA's breakdown of regions).

Further detail on consumption and production of fertilizers and of P2O5 per region of the world are additionally given in appendix 9.3 page 89.

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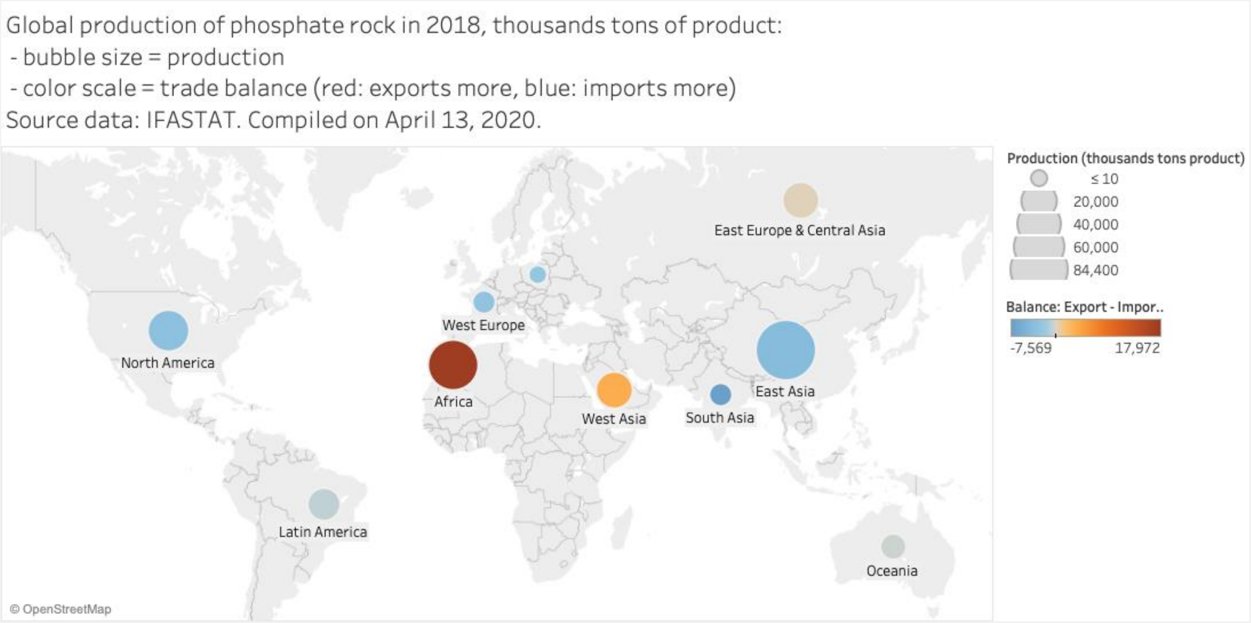
[27] OCP Group, *OCP 2017 Annual Report: Switch to Digital*.


Global production of phosphate rock in 2018, thousands tons of product:
- bubble size = production
- color scale = trade balance (red: exports more, blue: imports more)

Source data: IFASTAT. Compiled on April 13, 2020.

Figure 13: Production of phosphate rock per region of the world. Source data: IFASTAT. Color scale represents the trade balance with more exports (red) or imports (blue)

The map shows the two regions relying more heavily, in volume, on their exports: Africa, including (but not limited to) OCP group’s international sales, and West Asia, including especially Saudi Arabia where the group Ma’aden operates.

Figures from both US Geological Survey (appendix 9.1) and IFA (appendix 9.5) show the massive size of Chinese production, currently absorbed on the also massive Chinese internal market. It is striking to observe that Chinese’s apparent consumption in 2017, defined as the sum of internal production and imports, minus exports (data IFA, appendix 9.5) represents almost half of the world’s total production.

4.3. On-going transformation of OCP Group and current strategic crossroad

> *“Vertical integration, reduction of operational costs,* ***economies of scale****... OCP has a unique position in the industry through its considerable presence on the three sectors of the value chain: rock, acid, and fertilizers.” […]*
>
> *“The Group is implementing an ambitious* ***modular investment program*** *for upstream and downstream activities for the 2008 to 2027 period in order to meet the growing demand for food. This program represents an investment on the order of MAD 200 billion.” […]*
>
> *“OCP Group also has the ability to* ***quickly adapt its product offering in order to provide different volumes of phosphate rock, phosphoric acid, and phosphate fertilizers and adapt to a volatile and seasonal market.*** *This represents a significant competitive advantage. OCP’s* ***diverse portfolios***

> *(products, regions, customers), strong industrial development, and effective sales force provide maximum agility and flexibility that, in turn, strengthen the company's leadership."* [28]

In this context of an ambitious new industrial program launched in 2008 and the specific position of OCP group as a heavy player on the international trade, the company is ongoing an in-depth transformation (analyzed and acclaimed in different publications[29]): a great opportunity, that comes with real challenges. Basically, the group seems to have taken a strategical crossroad:

The historical activity, especially before 2008, was leaning essentially on the mining end of the spectrum of activities, with a product mostly commoditized. The recent transformation shifts the "gravitation center" closer to the chemical activities, with an ambitious expansion of capacities to produce fertilizers, and an extended portfolio of products. This transformation is complemented by in-depth organizational changes aiming to de-compartment the activities.

This strategy drastically changes the company's perspective: from a "mining mindset" which would push the products to the market, how to transition to a B2B or even eventually partly B2C company building different marketing strategy across its industrial broad capabilities?

4.4. Framework for the quantitative exploration of a broad strategical space

We suggest that the transition described in the previous paragraph, on top of the in-depth restructuration and strategic reorientation, also requires a fundamental change in strategic planning tools, in order to quantitatively assess and compare the effects of the strategic orientations highlighted in the quote above: modularity, flexibility in production, versatile production adapting to volatile markets. A step in that direction would be to develop the framework required to quantitatively assess the gain that could be expected from the group's increasing flexibility.

We have discussed the pitfalls that come with the use of deterministic tools, such as the cost-curve, when it comes to anticipate market prices, provided different examples of historical data and past forecasts, and explored different possible strategic postures for OCP and its competitors, to finally illustrate that markets are constantly changing and evolve unexpectedly, and that the strategic "design space" is broad.

We therefore propose to articulate the exploration of this broad strategical space based on the development of a screening model, complementing the in-depth industry model and detailed model that already exist with a new, preliminary approach (Figure 14). This screening model aims to recreate roughly but consistently the behavior of the system (OCP group industrial and commercial activities) under various sets of assumptions (uncertainties: potential states of the world), and therefore makes possible the rapid simulation of the system's performance under multiple different

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[28] OCP.

[29] Pascal Croset, *Ambition at the Heart of Change, A Lesson in Management from the South* (Dunod, 2013); Pascal Croset and Ronan Civilise, *L'entreprise et Son Mouvement - Acte 1 'Libérons Les Énergies'*, Intedyn Ed, 2017; Nick Gowing and Chris Langdon, *Thinking the Unthinkable: A New Imperative for Leadership in the Digital Age*, 2018.

designs (strategic planning) under a sufficient representative sample of future possibility: the distribution of results that is obtained is therefore a representation of the system's behavior, under uncertainties, with each chosen strategy, and allows for a realistic comparison of strategic possibilities. The result is a short-list of promising possibilities to explore in depth with more granular (and complex, and heavier to run) models.

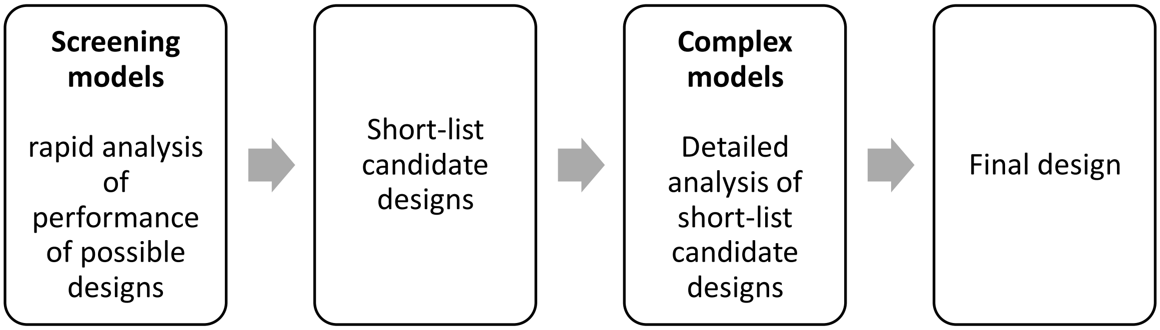

Figure 14: "Screening models precede and complement detailed design models." From de Neufville & Scholtes, p104, Figure 5.1.[30]

This proposed framework aims to provide different types of results that cannot be realistically achieved with the usual deterministic practices: it requires a change of mindset to evaluate the future as a range of possibilities instead of one most-likely possibility.

First, introducing uncertainties makes possible to spot major issues or opportunities that might arise, based on a quantitative evaluation of the impact they might have on the performance. Impact might be positive, for example if the system is able to move to new markets when they emerge (if they emerge), or negative, for example it can represent an economic risk when prices does not meet the expectation.

From this evaluation of impactful issues, the screening model is a tool to discuss and explore different strategic drivers and designs. Iterations have to occur to come up with relevant strategic drivers and tailored flexible options mitigating the risks and taking advantage of opportunities.

Last, the analysis of performance under uncertainties provides an understanding of important tradeoffs between risks and rewards: the methodology enables to identify the expected value of flexible design compared to static plans, therefore, to plan for flexibility upfront, intentionally, and based on a quantitative cost/reward analysis. Moreover, each strategy can be explored and discuss from different standpoints, for example more or less risk averse. The outcome is no more the proposition of "the best plan" but the description of possible strategies placed on a potential risks / rewards evaluation, showing average gains to expect in perspective with the extreme low and high results.

The next chapters apply this framework in the context of environmental risks. A comprehensive list of uncertainties related to environmental concerns associated with the use or consumption of

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[30] de Neufville and Scholtes.

fertilizers is first developed and synthetized in two major uncertainties we choose to address (section 5).

Then, based on the review of historical variations of inputs (section 3) and of our understanding of OCP group’s high-level decomposition of activities and strategical drivers (section 4), we develop the screening model and case study as presented in section 6.

Our case study and screening model is the first step of the whole framework described based on Figure 14. The limitations of this preliminary work, especially the additional iteration that are needed with OCP Group to confirm / adapt the assumptions made (about the system as well as about the potential range of variation and recursive effects for the inputs), and finally to update and adapt the possible flexible options explored are discussed in the recommendations (section 7)

5. Defining environmental uncertainties for the phosphate-fertilizer industry

The production and use of phosphate rock, phosphoric acid, and processed phosphate-based fertilizers are associated with a wide range of environmental concerns from the production side (by-production of toxic waste, significant use of water and energy, cases of environmental hazards at manufacturing facilities, issues to restore the land after mining activities) to the consumption side (negative impacts after excessive use of fertilizers, diffusion of unnecessary and toxic usual side-components of fertilizers such as cadmium).

In this context, OCP Group has started in 2006 an ambitious plan to adapt its production processes with the goal, mediatized, to improve the environmental footprint as well as costs of production, with a priority given to reducing water and energy consumption.

> *“**The OCP Group receives the IFA’s 2019 Industry Stewardship Gold Medal for the second year in a row.***[31]
>
> *The International Fertilizer Association prize was awarded by IFA’s President, Mr. Mostafa Terrab to OCP’s Senior Vice President - Sustainability Platform, Mrs. Hanane Mourchid, on Wednesday, November 20, 2019, at the IFA Strategic Forum in Versailles, France. The award recognizes OCP's strong commitment in terms of safety and confirms the group’s leadership in terms of sustainable development. This award follows the prize previously awarded last year for all the efforts that the group deploys to promote industry stewardship.”*

Those steps make sense from the environmental as well as the economic perspective, and they do represent what seems to be a necessary transformation. However, we want to explore environmental risks in a broader sense, accounting for the market shifts or disruption that could emerge from local distortions of the use or of the economic conditions of production for this industry.

In this chapter, we start first by exploring a list of concerns that are associated with the production and use of phosphate-based fertilizers. We highlight the kind of regulations, if any, that have regionally emerged to account for some of the negative externalities being generated.

Those local regulations could become more and more stringent. How strict and to what exact scope could those environmental constraints be applied in the near-term and long-term future is however very uncertain. That leads us to finally discuss how could, potentially, environmental regulations redistribute the regional economic contexts of fertilizers production and the global demand.

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[31] OCP Group, ‘OCP Group Receives IFA’s 2019 Industry Stewardship Gold Medal’, *OCP Press Release*, 2019.

5.1. Environmental regulations impact local contexts of production

As presented by Mosaic in its 2018 annual report[32], environmental concern impacts the group's activities at all phase: production process, product content, product use by final consumers:

> *"We are subject to an evolving complex of international, federal, state, provincial and local environmental, health, safety and security ("EHS") laws that govern the production, distribution and use of crop nutrients and animal feed ingredients. These EHS laws regulate or propose to regulate: (i) conduct of mining, production and supply chain operations, including employee safety and facility security procedures; (ii) management and/or remediation of potential impacts to air, soil and water quality from our operations; (iii) disposal of waste materials; (iv) reclamation of lands after mining; (v) management and handling of raw materials; (vi) product content; and (vii) use of products by both us and our customers."*

Overall, Mosaic group underlines that "*new or proposed regulatory programs can present significant challenges in ascertaining future compliance obligations, implementing compliance plans, and estimating future costs*". The expenditures taken from Mosaic's annual reports show the capital expenditures spent for environmental matters, especially towards land reclamation activities, waste management, water treatment activities, remediation: the expected environmental expenditures announced in 2019 for 2020 were in the magnitude of $300 million, 30% of the group's total capital expenditures of the past year.

The group also strongly highlights the associated uncertainties in its annual report: "*No assurance can be given that greater-than-anticipated EHS capital expenditures or land reclamation, Gypstack closure or water treatment expenditures will not be required in 2019 or in the future*".

We have only taken here the illustration of Mosaic, which is an US public company, for the accessible financial information that the group provides. Environmental regulations in the fertilizers and agricultural chemical manufacturing industry are globally rising[33].

In the regions where the regulation level is higher, the example of Mosaic shows non-negligible amounts of capital expenditure to meet the regulations and significant uncertainties regarding economic impacts of environmental laws. This more stringent, subject to public scrutiny, US context, is of course not applicable uniformly. However, recognizing the potential areas of future regulations and the potential impacts on production processes and costs helps represent a plausible future context of production in a mid or long-term perspective. Those impacts could be experienced by OCP group itself and / or by its competitors with different magnitude, either way generating a potential distortion of the industry as we know it today.

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[32] Mosaic, *The Mosaic Company: 2018 Annual Report*, 2019.

[33] Nathaniel Leach, *Global Fertilizers & Agricultural Chemicals Manufacturing*, 2019.

5.2. Production side

We list below examples of negative environmental impacts and reasons for concerns (concerns being then likely to mute in future regulation).

Those impacts seem to be generally well acknowledged but with different level of environmental risk assessment, as we see in the discussion about phosphogypsum recycling opportunities / constraints. Overall, the reduction of environmental impacts from fertilizers production would imply an increase in costs of operation and potentially call for new technologies, to go beyond the immediate improvement that can be made to reduce resources' consumption (water, energy) while also improving the operations' costs. Obtention of legal authorizations for mining in the US for the Mosaic group does not seem to be frightening to the whole mining activity, yet specific efforts are deployed in this juridical context to ease public opinion, ensure public safety (water quality, hazards prevention) and win in courts, with delays, new mining permits.

Use of resources (water and energy) during Mining activities

Mining requires extensive use of water to extract and clean the rock. In the assumption of increased water scarcity, arbitrage might occur to limit the use of clean water for industrial / mining uses, as it happened locally in Chile's desert of the Atacama, where the extraction of lithium was suspended[34]. The very context of the Atacama, the world's driest desert where copper mines are already numerous and tourism is a strong economic resource, is very specific. However, this case illustrates how local regulators driven by environmental considerations might raise the level of legal expectations to maintain the natural ecosystem while conducting mining or chemical activities, even for a booming industry such as the lithium carbonate production for ultralight battery metal.

In the context of the phosphate industry, decreasing the use of Water and Energy is already pinned as a top environmental objective for OCP, as presented by OCP's chairman Mr. Terrab to Morocco's "*Commission de contrôle des finances publiques*" and restituted in the online newspaper Media24[35].

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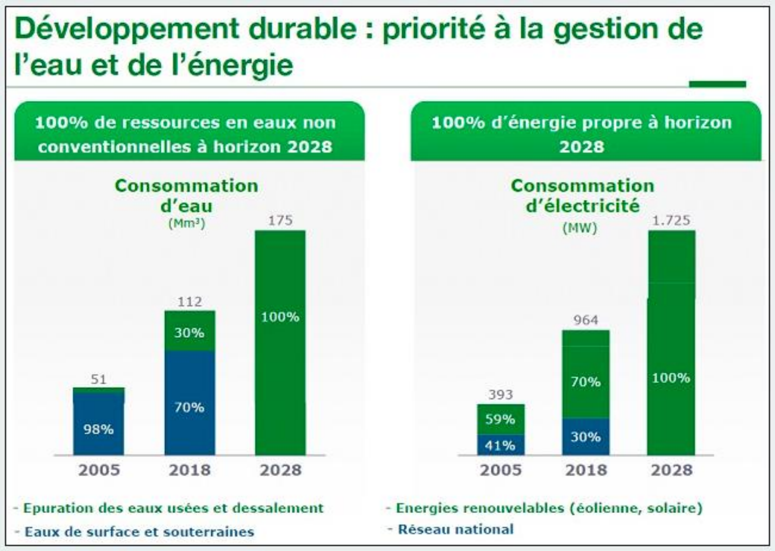
[34] Aisling Laing, 'Lithium Miner SQM Considering Options after Environmental Court Ruling', *Reuters*, 27 December 2019 <https://www.reuters.com/article/us-chile-sqm/lithium-miner-sqm-considering-options-after-environmental-court-ruling-idUSKBN1YV1JZ> [accessed 3 January 2020].

[35] Souhail Nhaili, 'Au Parlement, Mostafa Terrab a Raconté l'incroyable Transformation d'OCP', *Medias24* (Morocco, 18 December 2019) <https://www.medias24.com/au-parlement-mostafa-terrab-a-raconte-l-incroyable-transformation-d-ocp-6337.html>.



Développement durable : priorité à la gestion de l'eau et de l'énergie

100% de ressources en eaux non conventionnelles à horizon 2028

100% d'énergie propre à horizon 2028

Figure 15: slide restituted by Média24, from OCP presentation in December 2019. Water and energy consumption targets for 2028: 100% renewable energy sources, 100% recycled water targets in 2028

Waste and greenhouse gases generation during manufacturing

Phosphogypsum seems to be the most problematic waste. It is a by-product of phosphoric acid manufacture, primarily constituted of gypsum (source of Sulfur (S) and Calcium (Ca), valuable in agriculture), but also of various amounts of Arsenic, Barium, Cadmium, Chromium, Lead, Mercury, Selenium, Silver, and Fluorine, any one of which can be toxic above different concentration levels. In addition, phosphogypsum is also highly acidic, highly soluble. Lastly, the presence of radionuclides (especially radium -226, which is the source of the gas radon-222) made its use for example severely restricted in the US by the USEPA (Environmental Protection Agency)[36].

According to a 1988 study quoted by the US EPA:

> *"Approximately 5 tons of phosphogypsum are produced as a by-product in the production of 1 ton of phosphoric acid fertilizer. On a worldwide scale, of the residual phosphogypsum produced, 14% is reprocessed, 28% is discharged to water and 58% is stored in stacks". (1988)*

Contemporary information confirms that phosphogypsum still has little market value and mostly is stacked in huge waste piles[37].

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[36] Florida Industrial and Phosphate Research Institue (FIPR), *Influence of Phosphogypsum on Forage Yield and Quality and on the Environment in Typical Florida Spodosoil Soils*, 1996 <http://www.fipr.state.fl.us/publication/influence-of-phosphogypsum-on-forage-yield-and-quality-and-on-the-environment-in-typical-florida-spodosol-soils-volume-ii-environmental-aspects-associated-with-phosphogypsum-applied-as-a-source-of-s/>.

[37] US Environmental Protection Agency, 'TENORM: Fertilizer and Fertilizer Production Wastes, Radiation Protection', 2019 <https://www.epa.gov/radiation/tenorm-fertilizer-and-fertilizer-production-wastes#tab-2> [accessed 2 January 2020].

The industry encourages research to develop potential uses and reduce the disposal problem, but recycling is very constraint, as least in the US, for environmental reasons. Especially, it has been banned for use in road construction since 1992; however, later scientific publication keeps exploring and arguing for the possibility of using phosphogypsum for road construction[38]

Phosphate slag is a second type of fertilizer production wastes. It is produced from the thermal process for the conversion of phosphate rock to elemental phosphorus. Slag contains radioactive metals (uranium, thorium, radium), however the radiation is low enough to allow this waste to recycle as highway construction aggregate, Portland cement and concrete, or railroad ballast and general construction in the US. Moreover, decreasing demand and increasing energy cost associated with elemental phosphorus made the production steadily decrease and is currently almost over in the US[39].

Last, fertilizer manufacture releases greenhouse gas: nitrogen oxide (NO_x) and nitrous oxide (N_2O) present in nitric acid, and ammonia (NH_3). The world Bank has published emission guideline values for fertilizer plants: those guidelines are currently not met as reported by the IFA, yet IFA also notes a tendency to adopt environmental mitigation strategies and best available technologies across the global sector, in order to improve the conformance of the industry to the mission guideline values.

Environmental hazards (Sinkholes) in manufacturing facilities

Various hazards with environmental consequences, especially water contamination, are reported in the US (where the industrial activity is usually under scrutiny). Mosaic group has faced different federal lawsuits with costly settlements[40] and adverse public opinion reactions.

For example, the “New Wales Water Loss incident” as called by Mosaic after a 45-foot-wide sinkhole opened under a phosphogypsum stack in a Mosaic plant in Mulberry, Florida, in 2017, forced the company to a wide private drinking water testing campaign and specific onsite monitoring and pumping of groundwater in addition to the repair effort to restore the ground surface for heavy equipment use [41]. This event occurred despite previous efforts to ensure the proper treatment, storage and disposal of this hazardous waste, phosphogypsum, settled with the

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[38] Paul Clifford, *A Comparative Analysis of Environmental Impacts: Phosphogypsum versus Borrow Pits*, *University of South Florida, Florida Institute of Phosphate Research*, 2000 <http://fipr.state.fl.us/wp-content/uploads/2014/12/01-139-170Final.pdf>.

[39] US Environmental Protection Agency, ‘TENORM: Fertilizer and Fertilizer Production Wastes, Radiation Protection’.

[40] Galloni Taina, ‘A Sinking Feeling about Florida’s Phosphate Mines’, *Earthjustice* (Florida, 2016) <https://earthjustice.org/stories> [accessed 2 January 2020]; Christopher O’Donnell, ‘Mosaic Plant Sinkhole Dumps 215 Million Gallons of Reprocessed Water into Floridan Aquifer’, *Tampa Bay Times* (Tampa, 17 September 2016) <https://www.tampabay.com/news/environment/water/mosaic-plant-sinkhole-dumps-215-million-gallons-of-reprocessed-water-into/2293845/>.

[41] Mosaic, ‘New Wales Water Loss Incident Resources’, 2017 <http://www.aspire-potash.com/florida/new_wales_water_loss_incident_resources.htm> [accessed 27 December 2019].

US EPA (Environmental Protection Agency), resolving a series of alleged violations by Mosaic of the federal Resource Conservation and Recovery Act (RCRA)[42].

Land compensation after mining activities

Legal expectations for land compensation are already highly controlled in the US (as described in Mosaic 2018 annual report) but also start to become more stringent in Morocco. Land compensation is indeed pointed out by the "Cour des comptes" [43] as one of the main areas of improvement regarding OCP's mining activities in Morocco. The "Cour des comptes" reports a delay in land restauration by OCP and asks to increase efforts in order to catch up[44].

Effect of environmental concerns on permits issuance (delay, juridical battle, public opposition)

We take the example of the Mosaic group, which managed to acquire its last permit for new mining projects only after significant time and efforts in courts. This last permit obtained in Florida by Mosaic in 2019, for the "Ona project", ended a procedure started in 2011, with mining permits issued in 2015 from the State of Florida and local government permits eventually secured in 2018 [45]. This permit finally secures for Mosaic the exploitation of 22,483 acres of land including 16,778 acres permitted for mining, corresponding to "*160.2 million tons of phosphate rock*" according to Mosaic's press release.

Example of previous cases of permit demand illustrate the risk associated with the obtention of local government permits. A permit suspension happened in 2008 for Mosaic, based on Clean Water Act, the Administrative Procedures Act, and the National Environmental Policy Act, after the opposition in courts by several local associations on behalf of whom the NGO Earthjustice filed suit in October 2008. The phosphate mine permit (480 acres) that was just granted to Mosaic was then suspended by the US Army Corps of Engineers [46].

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[42] US Environmental Protection Agency, 'Enforcement: Mosaic Fertilizer, LLC Settlement', *October 1*, 2015 <https://www.epa.gov/enforcement/mosaic-fertilizer-llc-settlement> [accessed 6 January 2020].

[43] Medias24, 'OCP: La Cour Des Comptes Pointe Les Lacunes de La Gestion de l'activité Minière' (Morocco, 18 March 2019) <https://www.medias24.com/ocp-la-cour-des-comptes-pointe-les-lacunes-de-la-gestion-de-l-activite-miniere-918.html>.

[44] Royaume du Maroc - Cour des Comptes, *Contrôle de La Gestion de OCP.SA Activité Minière*, 2019 <http://www.courdescomptes.ma/fr/Page-42/actualites/avis/synthese-du-rapport-relatif-au-controle-de-la-gestion-de--locp-sa-activite-miniere/15-292/>.

[45] Mosaic, 'Mosaic Acquires Final Permit for Ona Phosphate Mining Project', *Company Press Release*, 2019 <http://investors.mosaicco.com/CorporateProfile> [accessed 28 December 2019].

[46] David Guest, 'Corps Suspends Phosphate Mine Permit', *Earthjustice* (Florida, 2008) <https://earthjustice.org/stories> [accessed 2 January 2020].

Maritime transportation costs increase?

Last, maritime transportation costs are today relatively cheap, but used to be more significant and could, in the perspective of carbon taxation systems applied to transportation, rise again.

Depending on the level of integration of the value chain from mining to the final product delivery to the farmer, distributors can be very specialized in logistics as illustrated by YARA, developing its own autonomous electric Ship[47].

The possibility of much higher transportation costs if a carbon tax were applied, at least in some parts of the world, could reshape prices of products at destination.

5.3. Demand side and fertilizers best management practices

We observe trends that might structurally change the quantity of mineral fertilizers needed for agriculture ("reasonable" use of fertilizers, circular economy), and we can imagine other changes in the overall context of agricultural production system that could minimize the need for mineral fertilizers. Globally, impactful factors that seem to shape the use of fertilizers are first population growth and agricultural production needs, then the availability of land and irrigation that influence production intensity, and lastly the practices in fertilizers uses. One could imagine a change in local agricultural policies, which might attempt to shape differently and more firmly the uses of fertilizer (e.g., prioritizing one nutrient over another, or aiming to decrease or increase the ratio of fertilizer use per hectare of land), making this last factor more impactful.

Preventing excessive use of fertilizers: "4 R rule"

Institutional as well as industrial stakeholders widely acknowledge the negative environmental impacts generated by excessive use of mineral fertilizers (inadequate quantity of product and / or time of application). Negative local environmental effects are eutrophication (accumulation of nutrients generating an excess of algae) and hypoxia (resulting oxygen depletion) of water bodies[48].

For example,

> *In China, the government acknowledged in 2013 that "25% of lakes have eutrophication; more than 50% of ground water has been polluted"*

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[47] Yara International, 'Yara Birkeland, the First Zero Emission, Autonomous Ship', *News and Media*, 2018 <https://www.yara.com/knowledge-grows/game-changer-for-the-environment/> [accessed 7 January 2020].

[48] IFA, 'Plant Nutrients and Clean Water', in *AGENDA 2030 Helping to Transform Our World*, 2018; MAAARO, 'Le Problème Du Phosphore!', *Ministère de l'Agriculture, de l'Alimentation et Des Affaires Rurales, Ontario*, 2014 <http://www.omafra.gov.on.ca/french/crops/field/news/croptalk/2014/ct-0914a8.htm> [accessed 27 December 2019].

Therefore, the Chinese Ministry of Agriculture published in 2015 its "*Action Plan for Fertilizer Consumption Zero Growth Rate by 2020*"[49].

In addition, decreasing the quantity of fertilizer consumed is also an objective for carbon emissions reduction policies[50]. Indeed, the application of fertilizer unleashes unwanted chemicals in the air, such as nitrogen (greenhouse gas effect). In addition, intensive use of soil for agriculture increases losses of carbon from the soil. For this reason, coming back to practices of crops rotation, reduced productivity of the soil, with use of organic fertilizers, is encouraged by some stakeholders in the objective to increase the soil's concentration in carbon[51].

Overall, the awareness of local and global environmental impacts caused by the use of fertilizers leads to promote "Fertilizer Best Management Practices" stated as:

> *the "4R rule": using the right product and right dose of fertilizers, at the right place, at the right time.*

This trend in the use of fertilizers can be referred to as "rational" or "reasonable" agriculture. As an example, among many others, the Ministry of Agriculture and Food in Ontario, Canada, refers to this trend as "Agriculture de Precision", which can be motivated both by economic and environmental incentives[52], and applies to large-scale agriculture.

Circular economy trends

The effort to precisely dose the amount of mineral fertilizer inputs needed can be coupled with the increasing trend of organizing a "circular economy". Public or private initiatives encourage the agricultural sector to recycle their waste and organize synergies with complementary industries.

Organic fertilization is then encouraged as a primary source of fertilizers that is to be complemented with a limited amount of mineral inputs. This practice requires different information and incentives, for the stock breeder to feed carefully their animals[53] and produce valuable organic waste, and for the farmers to take into consideration organic fertilizers sources before adding mineral fertilizers[54].

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[49] Olivier Hatfield, *China's Efforts to Improve Sustainability, Presentation by Argus Consulting*, 2019.

[50] Pierre Cazeneuve, Thuriane Mahé, and Julien Vert, *Le Marché Des Engrais Minéraux : État Des Lieux, Perspectives et Pistes d'action*, *Ministère de l'Alimentation de l'Agriculture et de La Pêche (France), Secretariat Général, Centre d'études et de Prospective*, 2010.

[51] Christine (MAAARO) Brown and others, *Guide Agronomique Des Grandes Cultures*, ed. by Ministère de l'Agriculture de l'Alimentation et des Affaires rurales Ontario (Toronto, Canada: Imprimeur de la Reine pour l'Ontario, 2017).

[52] Brown and others.

[53] MAAARO, 'Le Phosphore Alimentaire Chez Les Bovins Laitiers - Gestion Des Éléments Nutritifs et Protection de l 'environnement', *Ministère de l'Agriculture, de l'Alimentation et Des Affaires Rurales, Ontario*, 2004 <http://www.omafra.gov.on.ca/french/livestock/dairy/facts/04-002.htm>.

[54] Brown and others.

Overall, the demand for mineral fertilizers is perceived in some studies[55] as potentially significantly impacted by recycling efforts:

> *« Substantial measures exist that can substitute over half of phosphate rock mined today. About half of the potential can be obtained through products use and food waste reduction, the other half through waste streams and waterways phosphorus recycling. A thorough cost estimate of externalities including eutrophication and erosion is warranted to fully assess the economics.*
>
> *The introduction of recycling and use reduction can substantially improve the longevity of the resource base. In case of conservative known reserves phosphorus availability is extended under growing demand to the end of the 21st century, and when including potential reserves beyond the 23rd century. »*

We note with Figure 16 below that manure's use as a source of phosphate has been stable despite a fast increase in global livestock starting in the 1960's. Even if this increase in global livestock has an uneven distribution of growth per region of the world (e.g. in the US, numbers of cattle have decreased since the 1970's, according to US Department of Agriculture), the recycling of phosphate is a path quantified in different studies as the one quoted below.

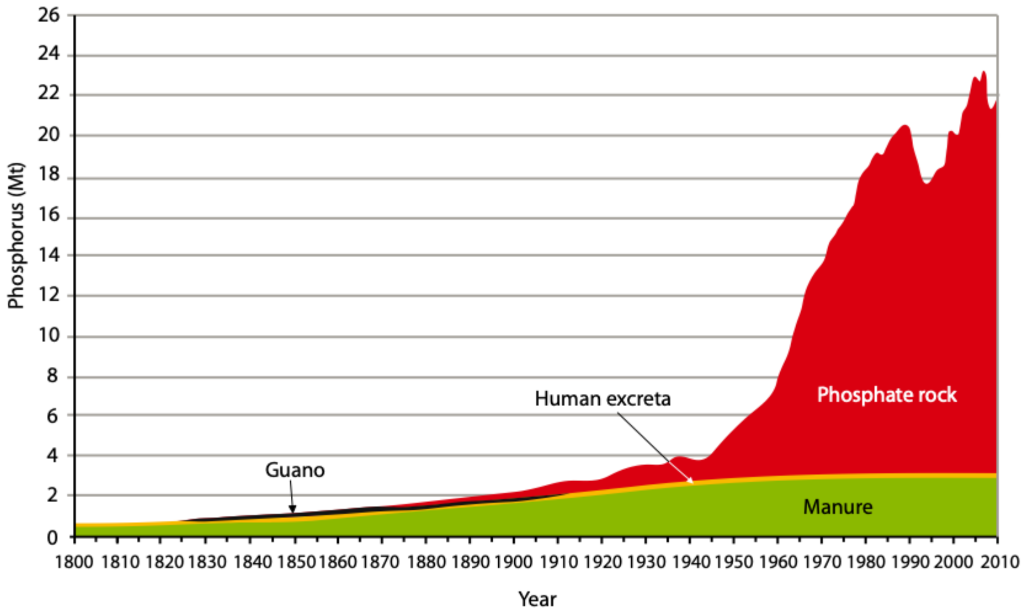

Figure 2: Global sources of phosphorus fertilizer. Since the mid-1940s, population growth accompanied by greater food demand and urbanization have led to a dramatic increase in the use of mined phosphate rock compared with other sources of phosphorus. *Source: Cordell et al. (2009)*

Figure 16: Global sources of phosphorus fertilizers shows stagnation of manure. Source: UNEP[56]

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[55] R. H.E.M. Koppelaar and H. P. Weikard, 'Assessing Phosphate Rock Depletion and Phosphorus Recycling Options', *Global Environmental Change*, 23.6 (2013), 1454–66 <https://doi.org/10.1016/j.gloenvcha.2013.09.002>.

[56] United Nations Environment Program (UNEP), *Phosphorus and Food Production*, *UNEP Year Book* (United Nations publication, 2011) <http://stapgef.unep.org/yearbook/2011/pdfs/phosphorus_and_food_productioin.pdf>.

Overall, it requires a system to recycle at a large scale the organic waste where it can be the most useful, not necessarily in an immediately close location, building partnerships across industries in a way that maximizes the recycling with comparable or improved economic performance [57]. Local studies can be found that provide example of local recycling "loops" enabling additional use of organic fertilizers, decreased used of mineral fertilizers (P,N), with overall higher productivity and less environmental negative impacts[58], with details provided in appendix 9.13 page 100.

Regional differences in the use of fertilizers per acre of land

A "reasonable" use of fertilizers is widely recommended by national institutions (US, Canada, European Union, Australia) and seems to have already bended the demand in at least some of these countries – and the consumption is not necessarily yet stretched at its "reasonable minimum".

For example, in France, large importer of mineral fertilizer, the consumption of phosphate and potash-based fertilizers was reduced by 60% between 1990 and 2010, while the volume of agricultural production was increased by 11%. In 2010, 55% of fertilization was organic, versus 45% mineral[59].

However, these practices seem to be adopted mostly in mature economies. The average use of fertilizer per acre of land is still very disparate across different regions of the world, and mineral fertilizers are still very under-used for example in Africa (see appendix 9.2).

Limitation of heavy metal concentration in soil fertilizers (cadmium)

The removal of unwanted components in fertilizers is already common practice, only for product efficiency and quality purpose. For example, selective removal of "unwanted metals" in phosphoric acid has been investigated primarily for iron, aluminum and magnesium, in order to improve the production of grade DAP (diammonium phosphate). Economically feasible solutions have been found and implemented since the late 1990's[60].

Today's emerging issue does not concern the product's efficiency, but specific chemical elements recognized as toxic in the environment. Cadmium appears to be the main issue for phosphate-based fertilizer.

Cadmium's toxicity on human health and human exposure to cadmium have been studied at least from the 1990's and human's exposure to cadmium is known to come from many different sources, mainly through cigarette smoke and food. Toxicity of cadmium is locally recognized as human

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[57] Institut National de l'Economie Circulaire (France), *Livre Blanc « Systèmes Agricoles et Agroalimentaires Circulaires »*, 2018.

[58] Hanhua Zhu and others, 'Improving Fertility and Productivity of a Highly-Weathered Upland Soil in Subtropical China by Incorporating Rice Straw', *Plant and Soil*, 331.1 (2010), 427–37 <https://doi.org/10.1007/s11104-009-0263-z>.

[59] Cazeneuve, Mahé, and Vert.

[60] Paul Clifford, *Removal of Unwanted Metals and Materials in Phosphoric Acid by Means of Magnetic Separation*, *University of South Florida, Florida Institute of Phosphate Research*, 1997 <http://fipr.state.fl.us/wp-content/uploads/2014/12/01-116-136Final.pdf>.

carcinogen and toxic air contaminant; however, the researchers point out limitation in the ability to isolate the effects of cadmium from potentially confounding exposures (Lead, cigarette smoking). Exposure might be broad: cadmium is relatively mobile for a heavy metal and can be absorbed by the oral, dermal, and inhalation routes of exposure. Absorption and retention of cadmium is then influenced by age, pregnancy, other components of the diet.[61]

Different jurisdiction in the world have therefore set legal restrictions on Cadmium in fertilizers, in some European countries (from 17.5 mg Cd/kg P205 in the Netherlands, the most stringent limit, to 90 mg Cd/kg P205 in Belgium), in some US states (California, Oregon, Washington), and less protective levels in Australia (131 mg Cd/kg P205) and Japan (148 mg Cd/kg P205). A push for more stringent cap on cadmium concentration in fertilizers is currently led in Europe[62] and in the USA. For example, based on the arguments that "*Vegetables and grains are the most common sources of fertilizer-derived cadmium in the diet*" and "*Fertilizer runoff into surface waters may also contribute to high levels of cadmium in fish and shellfish*", the Pollution Prevention Resource Center asks for higher limits in the US in order to meet "*health and environmental protection goals*"[63].

Behind the health and environment discussion is also a push from phosphate producers especially in Russia[64], where the phosphate is naturally lower in cadmium than in other parts of the world, especially Morocco.

Whatever the reasons for regulating the content of cadmium in fertilizers are, such cap or limitation could have different sorts of impact on the industrial activities, processes and costs.

On the long run, such limitation would probably call for new technology development: currently, Cadmium can be removed from phosphate ore and, less costly, from phosphoric acid, with still a "significant" impact on cost.[65] Technology improvement, scale effect, might improve costs, and additionally, the acceptance of additional costs for "cadmium-free" products is likely to increase. Products that would be considered excessively expensive today might become a new norm in the future.

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[61] Reproductive and cancer Hazard Assessment Section (RCHAS), Office of Environmental Health Hazard Assessment (OEHHA), and California Environmental Protection Agency (Cal/EPA), *Evidence on Developmental and Reproductive Toxicity of Cadmium*, *California Environmental Protection Agency*, 1996.

[62] Reuters, 'EU Agrees on Maximum Cadmium Level in Fertilisers', 2018 <https://www.reuters.com/article/us-eu-cadmium/eu-agrees-on-maximum-cadmium-level-in-fertilisers-idUSKCN1NP2CH> [accessed 12 November 2019]; European Commission, 'Commission Recommendation of 4 April 2014 on the Reduction of the Presence of Cadmium in Foodstuffs', 2014 <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32014H0193&from=EN> [accessed 12 November 2019].

[63] PPRC, *FAQs About Cadmium in Fertilizer : Fertilizer Laws and Limits*, 2017 <http://pprc.org/wp-content/uploads/2017/07/Cd-in-Fertilizer_Cd-Contamination-in-Plants_7-17-17.pdf>.

[64] Matt Apuzzo, 'A Vital Mineral, a Toxic Metal and Fears of a Russian Power Play', *New York Times* (New York, 22 October 2018), p. A-1 <https://www.nytimes.com/2018/10/21/world/europe/russia-europe-fertilizer-regulation.html>.

[65] J Keith Syers, 'Progress in the Development of Decadmiation of Phosphorous Fertilizers', in *Fertilizer Industry Federation of Australia, Inc., Conference*, 2001, pp. 101–6.

As an immediate effect, we assume that such cap on cadmium might reduce rock's "suitability". We note (appendix9.14 page 102) that the distribution of cadmium within each deposit is variable. Therefore, we assume that a first possibility as more stringent regulations on cadmium happen locally could be to proceed to additional filtering of the rock, to keep using untreated rock suitable for each market until technology development happens.

5.4. Analysis of the potential impacts on the system and takeaway

The comprehensive review of the different concerns or regulations motivated by environmental considerations have shown a series of potential local impacts on the system. On one hand, those impacts could produce a distortion of regional economic conditions of production, for the phosphate and phosphate-based fertilizers industry itself, but also for the non-integrated customers of rock and acid, and for the suppliers of raw materials. This distortion could have long-term impacts on the geographic distribution of the production facilities and on the costs of production. On the other hand, we also have observed potential changes in the demand structure (volume, and types of product) driven by new requirements (e.g., cadmium limitation) or new practices (e.g., circular economy).

Classification of the major risks and potential impacts on the system

We are interested to represent the potential impact of those multiple areas of uncertainties in potential in-depth transformation of the system's environment. We therefore classify the multiple local impacts we have observed into four major environmental risks (summarized in Table 1):

- Potential disruption in the supply available for international trade.
  East Asia, especially China, has currently huge capacities of production feeding massive internal market. A sudden push from local governments to adopt best management practices for the use of fertilizers and decrease even by a small fraction, the consumption, could have repercussions on the International supply. Even with higher costs of production, it is realistic to assume that mines and fertilizer plant wouldn't abruptly shut down but would more likely offer their production to the international trade, potentially generating a situation of over-supply. This scenario would have a direct impact on phosphate rock and fertilizers prices on the commodity markets (drop).
- Potential creation of parallel markets, or partial "de-commoditization" of the production.
  We assume that this shift could be caused by a change in requirement in the rock's composition (e.g., cadmium cap) and could first imply an adaptation of the mining flow (additional effort to sort out the rock, given the range of different cadmium concentration in a same phosphate reserve). On the longer term, this trend would be calling for the adoption of new technologies in acid or fertilizer production (e.g., cadmium removal techniques, at a cost) and a very partial "de-commoditization" of the fertilizer market with specific products tailored to some regions. This customization and creation of parallel markets could also happen for different reasons, such as the emergence of new demand for customized products to specific regions, depending on the soil's properties, the type of crops, ...

Additionally, in the longer run:

- Potential redistribution of the economic contexts of production, that could reorganize the global locations of capacities of production. This could impact the raw material supply (cost and, potentially, availability) as well as the markets (change in the non-integrated fertilizers manufacturer's locations or practices).
- Potential restructuration of the global demand, with a reinforcement of local autonomy and circular economy. This could change the trade balance in some region, calling for securing local markets, and potentially also for integrating additional downstream activities such as environmental consulting.

Table 1: Classification of key areas of uncertainties to address. <Uncertainty> causes <Risk/Opportunity> handled by <Mitigation/Exploitation> resulting in <Outcome>

Uncertainty	**Risk/opportunity**	**Potential Mitigation/Exploitation**	**Outcome**
i. Disruption in supply available for trade	Shock in price: revenue degradation or unsustainable fly-up	With lower costs of operation than most of the competitors, OCP group is in position to punctually adapt its margins. The type of commercial relationships (long term vs short term contracts and price revalorization) impacts the immediate sensitivity to market conditions. In the longer run, reconsidering the capacity expansion in case of lower margins becomes necessary to maintain a desired return from investments.	Robustness
ii. Discretization of requirements for the products (e.g. stringent cap on cadmium)	Market shifts, call for new capabilities	In the short-term, new requirements might impact the suitability of rock for specific markets, requiring sorting the rock on the basis of additional requirements, changing the flow of rock production. In the longer term, such market shifts would call for a portfolio perspective, with the ability to develop new technologies (removal unwanted materials) and adequate products as needed.	Evolvability
iii. Long term distortions in the production costs in different regions	Upstream: challenging raw material supply, Downstream: redistribution of the traditional markets for acid and rock.	Design choices in the supply chain (e.g., physical stocks for immediate security of raw material supply, but also partnerships with specific suppliers or non-integrated acid or fertilizer manufacturer, physical stocks)	Reliability
iv. In-depth transformation of the demand’s structure	Market shifts, call for complementary capabilities	Integration of downstream capabilities in distribution and consulting)	Evolvability

Takeaway

Climate change could be the issue that dominates the 2020s. It is important for companies to proactively adapt their practices to manage their carbon footprint, changing their value chains to optimize the use of energy, water, reduce the generation of waste and pollution, and, last but not least, communicate their progress and approach. Overall, environmental pressures might have a more systemic impact and change the relative economics: products that are considered expansive today may become standard. Social acceptability is also likely to evolve, impacting agricultural practices and policies with aftermaths effects for mineral fertilizers.

The main takeaway is then, to recognize that, environmental regulations are not only impacting today parts of the system (regulating the uses, regulating the production processes). They are also susceptible to cascade into a much deeper shift or disruption of the global market. Thus, the challenge for companies is also to think differently about the strategic planning: how to picture a companies' activities in a quite different "market equilibrium" – or world?

Overall, we chose to address the first two trends susceptible to emerge and lead to a restructuration of the industry under the constraints of environmental push:

- From the demand side, the already well identified trend to rationalize the use of mineral fertilizers, potentially coupled with a strongly reinforced effort to locally reuse the manure generated by the meat industry and improve "circular economy" (and regional independence), could disrupt the import / export trade balance. We pick the example of China to illustrate a plausible case of a very high production that could shift from local market to trade, and potentially in a quite abrupt way.
- Discretization of the fertilizer market: new stringent regulations or demand could also be susceptible to transform the production. The example of a limitation of targeted chemical elements (typically, heavy metals naturally present at different levels of concentration, as cadmium) in the products, could affect the mining process and create a need for additional selection of the rock used, or additional transformation during the chemical production, to come up with customized products for specific markets. In some proportion, this trend could replace commodity products with specialty products.

6. Case study: designing flexible strategy to address environmental uncertainties

6.1. Objectives and methodology

The objective is to develop a tool to quantitatively assess the effect of different uncertainties on our system's performance, namely OCP group's net present value: a high-level "screening model" of the group's cashflows resulting from their industrial and commercial operations. We discuss below the framing we choose to adopt to elaborate this model, and the overall methodology and use we propose to make of this tool.

Framing the screening model

The model aims to capture the effects of exogenous possible shocks to the system. We therefore want to have a granularity that might capture the effect of variations in upstream activities (supply of raw material) and downstream processes (sale price on international trade markets and market per type of products).

The model should enable the exploration of different strategic drivers, opening the usual design space for strategic planning. Accompanying OCP group's evolution towards partial "de-commoditization" requires thinking the industrial and commercial strategy across different dimensions that partly shape the model's elaboration. Beyond the capacity expansion given the market price (strategy based on volume), the model should enable the quantitative exploration alternative drivers, that we represent in Figure 17.

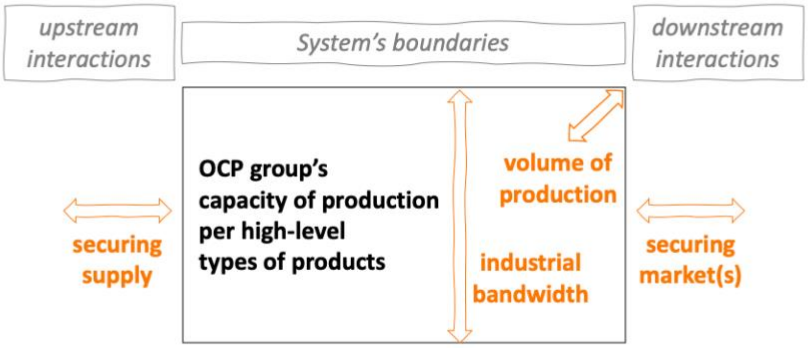

Figure 17: Alternative strategic drivers that could be quantitatively explored with the screening model, beyond the traditional "volume of production" driver.

Resulting from this intended exploration, the model should make it possible to:

- Think across the volume of production (historical approach): integrate the inputs describing the modalities (capital expenditures, timing) of any capacity expansion plan per type of product.

- Think across the industrial bandwidth: dissociate the cash-flows per high-level type of product and enable a systemic allocation of the production across the industrial bandwidth (arbitrage across the different lines of products). The specific context of environmental uncertainties also calls for considering an additional potential parallel market for fertilizers as a distinct family of product whose characteristics (cost of production, demand, sale price) could take separate path compared to the mainstream commoditized fertilizers family.
- Think about upstream and downstream integration: exogeneous inputs should reflect the upstream and downstream forces so different conditions might be tested.

Objective

Overall, the screening model aims to quantitatively explore the potential gains, and constraints to act on each strategic driver identified. This streamlined cashflow model makes it possible to rapidly test and compare different strategies, along different lines. In fine, through the Monte Carlo methodology described below, the model provides a quantitative evaluation of those potential strategies under the effect of macro-scale uncertainties described in the model's inputs. Based on this evaluation, we explore flexibility in strategic design that could be susceptible to increase the expected value from the industrial investments and reduce the downside.

This methodology aims to be easily replicable in different contexts: such screening model, being a simplified representation of the system's behavior, is a tool that can be relatively easily tailored to different assumptions and objectives. The purpose is to grasp promising strategic levers, based on quantitative comparison of realistic range of possible outcomes under each strategy, opening the discussion and testing the potential assumptions before picking one specific strategic driver to further study and evaluate.

Methodology

We proceed with a systemic approach adapting an existing path[66] to develop a screening model tailored to our context and case.

- We first elaborate and describe the screening model that provides a quantitative performance evaluation of the system depending on the set of variable inputs: circumstances and parameters. Our system is OCP group's industrial activities, producing and trading phosphate rock, phosphoric acid, fertilizers and customized "special" fertilizers (the latest line of products being in the perspective of a partial "de-commoditization" of the fertilizers market). We model streamlined cash-flows over a 10-year period, to obtain as key performance indicator the enterprise's Net Present Value (NPV).
- We then estimate the model's sensitivity to each input taken individually. Doing so, we get a sense of the system's response to good case / worst case assumptions for each variable, keeping all the other input variable at their nominal values.
- We proceed to a "randomization" of inputs: we generate random conceivable values over time, for the model's key uncertain inputs. The random generation of variables is drawn to

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[66] de Neufville and Scholtes.

mimic realistic distribution of input. In our case, we start with a very simple randomization process that should be reviewed and become more specific in the next iterative phase with OCP group.

- Using Monte Carlo simulation with our screening model, we get a realistic representation of the distribution of possible outcomes taking uncertainties into account.
- We finally model real options, as decision rules that could be physically implemented, changing the static base plan into a flexible strategy designed to adapt to actual circumstances.
- Last, we discuss the opportunity to further analyze each flexible strategy explored: what could be the expected gains generated by flexibility, to balance with what would imply the physical implementation of each real option, in terms of upfront allocation of resources or preparation.

6.2. High-level valuation model of the system's performance

A representation of the model's main inputs and output is presented in Figure 18 below and the main salient assumptions or simplifications that have been made are described in this section. For further details, a copy of the excel spreadsheet is given in Appendix 9.16 (page 105).

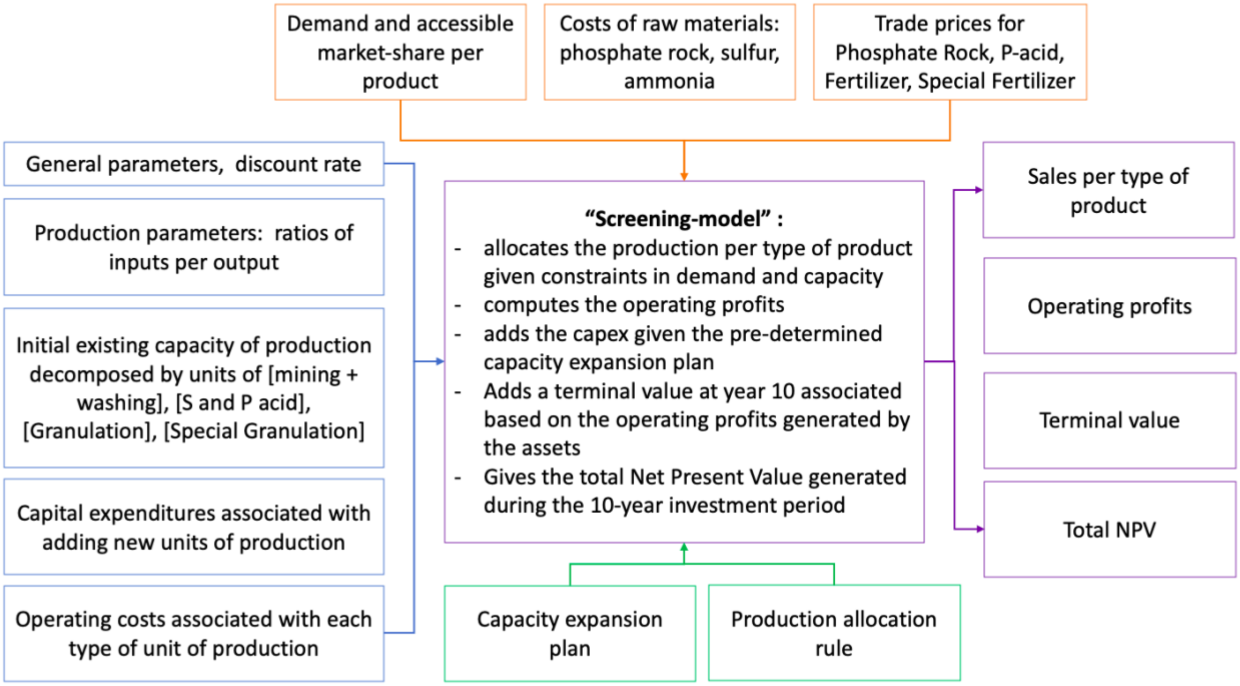

Figure 18: Overview of the Screening model's inputs (internal production parameters in blue, inputs considered as exogenous in orange, decisions in green) and outputs (in purple boxes).

We model the simplified cash-flow resulting from OCP industrial and commercial activities, breaking-down into four lines of products:

- phosphate rock: produced in aggregated mining + washing units of capacity,
- phosphoric acid: produced in chemical units that encompass sulfuric and phosphoric acid production, consuming sulfur and phosphate rock as raw material inputs.

- Mainstream fertilizer: DAP equivalent, produced in granulation units, consuming phosphate rock, phosphoric acid and urea as raw material inputs
- Special fertilizers: customized depending on possible parallel markets to meet a specific demand. Those fertilizers are produced in special granulation units (with customizable parameters compared to the base granulation units) that also consume phosphate rock, phosphoric acid and urea as raw material inputs.

Capacity of production and capital expenditures

We describe the production capacity as a break-down of different "units of production" with a given capacity of production, and the associated costs to build and operate.

The different units of production are:

- Aggregated mining + washing units of production, producing phosphate rock that can be traded or used internally
- Aggregated sulfuric acid and phosphoric acid units of production, producing phosphoric acid that can be traded or used internally
- Standard granulation units, producing mainstream fertilizers (e.g., DAP)
- Advanced granulation units, producing customized fertilizers (potential market segmentation)

We assume an initial capacity of production of OCP group and set up the capacity expansion plan we want to evaluate with the number of units of each type to build per year.

A strong simplifying assumption is to consider "instantaneous delivery" and capital expenditures charge: the capital cost associated with the construction of a new unit is counted all at once, on the same year, and unit of production is included in the total capacity of production the same year, with no ramp-up or even time to build. This could be adapted to a more realistic capital expenditure cash-flow, spreading the cost on several years and assuming a ramp-up time before the nominal capacity of production is reached.

Table 2 below presents the baseline case of capacity expansion we use in this case. This baseline capacity expansion does not refer to a specific plan from OCP, but only to a potential scenario of continuous capacity expansion focused towards granulation units, with a parallel ramp-up in rock and acid to maintain a market-share in a context of moderately increasing demand. This line capacity of production plan aims to be a moderately optimistic plan of reference.

Table 2: Baseline static capacity expansion plan

Baseline static capacity of production expansion plan (* = initial assets, red = investment plan)												
		Y0*	Y1	Y2	Y3	Y4	Y5	Y6	Y7	Y8	Y9	Y10
Mining and wash plants units	units	15	1	1	1	1	1	1	-	-	-	-
P acid units	units	15	-	-	-	1	-	-	-	-	-	-
Granulation unit	units	7	1	1	1	1	1	-	1	1	-	-
Granulation unit advanced	units	-	-	1	-	1	-	1	-	-	-	-

Infrastructures and other investments

We assume the cost of upgrading infrastructure as the production increases is embedded in the cost of the new units of production, which is a simplification. More sophisticated solution could be explored if of interest, to fully account for the steps in cost that could represent an infrastructure reinforcement.

We have also the possibility to integrate "other investments", not directly related to the investment in new units of production but that are either already planned (cost of infrastructures not related to the capacity expansion) or could be recurrent. Again, those cash-flows should be differently tailored to match the specific subject of exploration.

Terminal value of the assets

We choose to set the terminal value of the assets at the end of the 10-year period is the projection of the last year's operating profit, projected to the infinite using the discount rate and an assumed growth rate at the end of the period.

Operating costs

Operating costs are broken down into:

- Variable costs per line of production: we only focus on costs of raw material (phosphate rock, sulfur, urea). Their consumption follows the volume of production, based on different parameters entered for the different ratios of input per output.
- Fixed operational cost: applied per unit of production, independent of the capacity utilization.

Allocation of the production along the value chain

An interesting feature of the production is that the value chain can be interrupted at different stages: selling rock, acid, or the end-product fertilizer. There is an arbitrage, with a bounded capacity of production, to allocate each product to trade or to use in the downstream chain of production.

As a starting point, we choose an allocation rule that always prioritizes fertilizers, over acid, over rock. This baseline "allocation plan A" is directed to match the demand for fertilizers first, using the required quantities of acid and rock, and then trade the remaining acid, and rock (the detailed calculation is provided in appendix 9.18 page 112).

We additionally test and compare other allocation strategies that we will discuss in section 6.5.

Markets: demand, raw materials costs and sale price

We first make static assumptions for demand, costs of raw materials and prices on the commodity markets. We then acknowledge and integrate a range of uncertainty around the static trends as described in section 6.4.

Regarding the demand, we assume a global demand, and a percentage of accessible market-share for OCP group. The magnitude of the global demand is based on a projection of the historical trends for phosphate rock and phosphate-based fertilizers consumptions based mainly on the data collected from the IFA (presented in section 3.1).

The static assumptions about costs of urea and sulfur are based on historical data provided by The World Bank (commodity markets) and the US GS (presented in section 3.3). The assumptions for the phosphate rock price and fertilizer price are based on the World Bank data – we use DAP prices for fertilizers. Phosphoric acid price is extrapolated between its production cost and the fertilizer price. Special fertilizer price is assumed to not fluctuate with the commodity markets: as a special product on a parallel market, we assume it is sold at a set margin on the production cost – which makes this market safer, but also with no fly-up.

Output: enterprise's net present value (normalized)

Based on the screening model we have developed and on the set of static assumptions presented above, including our deterministic nominal forecasts for demand, costs of raw material, and products' sale price over the 10-year period of observation, we get a deterministic evaluation of the net present value, sum of the discounted cash-flows generated from the operations (profit), investments in new capacities of production (capital expenditures), and terminal value of the assets. We refer to this first result as the "static base NPV".

We systematically normalize the NPV presented, to prevent any disclosure of information sensitive to OCP group. We set that the baseline case under uncertainty at an expected NPV equal to 1. We keep this same normalization ratio for all the results, we therefore always present the normalized NPV as a relative NPV compared to the expected NPV under the baseline set of assumptions.

Let's insist that this screening model is not meant to provide a "truth", but only a good-enough approximation of the stream-lined cash-flows given different contexts, with the purpose of exploring and comparing new strategic drivers to manage environmental risks. A different focus could require a different framing, and all assumptions are meant to be tested, and adapted if needed. This tool is first useful to check and challenge the different intuitions we might have in mind, and then proceed to further exploration depending on potential surprising, maybe counter-intuitive results – which might either indicate a need to correct the tool or a need to update the mental-model.

6.3. Sensitivity analysis: how bad, how good could it get?

We first test the model's sensitivity to each input independently, to produce the "tornado diagram" to compare how potential changes in any input change the net present value, compared to the static base NPV.

Methodology

For each of the input variables, we assume a possible variation from the nominal value taken in our base case: a potential best case and worst case.

Every other variable being equal to its nominal value, we measure the difference the worst / best value makes to the outcome: the percentage variation of the NPV compared to the nominal static base case. Some input variables might be assumed to vary over a wide range, others do not. Overall, the focus is on the variation it causes on the net present value.

The detailed assumptions for each input's range of variation and the comprehensive list of results is presented in appendix 9.17 (page 109).

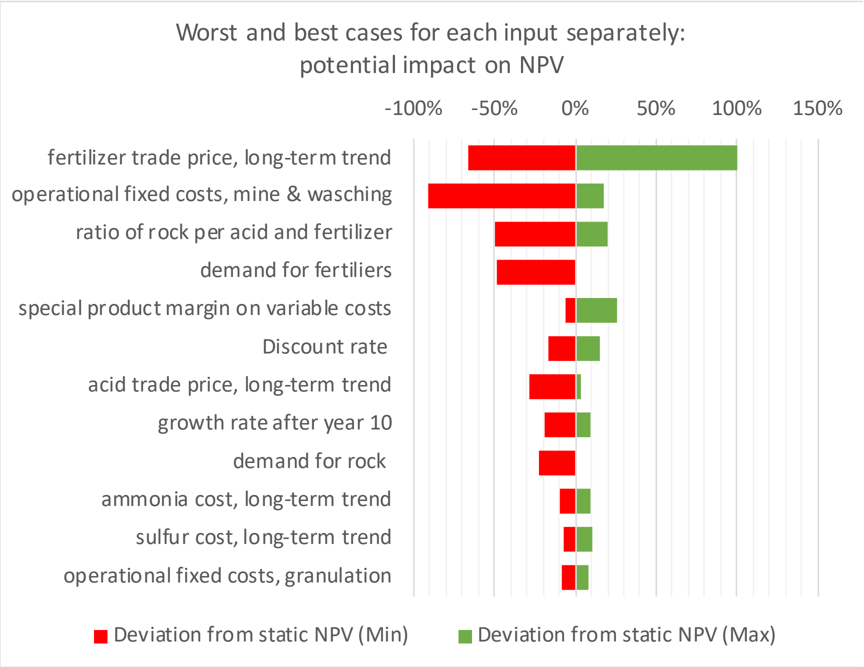

Figure 19: Tornado diagram showing the effect of worst / best case assumptions for each variable independently on the NPV for selected potentially most impactful input variables.

Takeaway

As we are focused on environmental risks, the range of variation we have imagined for the inputs results from two identified major uncertainties identified:

- The risk on new restrictions for chemical elements present in phosphate, typically heavy metals limitation (cadmium), is assumed to potentially generate significant extra operational costs in mining or impact the quantity of rock that is required to produce the same amount of acid of fertilizer. This risk could also directly hurt the demand for rock. Those three input variables have the ability to impact significantly the outcome, on the downside.
- The risk on over-supply on the fertilizer international commodity market is assumed to potentially hurt the long-term trend for the fertilizers, which also has the potential to significantly hurt the NPV. On the other hand, as a fly-up remains also an eventuality, we observe that the best-case with a significant increase in the long-term trend for fertilizers price boosts the NPV – providing the most positive possible variation compared to the base case.

Besides these potential significant deviations driven by the two identified environmental risks, the diagram also highlights the asymmetry of the possible impacts.

As we noticed, the variation on the fertilizer price could provide good as well as bad "surprises", which is also true for the raw material costs (sulfur, ammonia).

The asymmetry in some potential outcomes are interesting to note:

- Operational costs, production parameters, cost of capacity expansion can drive the NPV down in the worst cases, and not as good in the best case. We assume that the range of possible variation for those inputs is itself not symmetric: technological improvement could improve those costs and production parameters, but not as much as new requirements or construction delays and over cost could hurt them.
- Demand for rock, demand for fertilizers are assumed to potentially increase or decrease, with a symmetry in the range of uncertainty. However, we note that the system does not have the ability to make the best of the positive eventualities and additional demand. This produces the asymmetry in the range of NPV variation. The capacity being fully utilized in the base case, a variation in the demand is only susceptible to hurt.

6.4. Introduction of uncertainties

Overview of a "Monte Carlo simulation"

The Monte Carlo simulation relies on:

- The randomization of some selected input variables to mimic their potential distribution of variation during the 10-year period of observation.
- The repetition of the simulation: we run 5,000 times the model, each run with a new set of randomly generated input variables. We track the outcome (NPV, and as desired, intermediary results) for each run.

We therefore get a set of 5,000 potential outcomes. This covers a realistic set of potential outcomes, with some useful information to ground strategic planning: especially (but not limited to) the range of possible outcome, the distribution, the expected outcome (average NPV).

Modeling volatility and gradual uncertainties

The "randomization" is the introduction of realistic variation around the static base assumptions, given a chosen distribution of variation. We describe in this section the randomization of key uncertain inputs we have chosen.

We use a very simple method of variation, using only uniform distribution for the variation within the range we assume. This is a very rough first randomization, which tends to overvalue extremes scenario.

More realistically, the distribution of each input, reflecting actual probabilities of variation, is likely to have a specific mean, standard deviation, and mode, potentially skewed one end or another. Alternative methods of randomization matching better realistic distribution of potential scenarios should be used, with tailored distribution of variation or recursive effects to reflect the cyclicity of specific markets[67].

At this point, having no specific assumptions for each input's distribution, we use uniform distribution for demonstration purposes. Future iterations about this screening model should include first a review of each input's likely distribution, to define the randomization process more appropriately so it actually reflects the distribution of possible scenarios.

Randomized accessible market-shares of rock, acid, fertilizer, and special fertilizers:

We assume a range of variation (min and max %) of the accessible market-share that OCP group can fulfill and generate a random percentage of variation within this range, each year.

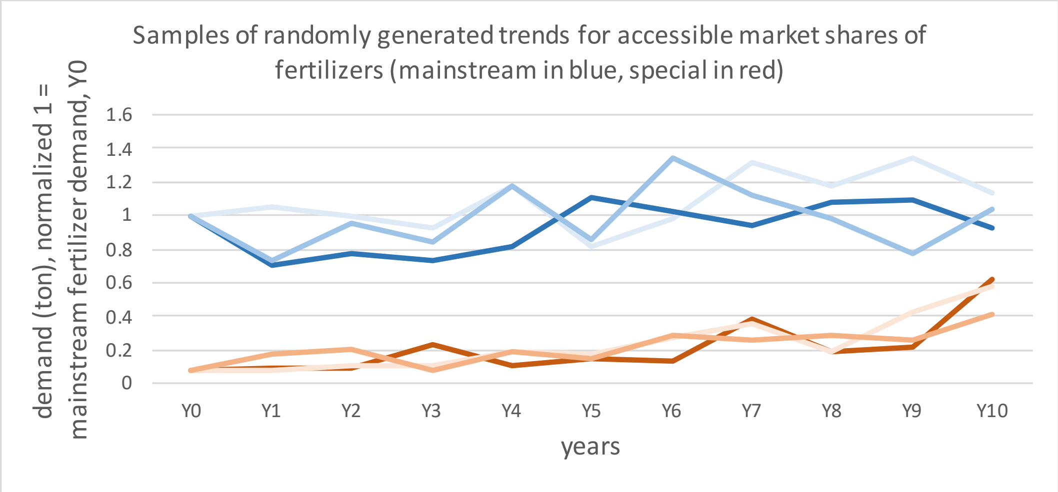

Figure 20: 3 samples of randomly generated trends for the accessible demand of fertilizers (mainstream in blue, base 1 at year 0, and special fertilizers in red).

The "accessible market-share" is the percentage of the global demand that OCP group can serve, depending on its capacity of production. In our set of assumption, this accessible demand is in most cases slightly above the capacity of production, which means that the capacity of production is the most limitative constraint. This could be adapted in other specific scenarios of interest.

Randomization of the cost of raw material supply:

The base static assumption is a linear increase assuming a long-term percentage of variation between year 10 and year zero. We define a range of uncertainty for this long-term variation (+ or - x% compared to the static range of variation) and generate a long-term random variation within the defined range.

On top of the long-term trend variation, we also generate an annual volatility range (+ or – y% compared to the long-term trend).

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[67] David Geltner and Richard de Neufville, *Flexibility and Real Estate Valuation under Uncertainty: A Practical Guide for Developers* (John Wiley & Sons, 2018).

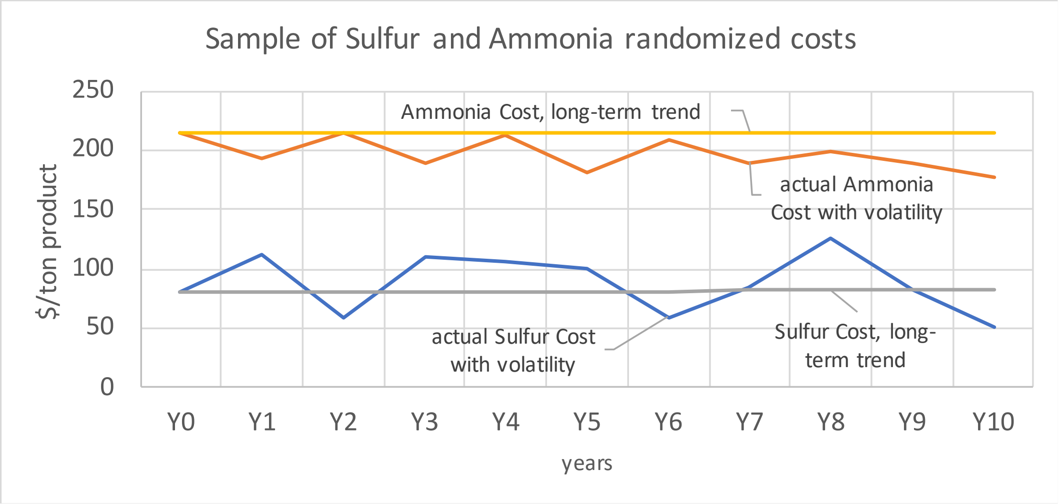

Figure 21: Samples of independent randomization generated for the long-term trends and annual volatility of sulfur and ammonia costs over time.

Note that despite some possible correlation between ammonia price and fertilizers cost (described in appendix 9.12 page 99), we have not reproduced any relationship between raw material costs and sale costs, with the intention to keep the embedded assumptions and randomization processes as simple as possible. This could be done more precisely with a different purpose.

Randomization of the market price for rock and fertilizers:

We use the same methodology than for the cost of raw materials, based on a range of variation for the long-term trend, and the addition of annual volatility.

The difference is that we synchronize the direction of change for phosphate rock and fertilizer prices: they increase or decrease in synch, but with different randomly picked within the assumed range (not correlated) magnitudes.

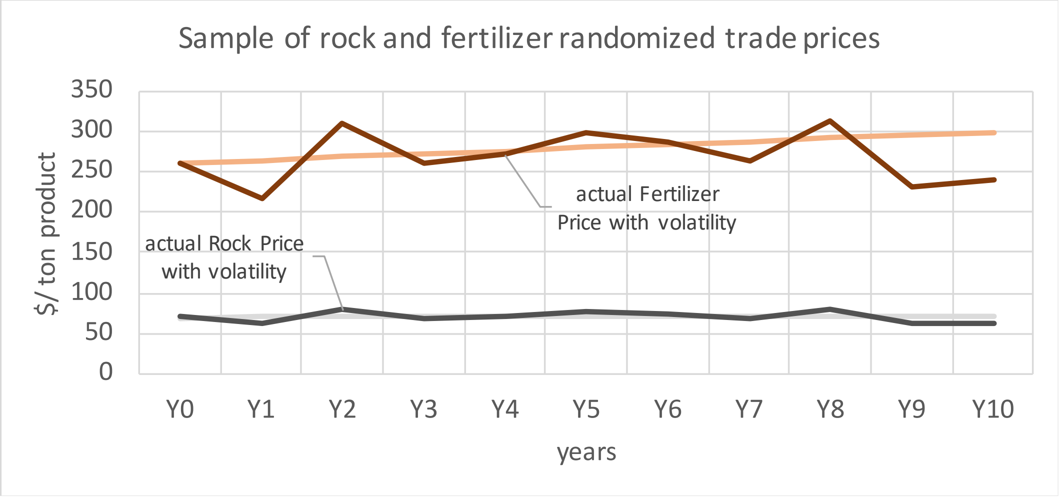

Figure 22: Samples of synchronized random long-term trends and "actual" with annual volatility for rock and fertilizers prices.

Modeling the possible occurrence of major disruption

Last, we add the possibility to create disruptive path, with a given probability of occurrence during the period.

We focus on the potentiality on a price drop for fertilizers, acid and rock, caused by a sudden over-supply of the international market.

We assume that this probability is null at first (year 0), increases linearly until year 5 (mid-term horizon) and then is constant from year 5 to 10. Our base case assumes a probability of disruption during the whole period of about 10%. We also test the simulations with a medium / high probability of disruption of 60%, as presented in the table below.

Table 3: Probability to have a sharp decrease of the phosphate prices starts at zero and increases until year 5, then remains constant, for an overall probability of occurrence of 0.1 in the base case.

	probability at year 0	probability at year 0 to 5	probability at year 5 to 10	**probability of occurrence over the whole period**
low probability (baseline)	**0**	**linear increase**	**0.01, constant**	**0.1**

We incorporate this base assumption of a 10% probability of occurrence, with a stronger chance during the second half of the period of observation, in the randomization of rock, acid and fertilizer prices.

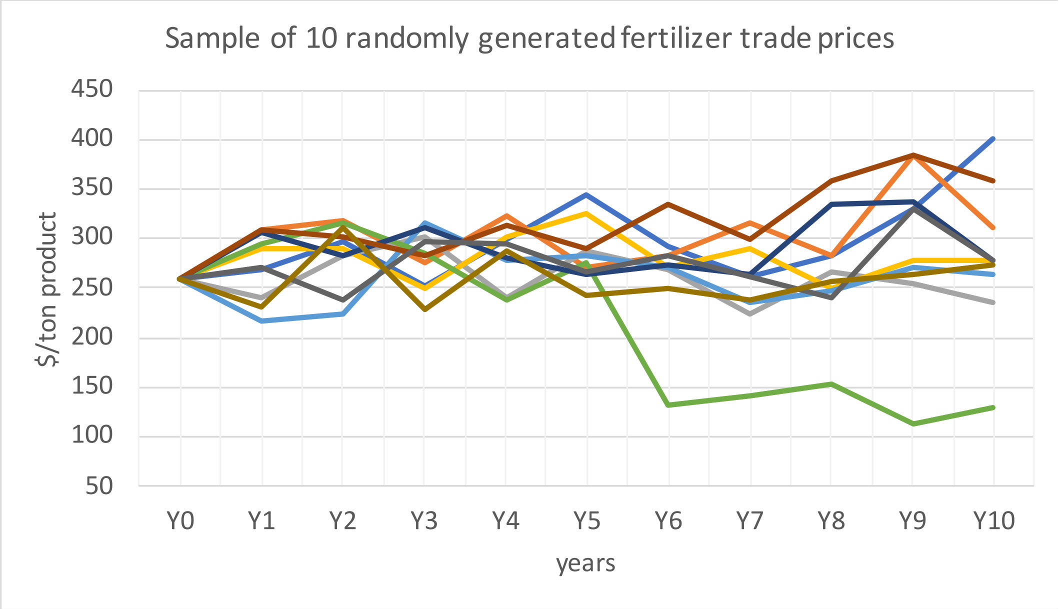

Figure 23: Sample of 10 randomized fertilizer prices showing 1 disrupted path.

We illustrate with Figure 23 above a sample of 10 randomized trends including one disruptive path, for the mainstream fertilizers price. Note that special fertilizer prices, being assumed to be sold on a “de-commoditized” parallel market, does not follow those randomized trends (as described in the previous section, the sale price ensures a constant profit margin on top of the production cost).

Effect of acknowledging uncertainties on the performance evaluation

Based on the set of assumption and randomization of key uncertain variables described, we proceed to a Monte-Carlo simulation, generating 5,000 runs and tracking the resulting NPV. We now can compare the deterministic case, that provides one value of NPV based on one set of deterministic forecasts, with the results from the simulation, distribution of possible NPV resulting for each potential set of input.

As a reminder, all the results are presented below in terms of normalized NPV: we apply systematically a factor that makes the expected NPV for our baseline case equal to 1. This is the reference value against which we measure all the results, under different circumstances or strategies.

Table 4: Summary of the configurations tested to illustrate the effect of uncertainties on the NPV.

configuration	capacity of production	uncertainties
Capacity expansion, No Uncertainty	Static baseline capacity expansion plan (Table 2)	No uncertainties. Deterministic forecasts for the inputs.
Capacity expansion		With uncertainties. Randomization of demand, costs, prices.
Constant capacity	No addition of new capacities on top of initial capacities.	

Figure 24 shows the effect of introducing uncertainties in the performance’s evaluation (net present value), and Table 5 below summarizes salient metrics to compare the results, that we discuss in the next paragraphs. Overall, we illustrate how an evaluation based on deterministic inputs (forecasts for variables are fixed) might be misleading. The “capacity expansion” plan, with no uncertainties, is supposed to achieve an NPV equal to $1.4 normalized NPV. Introducing uncertainties produces:

- A more realistic review of the expected NPV, now equal to $1 normalized NPV. The expected NPV is the mean of the 5,000 NPVs obtained with each run.
- The distribution of NPV, highlighting the values at risk or at gain

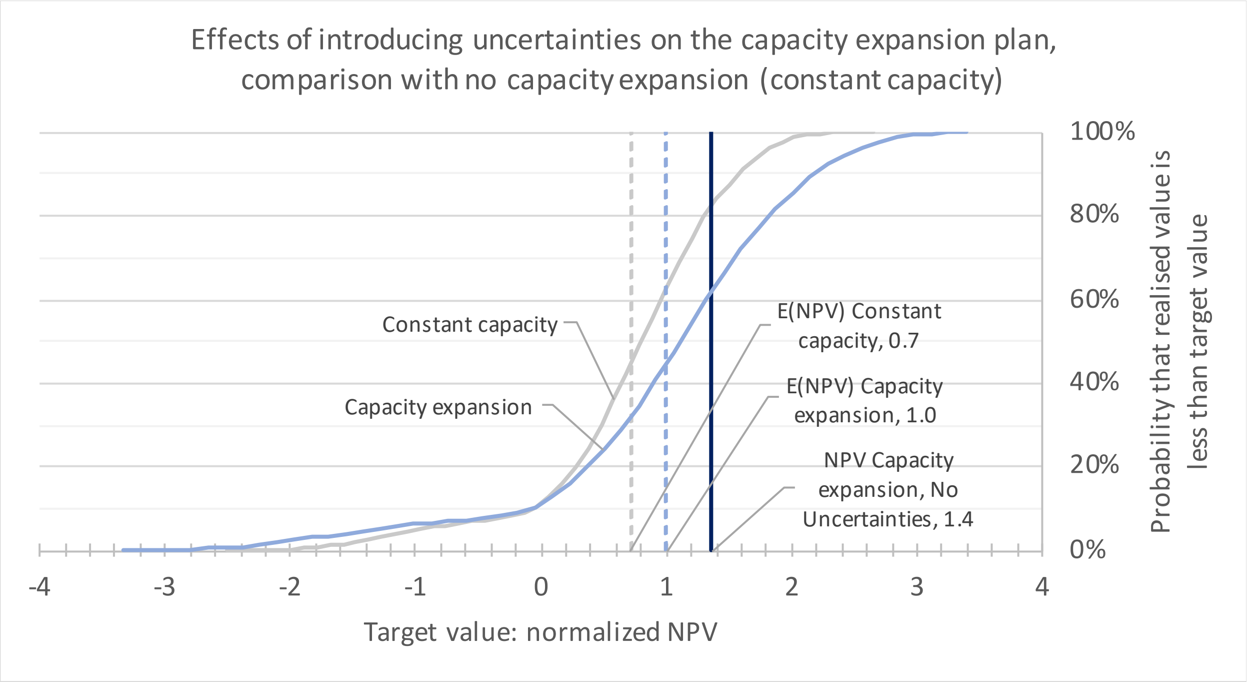

Figure 24: Introducing uncertainties shifts the expected NPV; the Zero Capex plan illustrates that in the worst cases (20%), no investments limits losses compared to the baseline.

Table 5: Comparison of results when introducing uncertainties: multidimensional analysis including perspective of minimum of maximum achievable results.

all results in normalized NPV units, *discounted @ year 0* *unless specified otherwise*		**capacity expansion**		**constant capacity**
		without uncertainty	**with uncertainty**	**with uncertainty**
Total Capex for additional units of production		0.46	0.46	0.00
NPV	**expected**	**1.38**	**1.00**	**0.74**
	VAR (cd 5%)	NA	-1.42	-0.96
	VAG (cd 95%)	NA	2.42	1.71
Terminal Value	**expected**	**0.92**	**0.75**	**0.35**
	as a % of expected NPV	*67%*	*75%*	*48%*

Deterministic evaluation

The “Capacity expansion, no uncertainty” scenario leads to a net present value equal to $1.4 normalized NPV. This single figure is however not realistic: it evaluates the performance with a deterministic set of forecasts, for a baseline capacity expansion plans tailored to this forecasted context – as if forecast were possibly true eventually. But as illustrated in the previous sections, prices, costs and demand are volatile and there is uncertainty regarding the long-term trends. This mode of evaluation does not provide any information on the most likely performance.

Results under uncertainty

The results of Monte Carlo simulation, or potential net present value resulting from thousands of possible alternative contexts, are presented as cumulative distribution curves, for the two scenarios “Capacity expansion” and “Constant capacity”.

The cumulative distribution shows, based on the thousands of outcomes generated, the probability of achieving less than the value of normalized NPV represented on the X-axis.

Comparing the NPV of capacity expansion without uncertainty and the distribution of possible NPV of the same capacity expansion plan, under uncertainty, we note that:

- The expected NPV, which is the mean of all the potential outcomes (each random run being as likely to happen as any other), decreases compared to the static case.
- The tail of the curve shows “how bad could it get”: we note that given our assumption of about 10% chance of disruption of the prices, the tail of the cumulative distribution shows potential losses (negative net present value) in the worst cases. But overall, there are also about 43% chances that the net present value is less or equal to the expected $1 normalized NPV.

  In the tables of results, we express the VAR (Value at Risk) associated with a 5% probability to reach that value or less.
- The top of the curve shows “how good could it get”: the distribution provided here shows for example a 10% chance to reach a $2.1 normalized NPV, or a 5% chance to get $2.5 normalized NPV.
- In the tables of results, we express the VAG (Value at Gain) associated with a 95% probability to reach that value or less (i.e., 5% probability to reach that value or more, best cases).

Why is it different? The evaluation of the performance is now: 1- more realistic, taking variations from the forecast – that are bound to happen – into consideration, and 2- multi-dimensional, based on the expected net present value but also the range of variation and distribution.

Overall, the realistic evaluation taken uncertainties into consideration leads to an expected NPV of $1 normalized NPV, when the unrealistic deterministic evaluation announced a net present value of $1.4 normalized NPV.

This change is significant and might change the assessment of the investments planned to increase the capacity of production.

This result illustrates a mechanism that has been already demonstrated in various context including for large interconnected facilities and infrastructure planning[68]. A capacity limited system cannot benefit from upside gain (typically, if demand eventually exceed the capacity) but can be hurt on

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[68] Davide Lasi, ‘Identifying Opportunities for Flexible Design of Infrastructure: Case Studies of a Space Launch Complex and LNG for Sardinia’ (Massachusetts Institute of Technology, 2018).

the downside. Given a symmetric uncertainty (e.g., demand is as likely to be better than to be worst worst), the system's asymmetry implies that the average performance is systematically lower than the deterministic average. With a static investment plan, the downside is likewise typically much worse than the downside is better.

We thereafter also compare the results under the baseline capacity expansion plan and under a constant capacity scenario, where no new capacity of production is added on top of the existing initial assets.

Comparing the "capacity expansion" and "constant capacity" plans under uncertainty

The cumulative distribution curve "Constant capacity" in Figure 24 shows the distribution of NPV when no new capacity is added on top of the initial assets. This scenario limits the downsides but does not reach as much NPV on the better cases.

Overall, as illustrated with the regret plot (Figure 25), in about 13% of the simulations, no capacity expansion provides a higher NPV than the baseline capacity expansion plan. The expected gain from expanding the capacity is equal to \$0.3 normalized NPV.

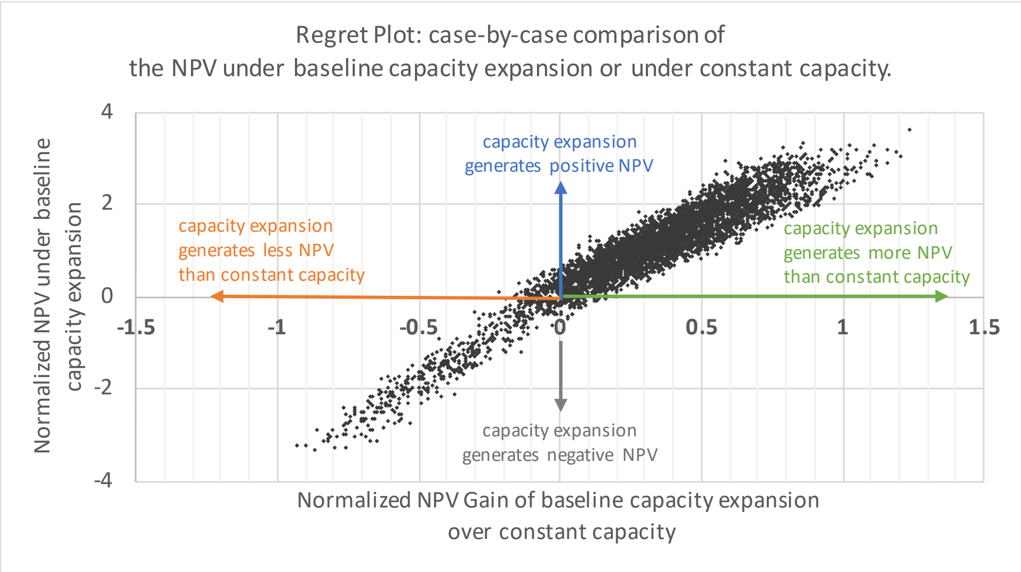

Figure 25: Regret plot: case-by-case comparison of the NPV under the baseline capex plan with the NPV under constant capacity. Upper right quarter shows the cases where the NPV under the baseline capex plan is positive and higher than with the zero-investment plan.

In conclusion, acknowledging and modeling uncertainties moves the discussion about strategic planning, from an evaluation based on one single, not so realistic, forecast, to a multidimensional evaluation where different criterion might be balanced, and expected net present value is discussed all together with minimum, maximum (or value at risk, value at gain), to balance with the chosen capital expenditure plan to assess the financial decision.

6.5. Comparison of possible approaches for exercising flexibility

Now that we have built a simulation tool that enable to test different strategies under realistic uncertain circumstances, we aim to improve the strategic planning integrating flexibility to minimize the downsides and take opportunity of the positive eventualities.

Based on our assessment of different risks (summarized in Table 1, page 52), we anchor our exploration into the shorter-term uncertain perspective of:

- A potential step-decrease in prices caused by a sudden over-supply on the international commodity market (sharp decrease in East Asian consumption example)
- Coupled with the emergence and consolidation of a parallel “special fertilizers” market, that would be de-commoditized and thus relatively protected from the fluctuations in price existing in the commodity markets and might come with a “lower suitability” of phosphate rock (cadmium example).

Given the different strategical drivers that we identify (Figure 17, page 54), we want to quantitatively measure the effects of different possible flexible strategies:

- Flexible strategy on volume: base the investment decision (build new capacity of production) to the actual context, on both the volume of construction and also on the type of units of production to prioritize.
- Flexible strategy on industrial bandwidth: adapt the investment decision (change the type of production units to build) depending on the context
- Flexible strategy on production allocation: adopting arbitrage across the industrial bandwidth to navigate a change in requirements for the rock’s chemical composition (e.g., very low concentration in heavy metal).

We could also further explore strategies, such as securing upstream raw material supply (one example is provided in appendix **Error! Reference source not found.**, page **Error! Bookmark not defined.**) or modeling the effects of downstream integration of new activities. However, those transformations, which would change the system’s boundary, are not for now: we rather focus on the two potentially short-term strategic drivers.

Flexible strategy on volume: “hold if…” decision rule

Motivation:

The introduction of uncertainties shows that there is significant probability to not reach the expected net present value, and thus to not achieve the return of investment associated with a deterministic analysis.

We want to quantitatively evaluate the flexibility to hold the investment in new units of production if the conjecture does not meet the forecast.

In practice, we can assume that new investments would be reconsidered, and potentially postpone or cancelled, in such case of conjuncture worse than expected. The point here is to quantitatively assess the gain that could be made, given our specific assumptions (e.g., units type, size and costs), by postponing their construction when circumstances are not good. This evaluation will help inform the upfront cost that could be required to develop this flexibility.

Indeed, the flexibility to hold the development of new units is not obvious and requires designing each unit with sufficient modularity, as well as developing adaptable infrastructure and transportation functions.

Implementation in the model:

The baseline capacity expansion plan is still as presented in Table 2, page 57.

A flexible "hold capacity if" plan is implemented in the model as a decision rule: each year, instead of following the static capacity expansion plan, we make the decision:

- if the prices are at least X% as forecasted in the static forecast, build the new units of capacity as planned for the current year
- if the prices are less than X% forecasted in the static forecast, do not build any capacity for the current year
- "X%" is one decision variable, that we set equal to 85% after a short exploration (we discuss this choice in the results' presentation).

We follow the same logic for each type of capacity expansion: mining and wash plants units (based on the observation of rock trade price), phosphoric acid units (based on the phosphoric acid trade price), and special granulation units (based on special products price – which depends on production costs).

Note that the decision rule is made very simple, to generate discussion. It could be made much more sophisticated and integrate various other parameters, such as:

- additional conditions based on the capacity utilization,
- additional conditions based on the past n-years trends,
- …

Table 6: Summary of the configurations tested to illustrate a flexible capacity expansion on volume

configuration		**capacity of production**
static plans	Constant capacity	No addition of new capacities on top of initial capacities.
	Capacity expansion	Baseline static capacity expansion plan (Table 2)
flexible plan	Hold capacity if	Follow the capacity expansion plan only if prices are at least as forecasted initially

Results

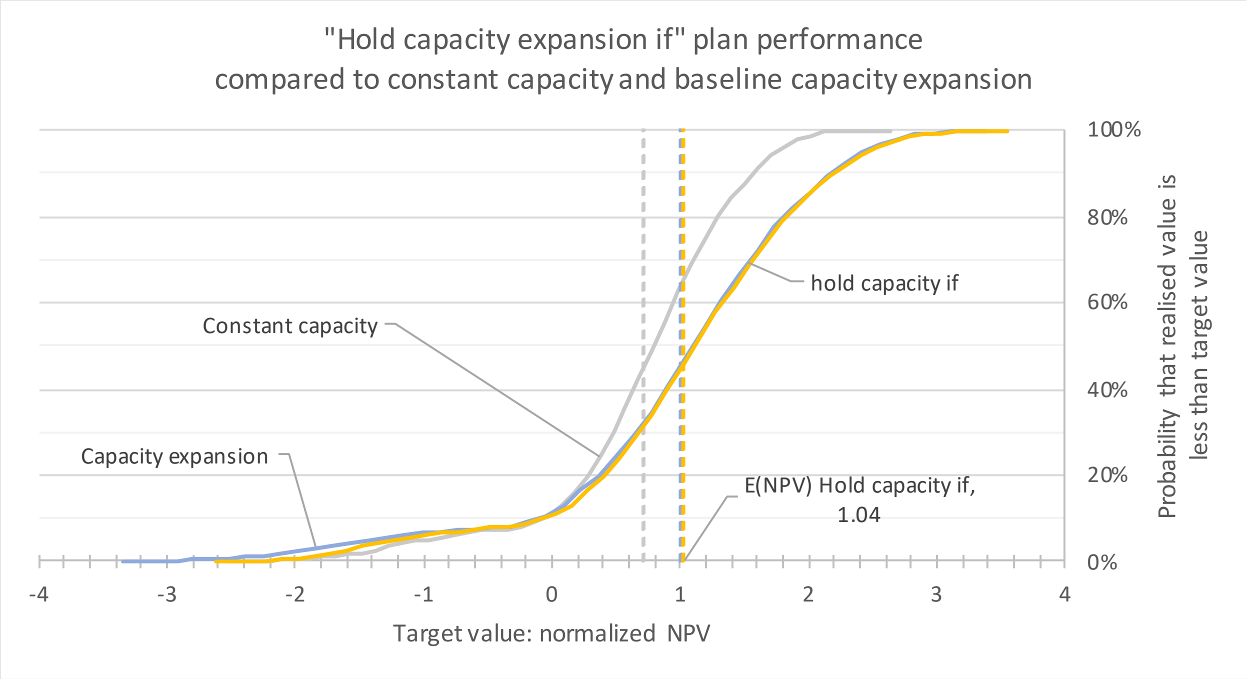

Figure 26: The "Hold Capacity If" flexible option limits the downsides yet does not improve the expected NPV ($1.04 to compare to $1.00 with the static capacity expansion)

The distribution of potential NPV with the flexible "hold capacity if" plan shows that risks are mitigated on the downsides (the tail of the curve gets closer to the "constant capacity" conservative strategy), but does not yet enable to reach as high NPV as the "capacity expansion" static plan. Indeed, in very favorable conjectures, the volume of production (lower on average, see detailed capex on

Table 7) does not allow to achieve as much sales as with the "capacity expansion" plan.

Overall, this first option appears to be mitigating the risks, achieving overall a similar expected NPV, but does not yet improve the expected performance. We therefore test the next option, to adapt capacity expansion when needed.

Discussion of the decision rule:

We underline that the design of the decision rule should be challenged, and variations can be tested within each architecture. We have chosen as an illustrative example to trigger the build / no build decision regarding the goods' prices, compared to the initial forecast. This architecture could change, and be more sophisticated, including considerations on demand or trends over a couple of years, for example.

Furthermore, within this decision rule, one important decision variable is the trigger value. We have chosen here to compare actual prices to 85% or forecasted prices, after a short exploration of the effects of this decision variable on the expected NPV, as shown in Figure 27.

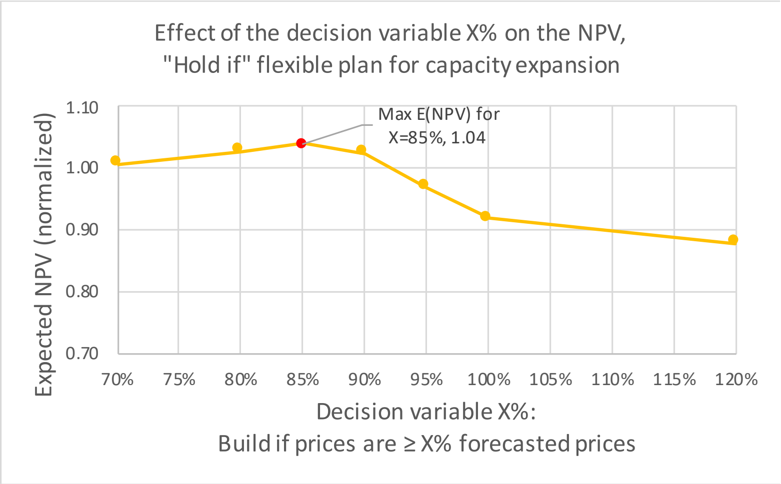

Figure 27: Effect of changing the decision variable X% on the expected NPV, "Hold If..." plan.

We also note that the actual chances to implement the decision to add capacities have a different distribution depending on our decision variable. Figure 28 shows the cumulative distribution of total capital expenditures for new units of production with two different values for the decision variable.

When we set X = 95% (which is more restrictive) we have a 47% probability to spend less than the average total capex, whereas with X = 85% (which is a less stringent constraint and therefore tends to increase the probability of a higher total capital expenditure), the probability to spend less than the average capex decreases to 35%.

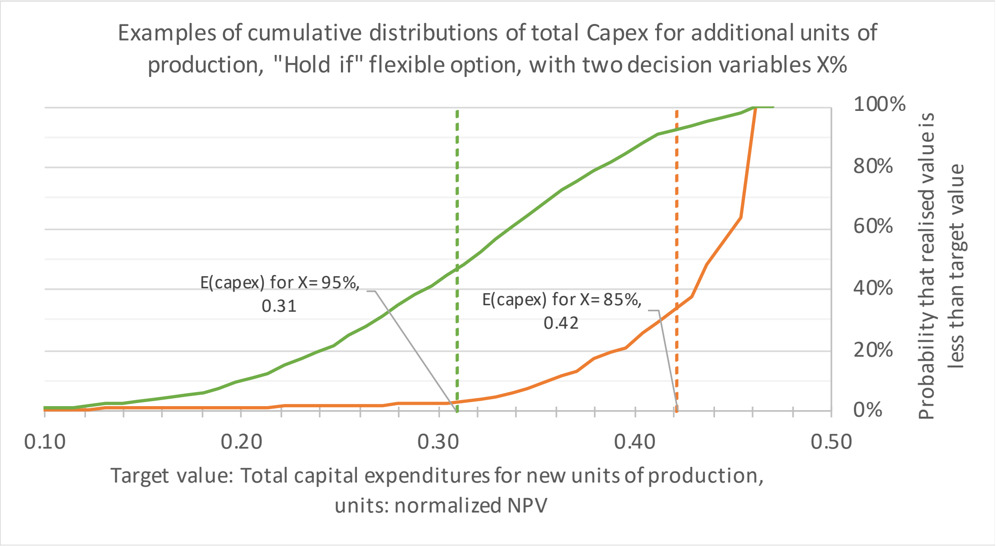

Figure 28: The choice of the decision variable impacts the cumulative distribution of total capital expenditures for additional units of production, within bounded min and max values.

Overall, given our decision's architecture referring to an envelope of capacity expansion plan, the upper value is bounded, which produces the sharp increase in the distribution as soon as we have "built it all". We discuss an alternative flexible rule below, "adapt if…", but recognize that more variations should be tested, especially unbounding the expansion plan if conjecture is better than expected (defining “better” in different possible ways: relatively to costs, demand, prices... or a conjunction of it).

Flexible strategy on volume and type of units: “Adapt if...” decision rule

Motivation:

We couple the adaptation to the downsides with the ability to take advantage of potential opportunities. Under our assumption of the emergence of a parallel market of special fertilizers, less volatile in price, we integrate a flexible option to adapt the balance between mainstream granulation and special granulation units if needed. This flexible option, comparably to the previous one, also requires designing a very modular system of production, which can be challenging.

Implementation:

Each year, we make the following decision implemented in the screening model:

- if the prices are at least as forecasted in the static forecast, build the new units of capacity as planned for the current year
- For mining, chemical, mainstream granulation units: if the prices are less than forecasted in the static forecast, do not build any capacity for the current year.
- For special granulation units: follow the capacity expansion plan and build additional specialized granulation units for any mainstream granulation units that has not been built.

Results:

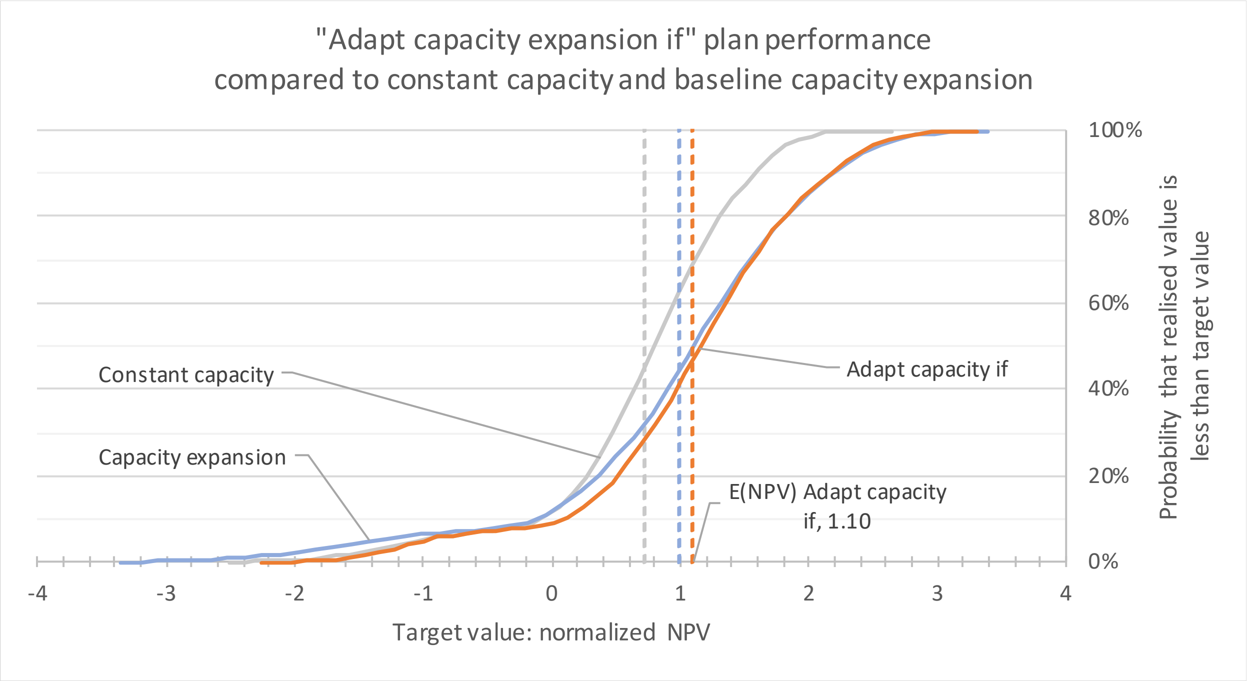

Figure 29: Performance of the adaptable capacity expansion plan compared to the static capacity expansion or constant capacity plans: shifts the distribution of outcomes, mitigating risks on the downside while catching up with the performance of the baseline investment plan on the upside, with an overall improvement in the expected NPV.

We now observe that the “Adapt capacity if” rule shifts the distribution on the downsides, minimizing the losses, while also reaching the best outcomes (when the “hold if…” case couldn’t achieve as good results in the best cases). Overall, we note a 10% increase in expected NPV. The flexible adaptation of the production mitigates risks (meeting the “constant capacity” plan on the downside), increases the expected value (average gain from flexibility), and still meets good performance in the upside.

Table 7: Comparison of results and value of flexibility compared to static plan

all results in normalized NPV units, discounted @ year 0 unless specified otherwise		**static plans**		**flexible options**		**value of flexibility compared to the static capacity expansion**	
		constant capacity	**capacity expansion**	**Hold if**	**Adapt if**	**Hold if**	**Adapt if**
Total Capex for additional units of production	**expected**	**0.00**	**0.46**	0.42	0.44	-8%	-3%
	min, cp 5%	0.00	0.46	0.33	0.38	28%	16%
	max, cp 95%	0.00	0.46	0.46	0.46	1%	1%
NPV	**expected**	**0.74**	**1.00**	1.04	1.10	4%	10%
	VAR, cp 5%	-0.96	-1.42	-1.23	-1.00	14%	30%
	VAG, cp 95%	1.71	2.42	2.41	2.40	0%	-1%

We now can compare, with

Table 7, the different plans with the risk/reward tradeoff in mind.

The “constant capacity” plan is the no-risk reference and as such does not provide as much expected value – still, $0.74 normalized NPV – and does not allow to hope for high NPV (VAG would be $1.71 normalized NPV, -29% compared to the VAG equal to $2.42 normalized NPV achieved with capacity expansion).

The flexible “Adapt if” option is interesting for different aspects, as highlighted in green: the value at risk VAR is minimized (by 30%), cutting some risks, and the expected value is increased by 10%, without compromising the best values (minor -1% decrease in the VAG). This distribution of performance is particularly interesting to balance with the capital expenditures spent in each plan for the capacity expansion: with slightly lower capex on average (-5% with “adapt if”, -11% with “hold if”), the expected NPV and VAG / VAR cases could be weighted with more details.

Especially, a common practice for companies is to maintain a healthy ratio of current earnings (EBITDA) to debt, or “debt coverage”, which can be critical to signal an ability to pay back loans: a degradation of debt coverage could result in a downgraded credit rating, which in turn can make it impossible for low-risk investors (pensions, Insurance funds) to own the debt, generating more difficulties to borrow money at good rates. In short, fewer earning with static debt produces additional substantial penalties in addition to the loss of earnings by itself.

Flexible allocation of production: change production prioritization to maximize revenue

Motivation:

We now want to explore the arbitrage that can be made, more or less intentionally, across the value chain. The more fertilizers and acid are made, the more rock and acid need to be used internally and cannot be directly traded. Instead of marketing each resource (rock, acid, fertilizer) independently, the company might try to optimize sales of all products together – that is, sales group for rock might raise its prices, lose sales (and commissions) so that total income of company might be greater.

We compare different static allocation rules, and then move to a flexible allocation that would be a shift to a more systemic approach to the sales. Instead of fulfilling demand based on a market-share planed by line of product, a flexible allocation would require making arbitrage across the production, changing priorities depending on the market condition.

This flexibility is not obvious and can have an associated upfront cost. Systemic and flexible allocation of production to markets requires the ability to have a transversal management of commercial activities and production, and the flexibility with the customers to adapt the demand fulfilled as needed in the company's preferred interest.

Implementation:

We start by testing allocation plans A, B, C, D, presented in Table 8. It represents a non-exhaustive selection of possible rules.

Table 8: Summary of configurations tested to evaluate the flexible option to allocate the production across the industrial bandwidth under uncertainties.

Allocation plan	**priority**			
	1	**2**	**3**	**4**
A	Special Fertilizers	Mainstream Fertilizers	P-acid	Rock
B	Rock	Special Fertilizers	Mainstream Fertilizers	P-acid
C	P-acid	Special Fertilizers	Mainstream Fertilizers	Rock
D	Special Fertilizers	Mainstream Fertilizers	Rock	P-acid
Flexible	***pick operating profit-maximizing plan between plans A, B, C, D***			

As a reminder, the allocation we assumed of the production to the market or to the down-stream processes happens step by step by order of priority: first allocate the production for first ranked priority product, to fulfill as much demand as possible given the production capacity constraints, then update the remaining capacity for the input products (rock, acid), then move on to the second ranked priority product. A detailed description for the example of the allocation plan A (baseline) is given in appendix 9.18 page 112.

We then build in the model the flexible allocation option, with the decision, each year, to:

- Allocate the production that generates the highest operating profit, based on a comparison of possible results with plans A, B, C and D.

We test the different allocation plans and the flexible allocation in two alternative contexts:

- in the baseline context, with no specific constraints on the rock availability
- in a "lower rock availability" context: we assume than environmental regulation, such as a stringent cap on cadmium, could as a first result decrease the flow of "suitable" rock that can be mined (due to additional delays to sort the rock). This impact would happen before the new technologies, presumably more costly, are adopted (e.g., cadmium removal during acid or fertilizer production).

Results under each context:

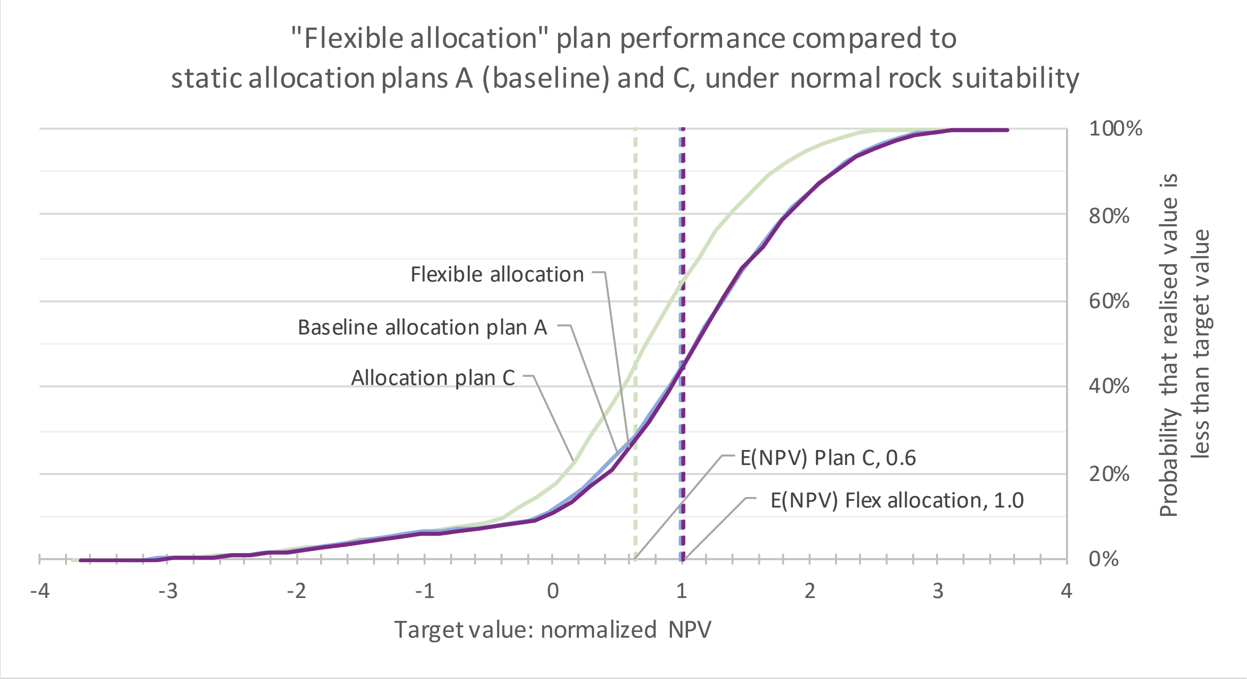

Figure 30: Comparing different allocation rules and the flexible allocation of production. Results of plan A, B, D are very close to the flexible allocation, under the baseline rock production capacity.

Under normal conditions, the allocation "plan A", which has been our baseline, already provides good results, that are not improved much by the flexible allocation option: the expected result and the distribution are quasi-identical.

We note that a different static alternative, plan C, which prioritizes P-acid over rock and fertilizers, achieves significantly lower result on average (expected NPV $0.6 normalized NPV) and best possible outcome (shift of the curve on the upside). Plans B and D, which both put acid last, also achieve good if not slightly better performance than the plan A. However, this result is to be taken cautiously: it relies on the set of assumptions taken, especially for the demand and market-share targeted compared to the capacity. When acid is prioritized, with a high demand, most of the acid capacity is allocated to acid to trade, detrimentally to the fertilizers production, and using a potentially important share of the rock production. Then, the differences of margin per product and volume of sales generates different outcomes.

If these first results initiate a call for arbitrating the allocation of production at the system's level (as opposed to a strategy per product), it does not yet illustrate a gain from flexible allocation.

We then introduce an alternative context of exploration, aligned with the potential uncertainty on a cadmium cap on fertilizers' content. In this perspective, we have assumed that an immediate effect could be a lower "suitability" of rock, i.e. additional screening of the rock and slightly lower flow of "suitable rock" production. This creates a relative "scarcity" of rock compared to the baseline and makes the allocation of production resources more critical.

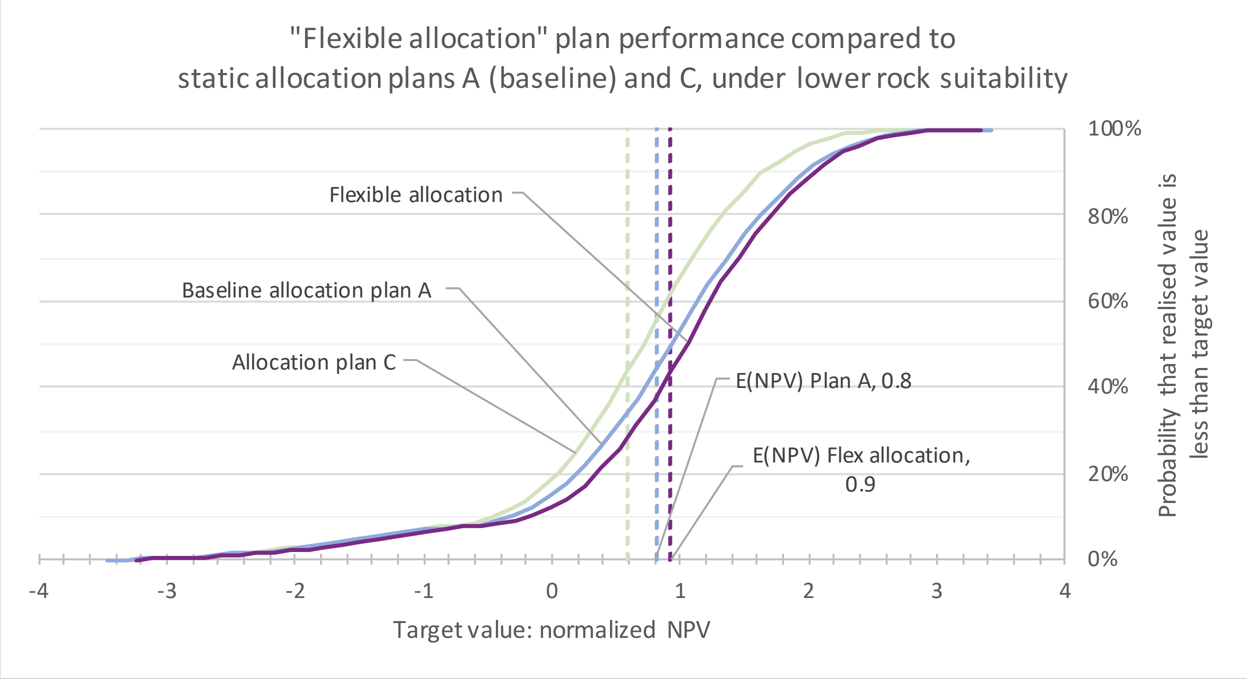

Figure 31: A lower suitability of phosphate rock, slightly decreasing the capacity of production, increases the shift of the distribution of NPV achieved with a flexible allocation compared to the static plan A.

We observe (Figure 31, Table 9) that the new context reduces the performance for the baseline plan A: expected NPV decreases from $1 normalized NPV to $0.8 normalized NPV, which is not surprising since the volume of rock that can be produced each year is slightly smaller (-10% at year 0).

Table 9: Summary of results for different allocation rules compared to the flexible allocation strategy: if static plans can achieve good results, moving to a flexible allocation strategy offers better than our baseline allocation rules, especially in a context of lower rock suitability.

all results in discounted normalized NPV units, *unless specified*		**Plan A**	**plan B**	**Plan C**	**Plan D**	**Flex allocation**	**value of flexibility compared to static plan A**
baseline context							
NPV	**expected**	**1.00**	**1.05**	**0.67**	**1.04**	**1.05**	5%
	VAR 5%	-1.42	-1.54	-1.37	-1.55	-1.18	17%
	VAG 95%	2.42	2.40	1.96	2.41	2.51	4%
operating profits	expected	1.39	1.41	1.28	1.41	1.41	1%
	min, cp 5%	0.76	0.79	0.65	0.79	0.79	4%
	max, cp 95%	1.91	1.90	1.72	1.90	1.90	1%
context of lower rock suitability							
NPV	**expected**	**0.84**	**0.94**	**0.62**	**0.93**	**0.95**	13%
	VAR 5%	-1.40	-1.39	-1.53	-1.31	-1.36	3%
	VAG 95%	2.32	2.31	1.89	2.25	2.26	2%
operating profits	expected	1.31	1.37	1.24	1.37	1.38	5%
	min, cp 5%	0.72	0.77	0.63	0.77	0.78	8%
	max, cp 95%	1.81	1.85	1.67	1.85	1.86	3%

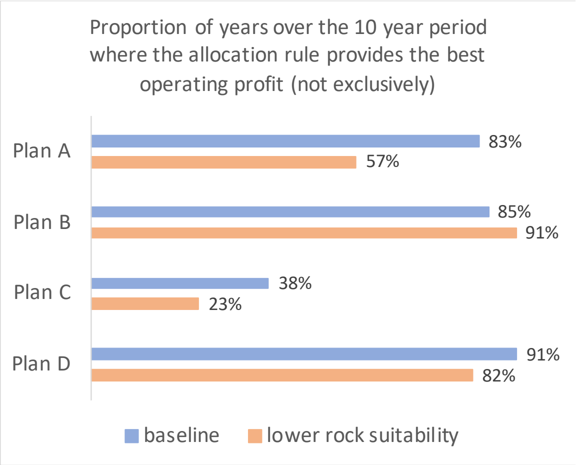

Figure 32: Proportion of years where each plan provides the best net operating profit (not exclusively from others).

Allocation plan C, which prioritizes P-acid, is less favorable under our set of assumptions. Plans A, B, D give close results, without achieving the best possible profit in all cases.

We also see (Figure 32) that a change in context might redistribute the ranking of the static strategies: if plan B that maximized the rock sold seemed to be the most relevant in the base context, plan D that now prioritizes fertilizers over rock over acid reaches highest best NPV in the new context tested (Table 9). Indeed, decreasing the ability of rock makes more critical its allocation to trade or to internal production: the capacity does not allow to meet all demands (rock, acid and fertilizer) in the new context and plan D offers now better results than plan A. Besides, none of the static strategies provides the best possible outcome 100% of the years.

Overall, the comparison of the flexible option with the static baseline plan A show better results in both contexts, with a reinforced effect in the context of lower rock suitability. As we introduce the eventuality of a lower rock production, making the allocation more critical, the allocation process produces greater differences in results. The flexibility enables the system to capture the best possible operating profits each year, and to almost maintain its expected NPV, whereas the NPV resulting from plan A drops.

These results suggest that the internal mechanisms of production allocation are worthwhile to be explored and challenged. This path is very preliminary and requires additional iterations to produce a tangible adaptation of the production allocation process. Still, results point up a promising way to adapt to contextual changes and call for an evaluation of the arbitrage between product at the system's level.

7. Conclusions and articulation with OCP group transformation

Environmental risks call for a shift in practices for strategic planning: move away from the usual practice of grounding strategies based on a deterministic set of forecasts, to recognize the uncertainties and their potential effects on performance. It is necessary to evaluate and design strategies with a more realistic perspective of the whole distribution of potential outcomes.

We have applied this framework to the case of the phosphate fertilizers industry, in the specific context of a “system” inspired by the case of OCP group.

Especially, we have broken-down the system’s different activities into to production of rock (through mining and washing processes), phosphoric acid (chemical transformation), mainstream and specialized fertilizers (chemical production), logistics and trade. Upstream interacting processes would be to supply raw materials (we considered only sulfur and ammonia), downstream immediately interacting processes are shipping and distributing.

Based on this high-level decomposition, we have implemented a screening model as a tool enabling the quantitative evaluation of uncertainties on the enterprise’s performance, measured in net present value ($). The model is inspired by the OCP system and demonstrates the kind of analyses and results that can be obtained. More work, and more data is necessary to transform the current model to one that would correctly describe the actual OCP fully. This initial model allowed us to explore the potential “design space” for strategic planning. It enabled us to specifically test and discuss two promising areas of flexibility that might improve overall performance.

First, a flexible capacity expansion, both in terms of volume of capacity and type of production, seems susceptible to significantly improve the group’s result. Especially, the potential emergence of specialized fertilizers in parallel markets, creates opportunities to develop capacity in new markets assumed as less risky. The flexibility in planning allow to make this decision as events occur and opportunities become more tangible. Such flexibility in capacity expansion is however far from obvious in its implementation, since it requires modularity in the industrial network that has to de designed upfront. Further exploration of this path should provide a more trustful evaluation of potential gains from flexibility, and therefore enable a cost / reward approach when considering those potential upfront change in design.

We also examined the conditions in which a flexible allocation of production to markets becomes critical, and find that a lower availability of rock (smaller flow of production, for example induced by new requirements that would require additional screening of the rock) could possibly make it worthwhile to embrace a systemic allocation of products, as opposed to a plan by line of products.

These results are far from definitive recommendations. They illustrate the potential direction that could take further development of this work. Iterations with OCP Group, with its knowledge of the industry and its practice, would be necessary. Steps in that direction would include:

- Discussion of the assumptions and causalities embedded in the screening model, and the strategic drivers that have been identified
- In-depth review and more careful description of the inputs, especially their potential distribution of variation and possible correlations

- Tailoring potential decision rules and flexible options to match realistically possible decisions and implementable options, with an understanding and evaluation of what would actually require such flexibility.
- Exploring more strategic drivers, such as securing upstream and downstream interactions.

Overall, this proposed framework might modestly participate in building a new mindset and new practices for the group’s industrial planning, exploring a larger strategic space, complementary with the already existing ongoing effort.

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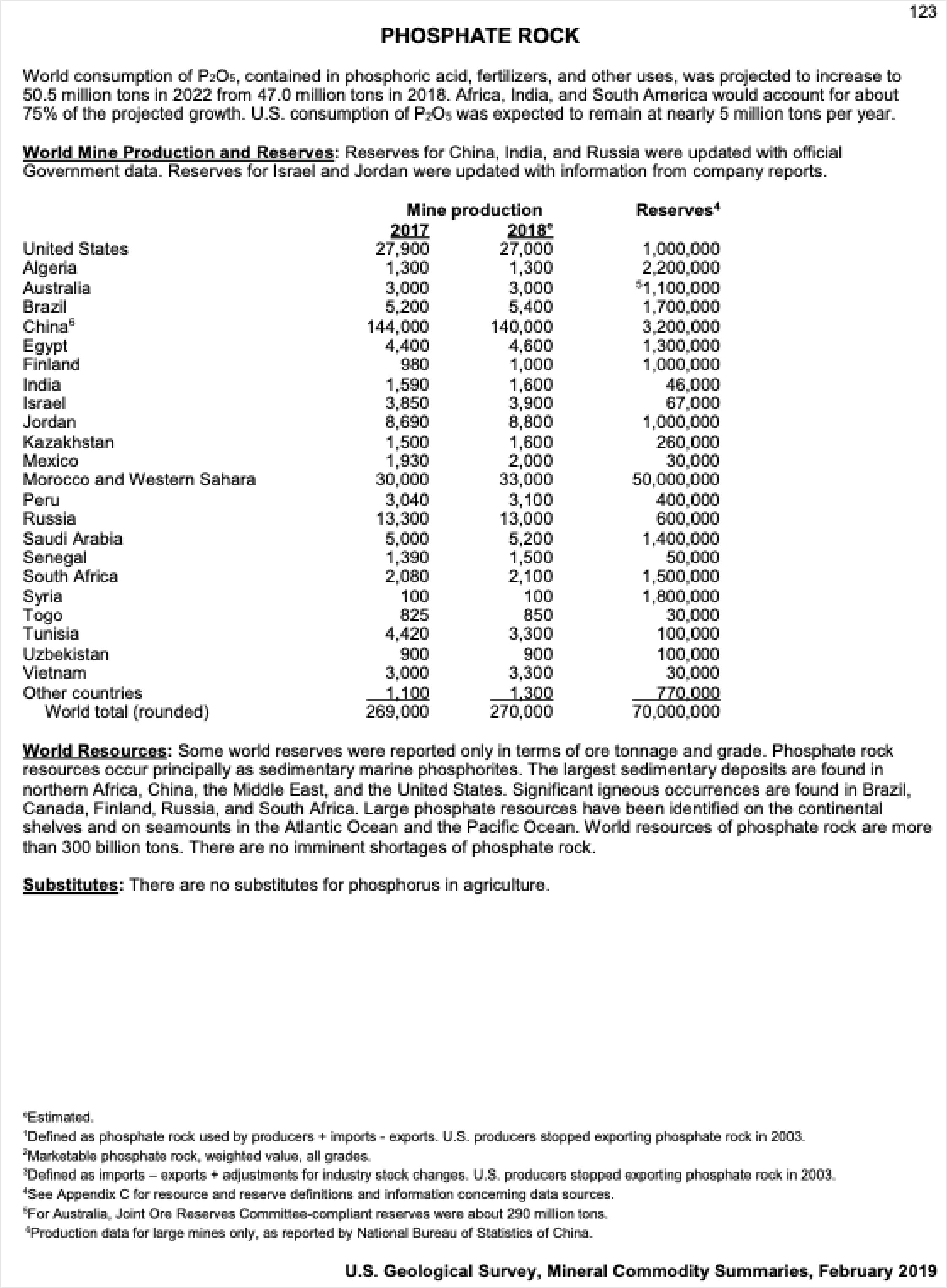
9. Appendices

9.1. Phosphate rock world’s reserves (Source: USGS)

Table 10: Phosphate Rock production and reserve per countries, Thousands metric tons. Source US Geological Survey, Mineral Commodity Summaries, February 2019.



PHOSPHATE ROCK

World consumption of P_2O_5, contained in phosphoric acid, fertilizers, and other uses, was projected to increase to 50.5 million tons in 2022 from 47.0 million tons in 2018. Africa, India, and South America would account for about 75% of the projected growth. U.S. consumption of P_2O_5 was expected to remain at nearly 5 million tons per year.

World Mine Production and Reserves: Reserves for China, India, and Russia were updated with official Government data. Reserves for Israel and Jordan were updated with information from company reports.

	Mine production		Reserves[4]
	2017	2018[e]	
United States	27,900	27,000	1,000,000
Algeria	1,300	1,300	2,200,000
Australia	3,000	3,000	[5]1,100,000
Brazil	5,200	5,400	1,700,000
China[6]	144,000	140,000	3,200,000
Egypt	4,400	4,600	1,300,000
Finland	980	1,000	1,000,000
India	1,590	1,600	46,000
Israel	3,850	3,900	67,000
Jordan	8,690	8,800	1,000,000
Kazakhstan	1,500	1,600	260,000
Mexico	1,930	2,000	30,000
Morocco and Western Sahara	30,000	33,000	50,000,000
Peru	3,040	3,100	400,000
Russia	13,300	13,000	600,000
Saudi Arabia	5,000	5,200	1,400,000
Senegal	1,390	1,500	50,000
South Africa	2,080	2,100	1,500,000
Syria	100	100	1,800,000
Togo	825	850	30,000
Tunisia	4,420	3,300	100,000
Uzbekistan	900	900	100,000
Vietnam	3,000	3,300	30,000
Other countries	1,100	1,300	770,000
World total (rounded)	269,000	270,000	70,000,000

World Resources: Some world reserves were reported only in terms of ore tonnage and grade. Phosphate rock resources occur principally as sedimentary marine phosphorites. The largest sedimentary deposits are found in northern Africa, China, the Middle East, and the United States. Significant igneous occurrences are found in Brazil, Canada, Finland, Russia, and South Africa. Large phosphate resources have been identified on the continental shelves and on seamounts in the Atlantic Ocean and the Pacific Ocean. World resources of phosphate rock are more than 300 billion tons. There are no imminent shortages of phosphate rock.

Substitutes: There are no substitutes for phosphorus in agriculture.

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[e] Estimated.

[1] Defined as phosphate rock used by producers + imports - exports. U.S. producers stopped exporting phosphate rock in 2003.

[2] Marketable phosphate rock, weighted value, all grades.

[3] Defined as imports – exports + adjustments for industry stock changes. U.S. producers stopped exporting phosphate rock in 2003.

[4] See Appendix C for resource and reserve definitions and information concerning data sources.

[5] For Australia, Joint Ore Reserves Committee-compliant reserves were about 290 million tons.

[6] Production data for large mines only, as reported by National Bureau of Statistics of China.

9.2. Regional disparities in the consumption of fertilizers per acre of land and per crop

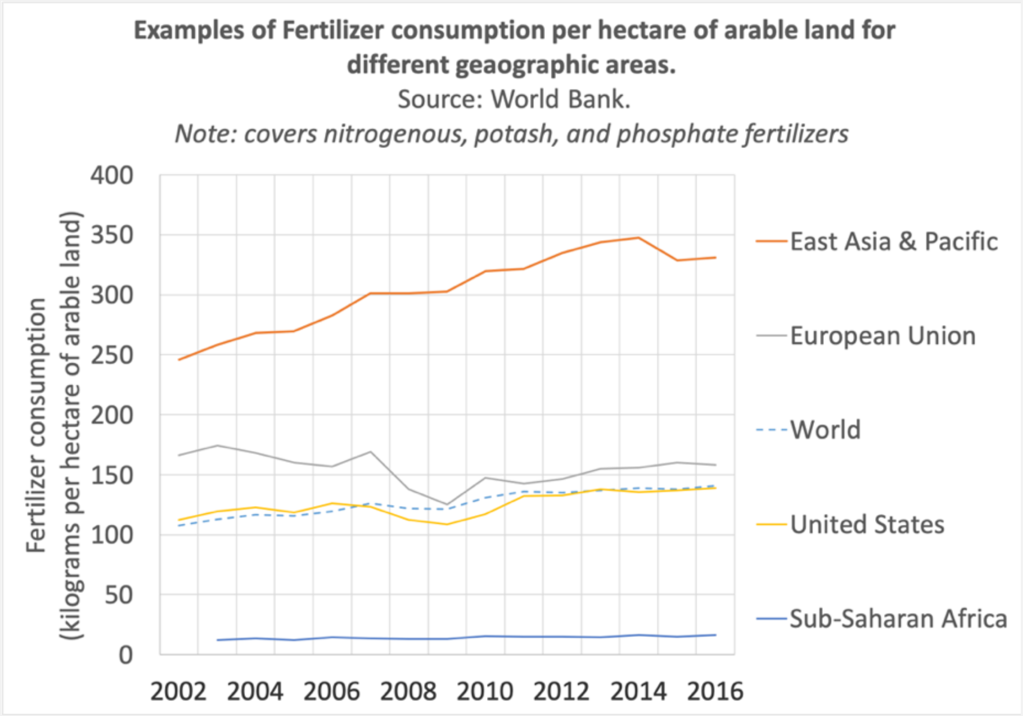
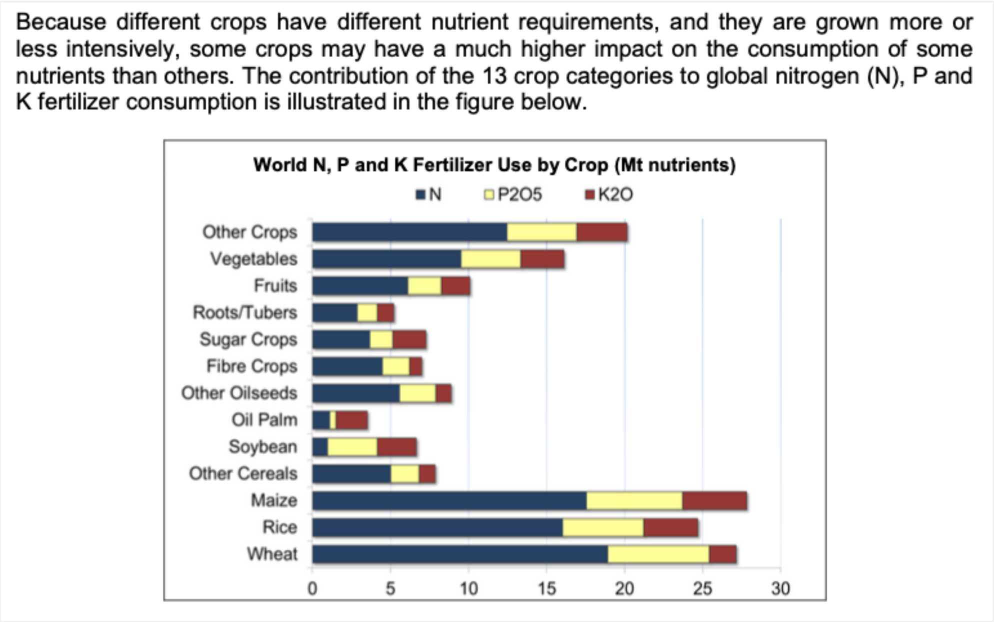

Examples of Fertilizer consumption per hectare of arable land for different geaographic areas.
Source: World Bank.
Note: covers nitrogenous, potash, and phosphate fertilizers

Figure 33: Disparities of fertilizer consumption per hectare of arable land in different regions of the world. Source data: The World Bank.


Because different crops have different nutrient requirements, and they are grown more or less intensively, some crops may have a much higher impact on the consumption of some nutrients than others. The contribution of the 13 crop categories to global nitrogen (N), P and K fertilizer consumption is illustrated in the figure below.

World N, P and K Fertilizer Use by Crop (Mt nutrients)

Figure 34: total N:P:K nutrient use per crops. Source IFA's "Assessment of Fertilizer Use by Crop at the Global Level[69]

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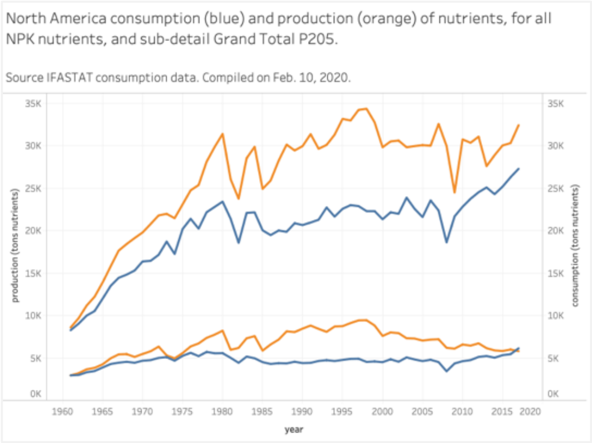
[69] Heffer, Gruère, and Roberts.

9.3. Consumption and production of nutrients (NPK, P2O5) per region (Source data: IFA)

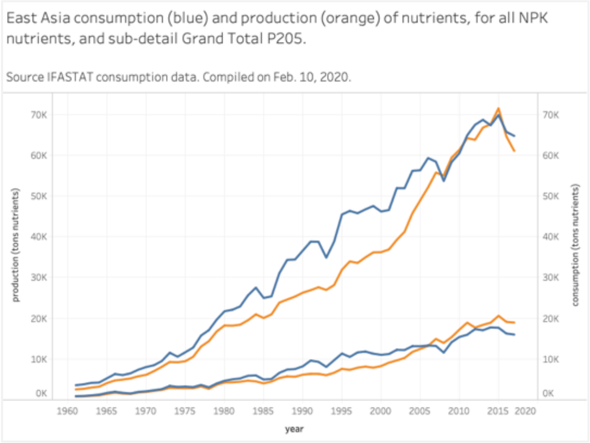
Figure 35: Consumption (blue) and production (Orange) of all NPK and P2O5 nutrients. Different trends in different regions of the world (source IFASTAT):

a) North America: overall declining production of Grand Total P2O5 to match internal demand.
b) East Asia, including China: high volumes, increasing, shift from importer to exporter.
c) Africa, including Morocco: moderate consumption, increased exports.
d) West Europe: steadily declining
e) Latin America, including Brazil: increased consumption and imports

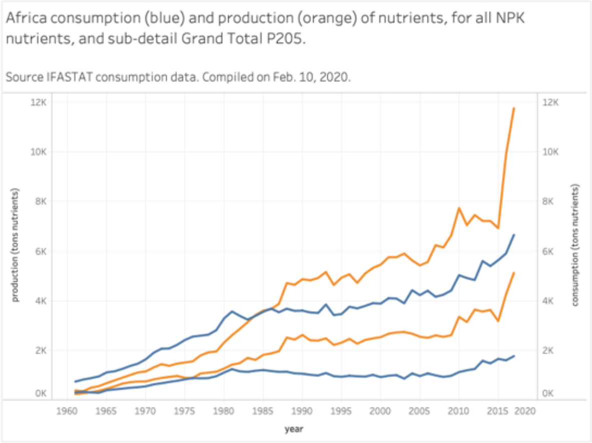

North America consumption (blue) and production (orange) of nutrients, for all NPK nutrients, and sub-detail Grand Total P205.

Source IFASTAT consumption data. Compiled on Feb. 10, 2020.

a) North America


East Asia consumption (blue) and production (orange) of nutrients, for all NPK nutrients, and sub-detail Grand Total P205.

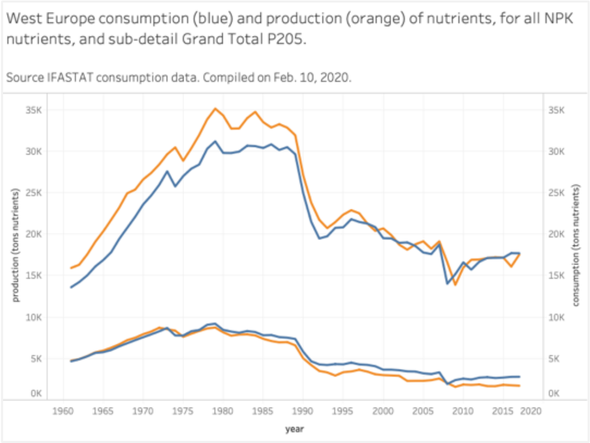
Source IFASTAT consumption data. Compiled on Feb. 10, 2020.


Africa consumption (blue) and production (orange) of nutrients, for all NPK nutrients, and sub-detail Grand Total P205.

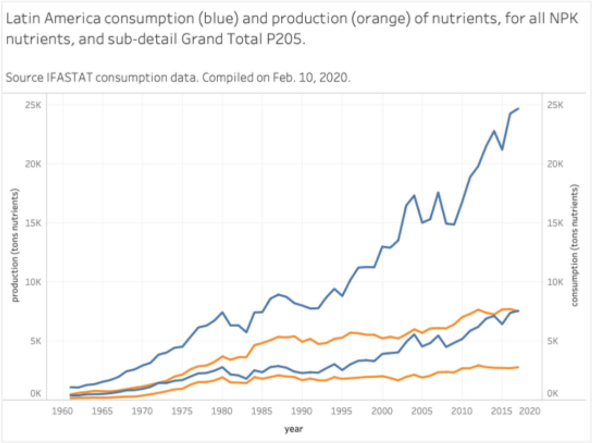
Source IFASTAT consumption data. Compiled on Feb. 10, 2020.

b) East Asia

c) Africa


West Europe consumption (blue) and production (orange) of nutrients, for all NPK nutrients, and sub-detail Grand Total P205.

Source IFASTAT consumption data. Compiled on Feb. 10, 2020.


Latin America consumption (blue) and production (orange) of nutrients, for all NPK nutrients, and sub-detail Grand Total P205.

Source IFASTAT consumption data. Compiled on Feb. 10, 2020.

d) West Europe

e) Latin America

9.4. World Phosphate Rock production and capabilities (source data: IFA)

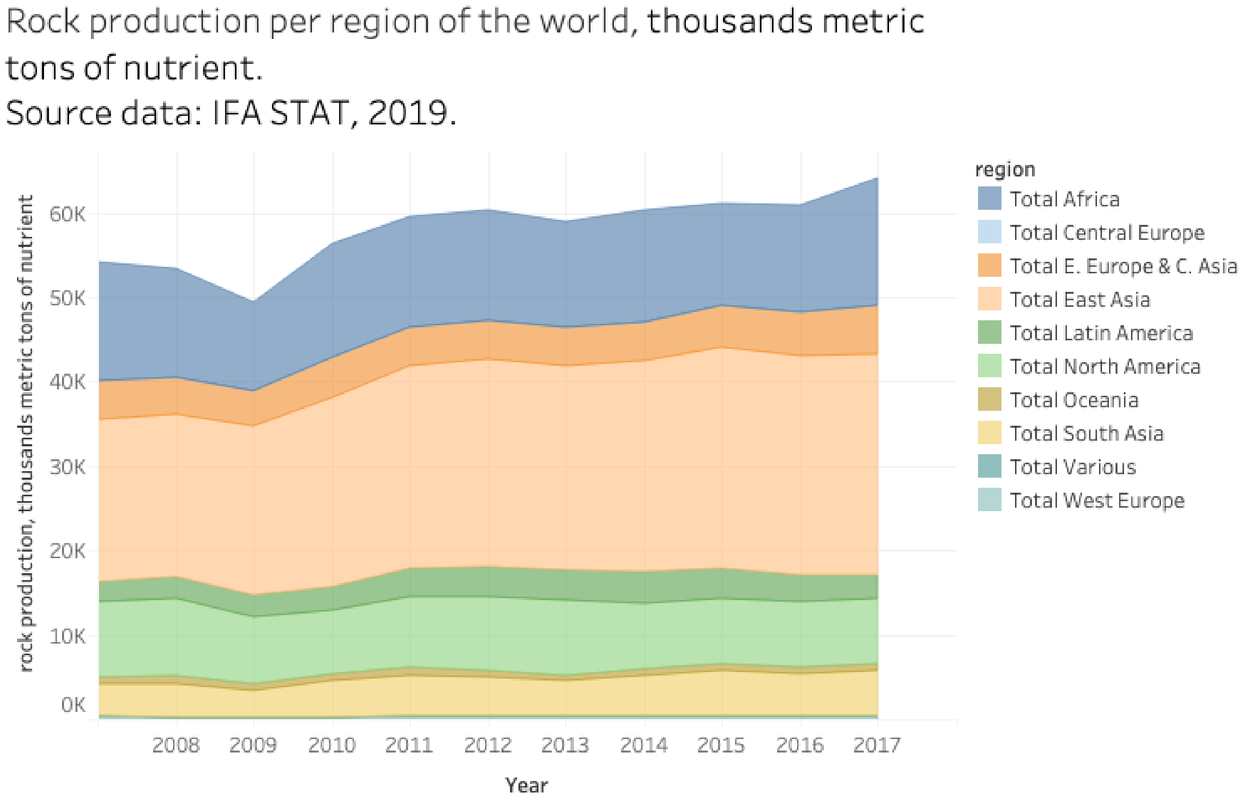
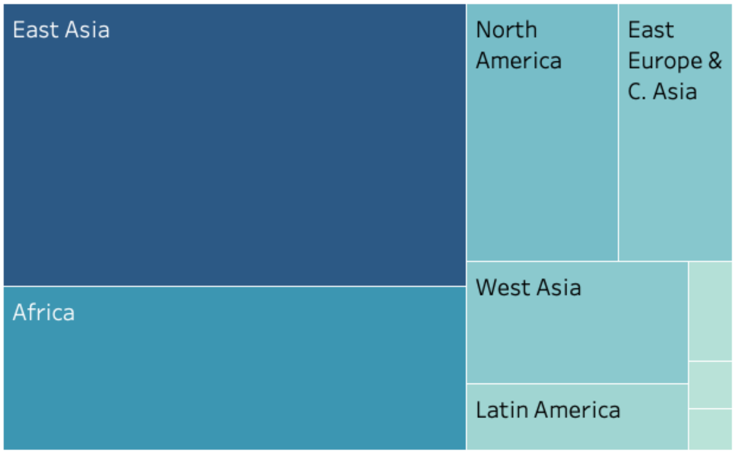

Rock production per region of the world, thousands metric tons of nutrient.
Source data: IFA STAT, 2019.

Figure 36: World Phosphate rock production, thousands metric tons of nutrient. Compiled from data IFASTAT 2019.

9.5. Phosphate rock production, import, export and consumption in 2017 (Source data: IFA)

Table 11: Production of Phosphate rock per region of the world, in 2017 (global production: 64,000 kilo tons of nutrient). Source data: IFASTAT, compiled on April 13, 2020.



Region	
Africa	14,988
Central Europe	0
East Asia	25,740
East Europe & C. Asia	5,774
Latin America	2,921
North America	7,695
Oceania	867
South Asia	407
West Asia	5,292
West Europe	364

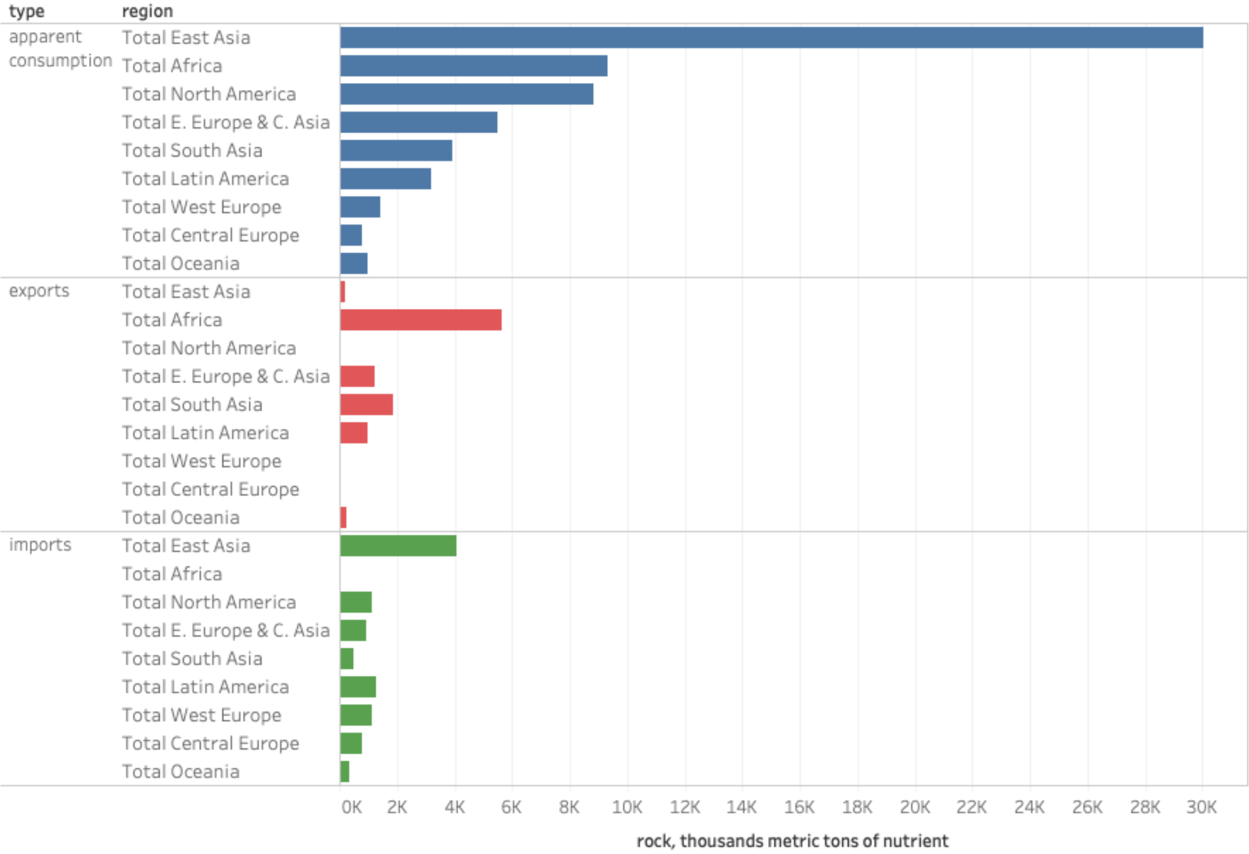
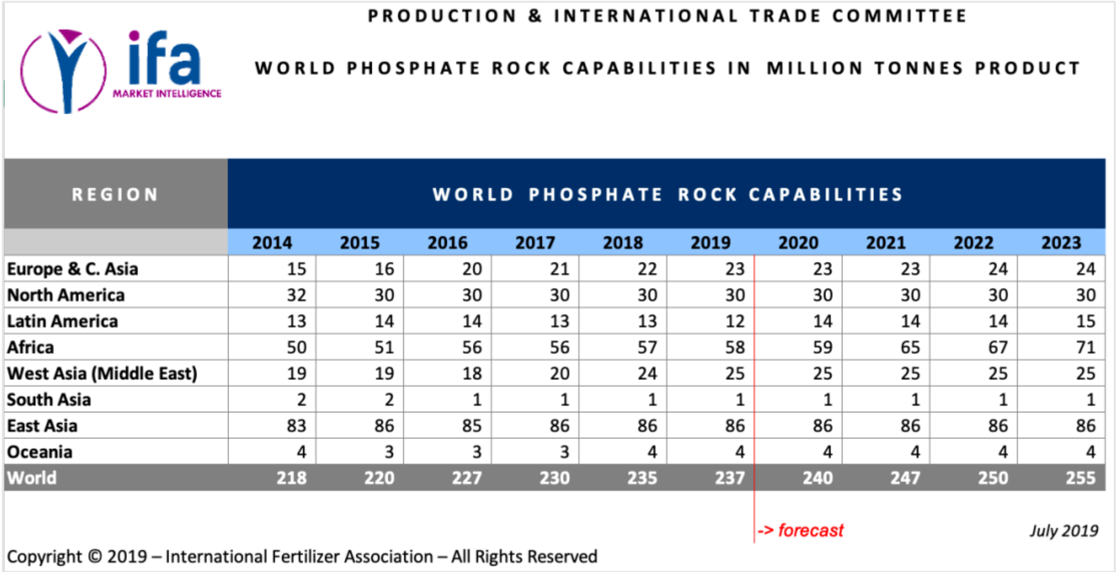


Figure 37: Apparent consumption of phosphate rock per region of the world, and exports and imports, in 2017. Note: Apparent consumption = production + imports - exports. Source Data: IFASTAT, compiled on April 13, 2020.

9.6. IFA’s observations of rock and DAP capabilities, forecast after 2019 (Source: IFA)

Table 12: World phosphate rock capabilities, source IFA © 2019



PRODUCTION & INTERNATIONAL TRADE COMMITTEE

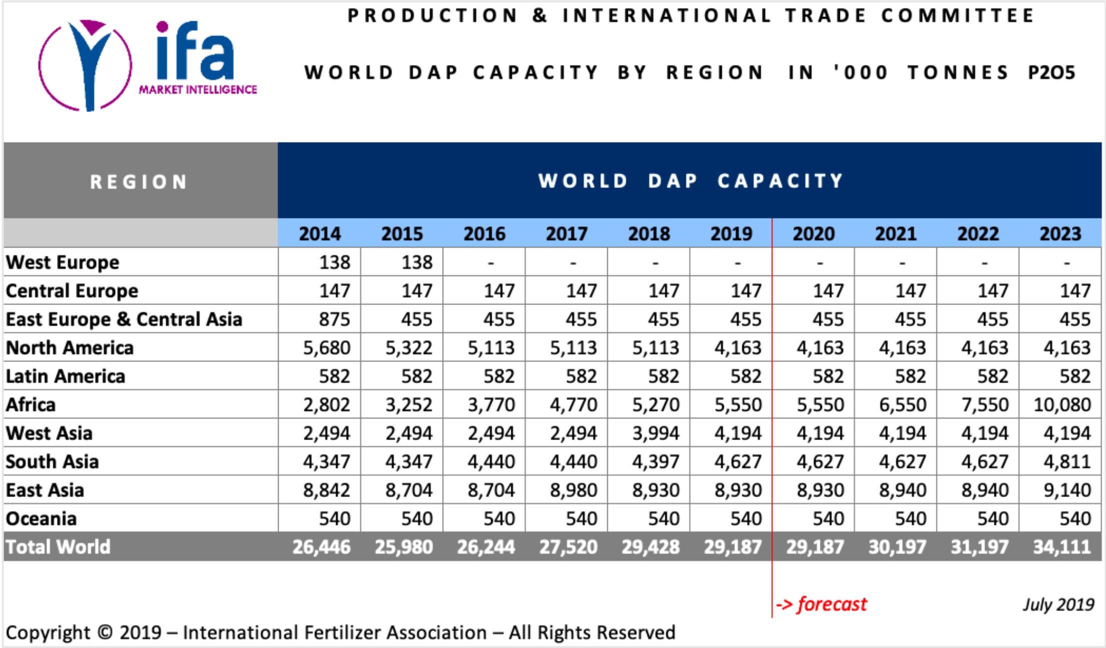
WORLD PHOSPHATE ROCK CAPABILITIES IN MILLION TONNES PRODUCT

REGION	WORLD PHOSPHATE ROCK CAPABILITIES									
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Europe & C. Asia	15	16	20	21	22	23	23	23	24	24
North America	32	30	30	30	30	30	30	30	30	30
Latin America	13	14	14	13	13	12	14	14	14	15
Africa	50	51	56	56	57	58	59	65	67	71
West Asia (Middle East)	19	19	18	20	24	25	25	25	25	25
South Asia	2	2	1	1	1	1	1	1	1	1
East Asia	83	86	85	86	86	86	86	86	86	86
Oceania	4	3	3	3	4	4	4	4	4	4
World	**218**	**220**	**227**	**230**	**235**	**237**	**240**	**247**	**250**	**255**

-> forecast

July 2019

Table 13: World DAP capacity by region, Source IFA © 2019.



PRODUCTION & INTERNATIONAL TRADE COMMITTEE

WORLD DAP CAPACITY BY REGION IN '000 TONNES P2O5

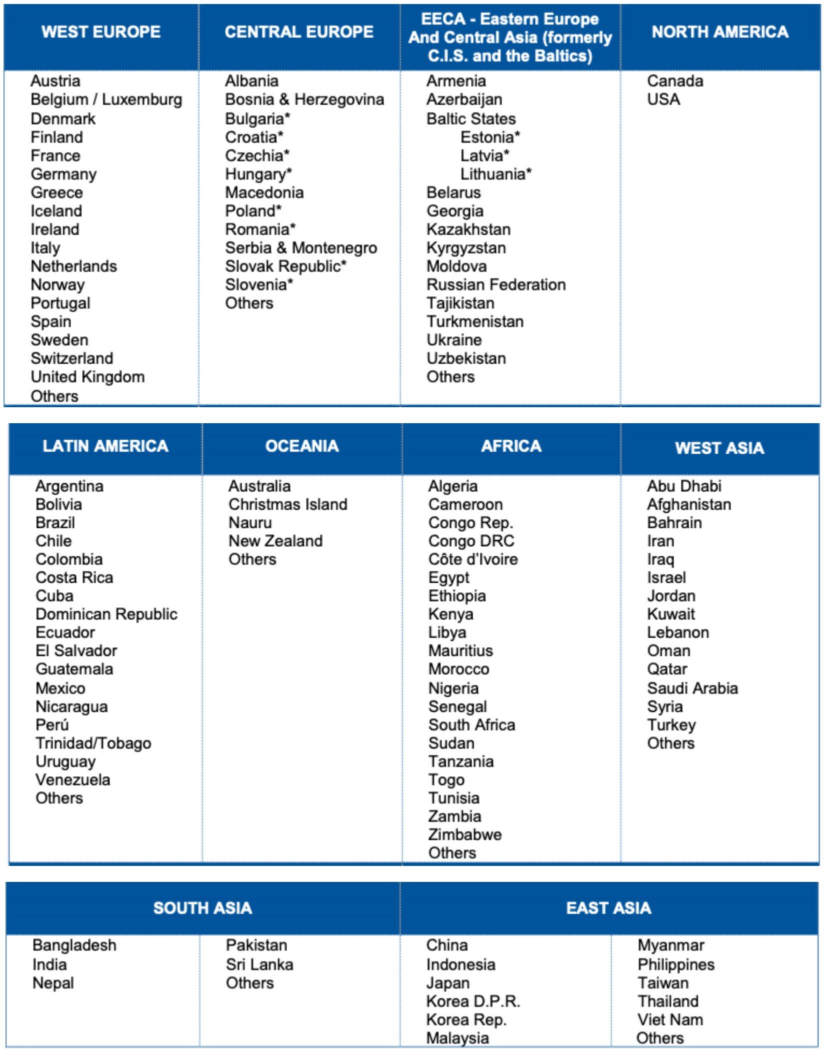
REGION	WORLD DAP CAPACITY									
	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
West Europe	138	138	-	-	-	-	-	-	-	-
Central Europe	147	147	147	147	147	147	147	147	147	147
East Europe & Central Asia	875	455	455	455	455	455	455	455	455	455
North America	5,680	5,322	5,113	5,113	5,113	4,163	4,163	4,163	4,163	4,163
Latin America	582	582	582	582	582	582	582	582	582	582
Africa	2,802	3,252	3,770	4,770	5,270	5,550	5,550	6,550	7,550	10,080
West Asia	2,494	2,494	2,494	2,494	3,994	4,194	4,194	4,194	4,194	4,194
South Asia	4,347	4,347	4,440	4,440	4,397	4,627	4,627	4,627	4,627	4,811
East Asia	8,842	8,704	8,704	8,980	8,930	8,930	8,930	8,940	8,940	9,140
Oceania	540	540	540	540	540	540	540	540	540	540
Total World	**26,446**	**25,980**	**26,244**	**27,520**	**29,428**	**29,187**	**29,187**	**30,197**	**31,197**	**34,111**

-> forecast

July 2019

9.7. IFA regional classification of countries (source: IFASTAT)

Table 14: IFA Regional Classification of Countries (IFASTAT, 2019)

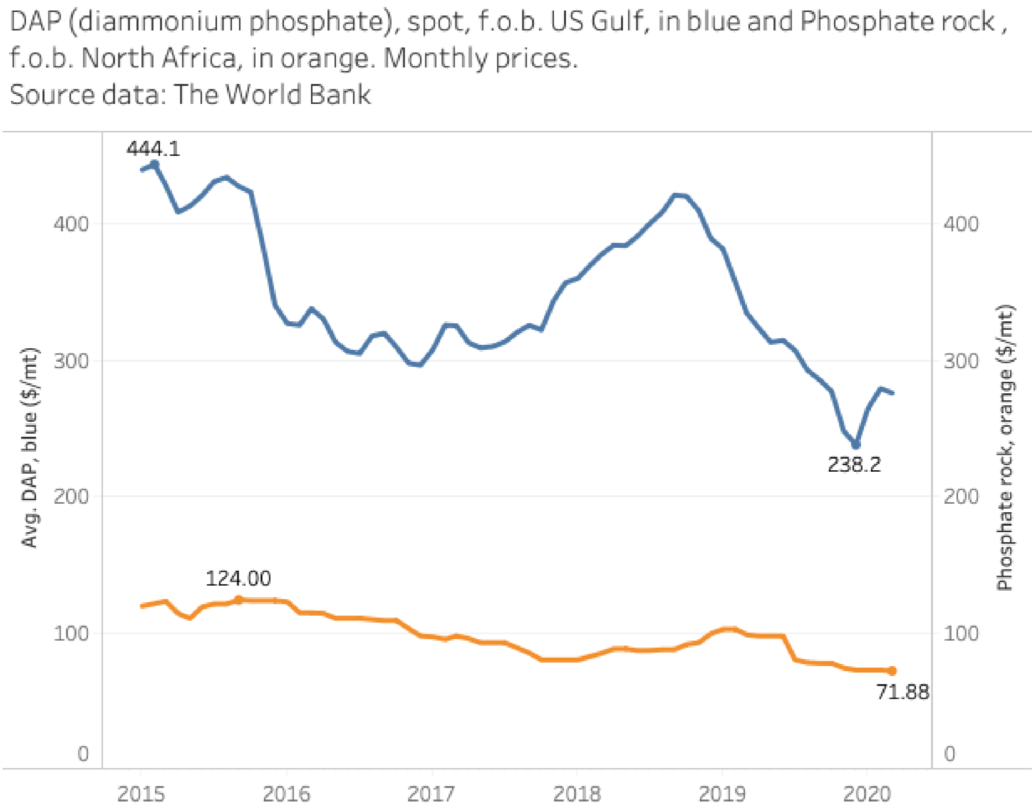


WEST EUROPE	CENTRAL EUROPE	EECA - Eastern Europe And Central Asia (formerly C.I.S. and the Baltics)	NORTH AMERICA
Austria Belgium / Luxemburg Denmark Finland France Germany Greece Iceland Ireland Italy Netherlands Norway Portugal Spain Sweden Switzerland United Kingdom Others	Albania Bosnia & Herzegovina Bulgaria* Croatia* Czechia* Hungary* Macedonia Poland* Romania* Serbia & Montenegro Slovak Republic* Slovenia* Others	Armenia Azerbaijan Baltic States Estonia* Latvia* Lithuania* Belarus Georgia Kazakhstan Kyrgyzstan Moldova Russian Federation Tajikistan Turkmenistan Ukraine Uzbekistan Others	Canada USA

LATIN AMERICA	OCEANIA	AFRICA	WEST ASIA
Argentina Bolivia Brazil Chile Colombia Costa Rica Cuba Dominican Republic Ecuador El Salvador Guatemala Mexico Nicaragua Perú Trinidad/Tobago Uruguay Venezuela Others	Australia Christmas Island Nauru New Zealand Others	Algeria Cameroon Congo Rep. Congo DRC Côte d'Ivoire Egypt Ethiopia Kenya Libya Mauritius Morocco Nigeria Senegal South Africa Sudan Tanzania Togo Tunisia Zambia Zimbabwe Others	Abu Dhabi Afghanistan Bahrain Iran Iraq Israel Jordan Kuwait Lebanon Oman Qatar Saudi Arabia Syria Turkey Others

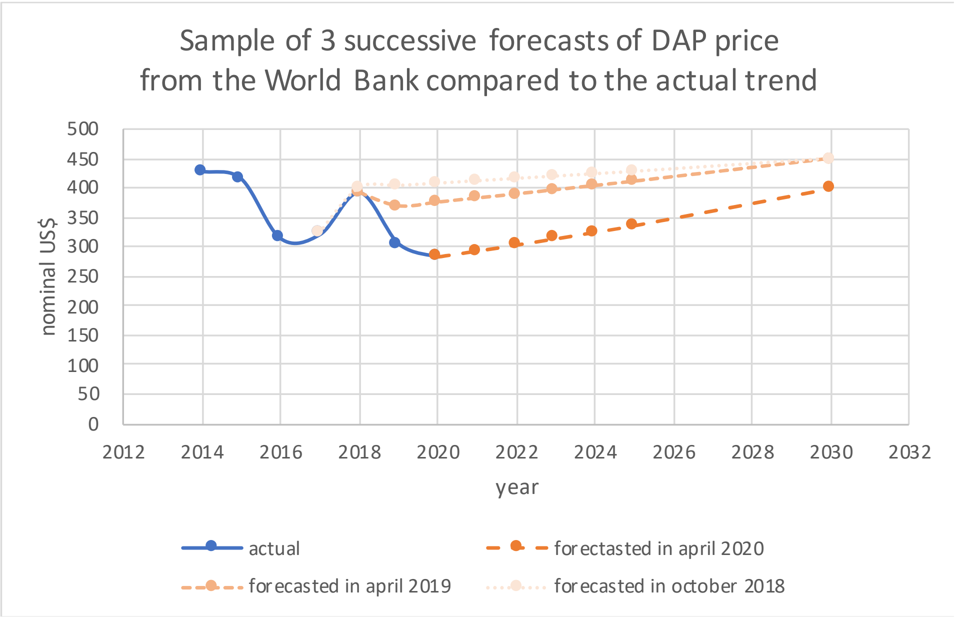
SOUTH ASIA		EAST ASIA	
Bangladesh India Nepal	Pakistan Sri Lanka Others	China Indonesia Japan Korea D.P.R. Korea Rep. Malaysia	Myanmar Philippines Taiwan Thailand Viet Nam Others

9.8. Monthly prices of phosphate rock and DAP prices over the past 5 years



DAP (diammonium phosphate), spot, f.o.b. US Gulf, in blue and Phosphate rock, f.o.b. North Africa, in orange. Monthly prices.
Source data: The World Bank

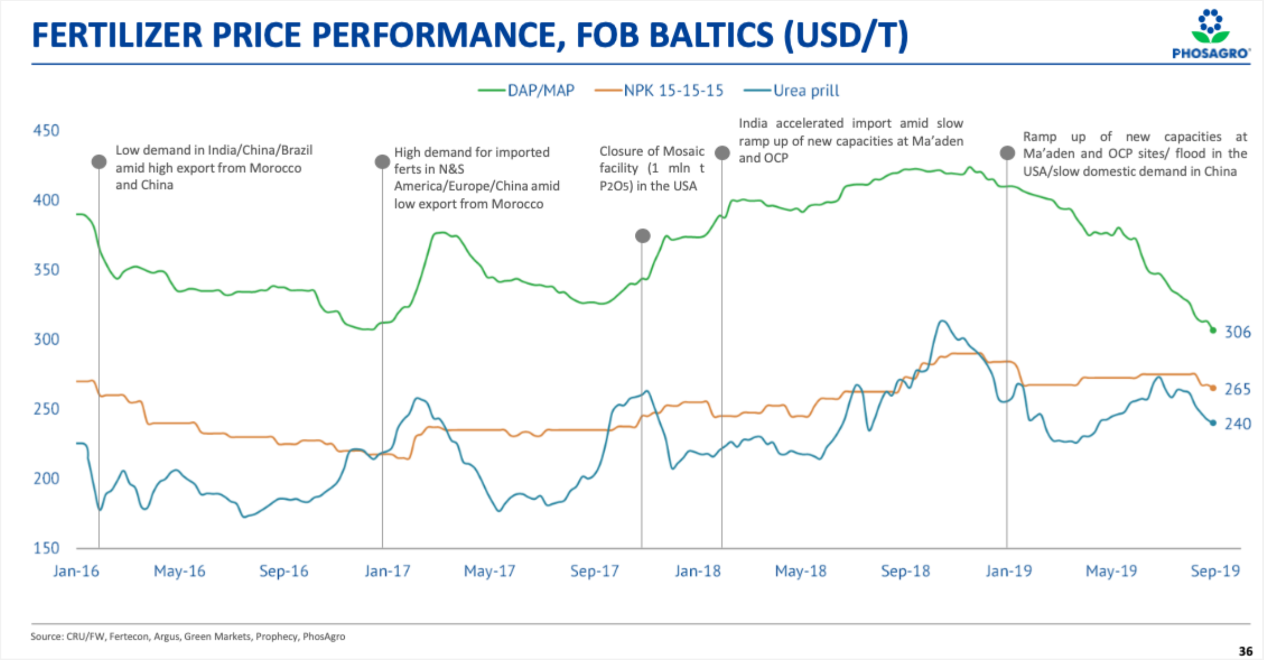
Figure 38: Phosphate rock and DAP monthly prices with max and min highlighted, Jan 2015-March 2020. Source data: The World Bank.



Sample of 3 successive forecasts of DAP price from the World Bank compared to the actual trend

Figure 39: Successive forecasts of DAP price compared to the actual trend. Source data: The World Bank.

9.9. Example of demand / supply / prices interactions and DAP/MAP cost-curve



FERTILIZER PRICE PERFORMANCE, FOB BALTICS (USD/T)

Low demand in India/China/Brazil amid high export from Morocco and China

High demand for imported ferts in N&S America/Europe/China amid low export from Morocco

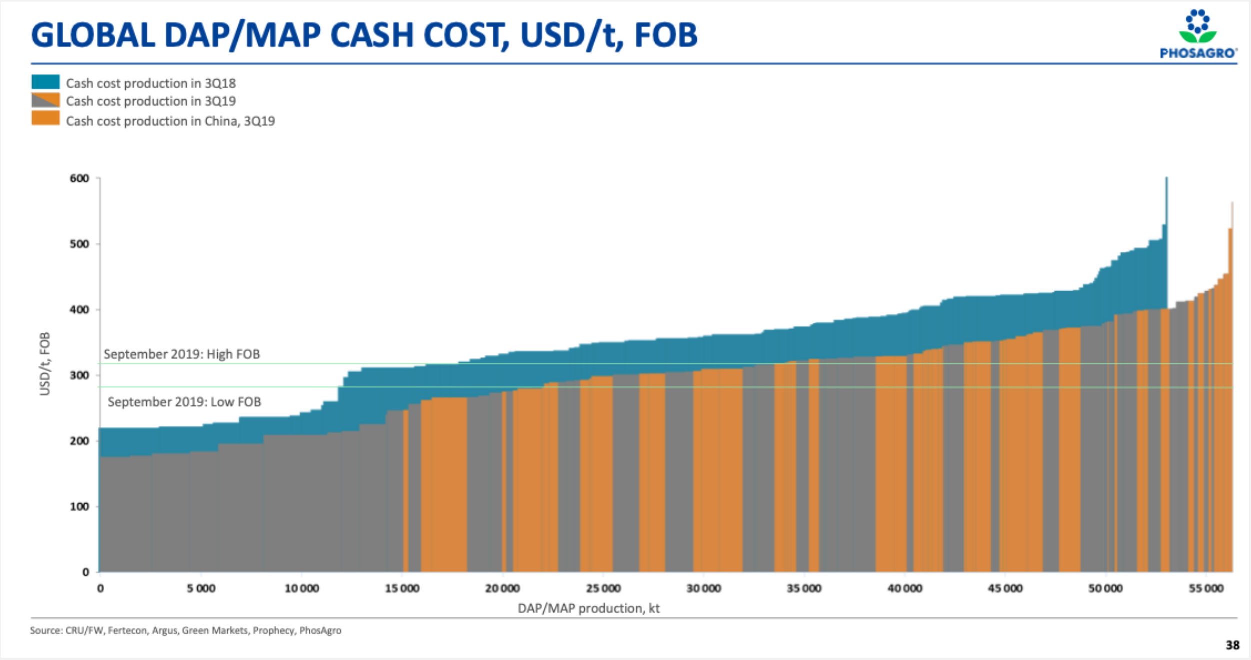
Closure of Mosaic facility (1 mln t P2O5) in the USA

India accelerated import amid slow ramp up of new capacities at Ma'aden and OCP

Ramp up of new capacities at Ma'aden and OCP sites/ flood in the USA/slow domestic demand in China

Source: CRU/FW, Fertecon, Argus, Green Markets, Prophecy, PhosAgro

Figure 40: Illustration of interactions that possibly shape the price as presented in [Phosagro, 2019][70]



GLOBAL DAP/MAP CASH COST, USD/t, FOB

Source: CRU/FW, Fertecon, Argus, Green Markets, Prophecy, PhosAgro

Figure 41: Example of a cost-curve for DAP-MAP. The 2 horizontal lines are the prices High and Low FOB in September 2019 (time of the publication), Source: Phosagro op.cit.

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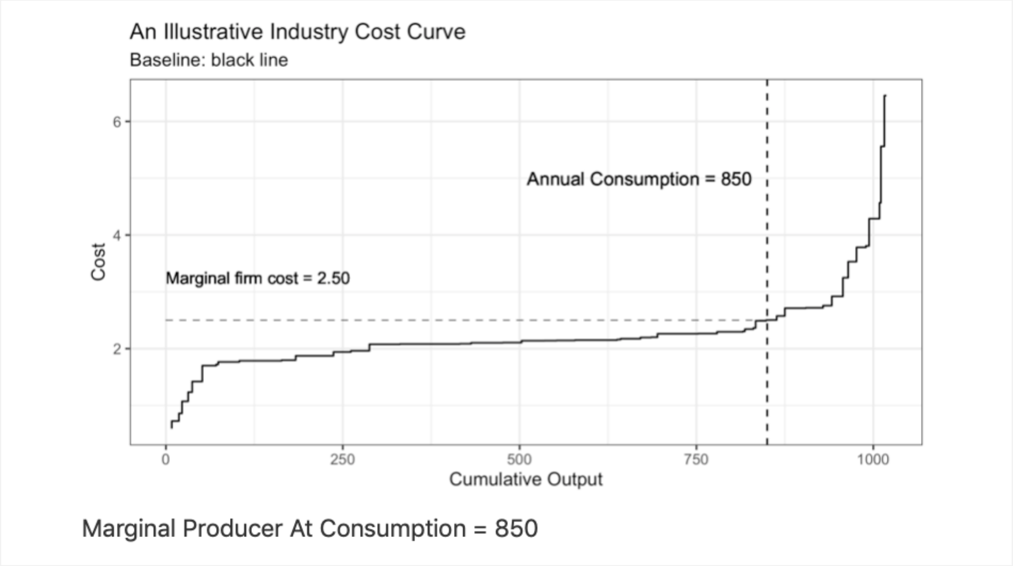
[70] PJSC Phosagro, *Presentation at Capital Markets Day 2019* (London, 2019).

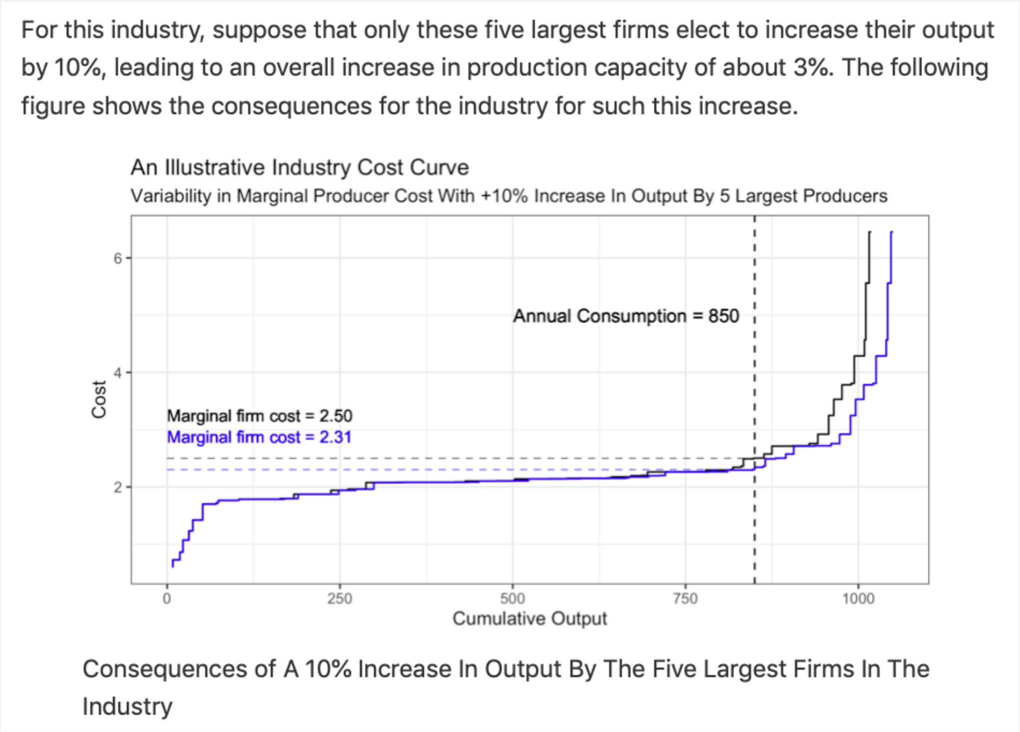
9.10. Illustration of the possible fuzziness of a cost-curve

Illustrative example of the possible fuzziness of the cost-curve when testing a potential move of the 5 largest firms to increase their production. These illustrations are taken from a work-in-progress by Dr Frank Field, Materials Systems Laboratory, Massachusetts Institute of Technology (April 2020)



Marginal Producer At Consumption = 850

Figure 42: "An illustrative Industry Cost Curve"



For this industry, suppose that only these five largest firms elect to increase their output by 10%, leading to an overall increase in production capacity of about 3%. The following figure shows the consequences for the industry for such this increase.

Consequences of A 10% Increase In Output By The Five Largest Firms In The Industry

Figure 43: "Consequence of a 10% increase in output by the five largest firms in the industry"

9.11. Detailed sulfur and urea volatility over time, historical data

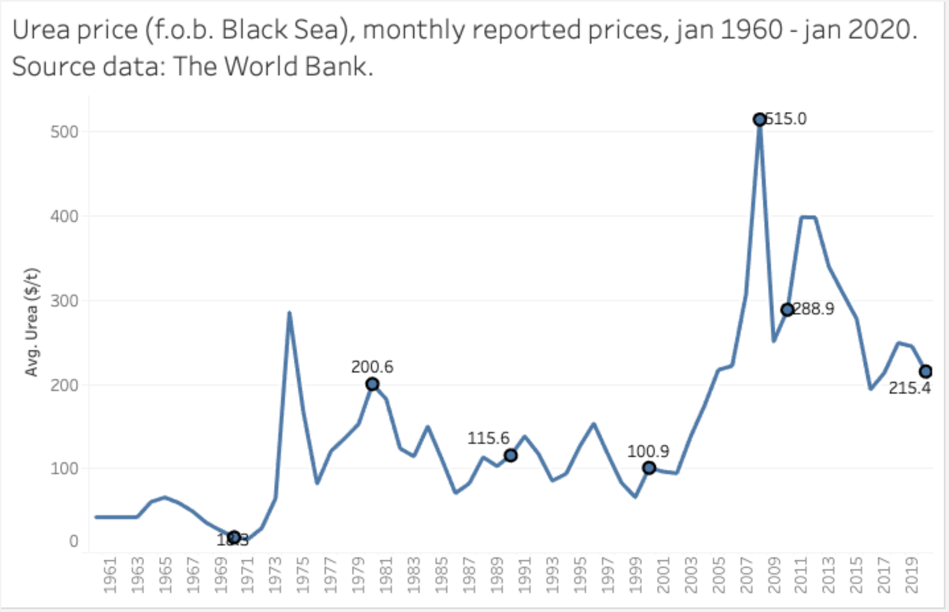

Urea price (f.o.b. Black Sea), monthly reported prices, jan 1960 - jan 2020.
Source data: The World Bank.

Figure 44: Average annual Urea price from 1960 to 2020 (source: The World Bank)

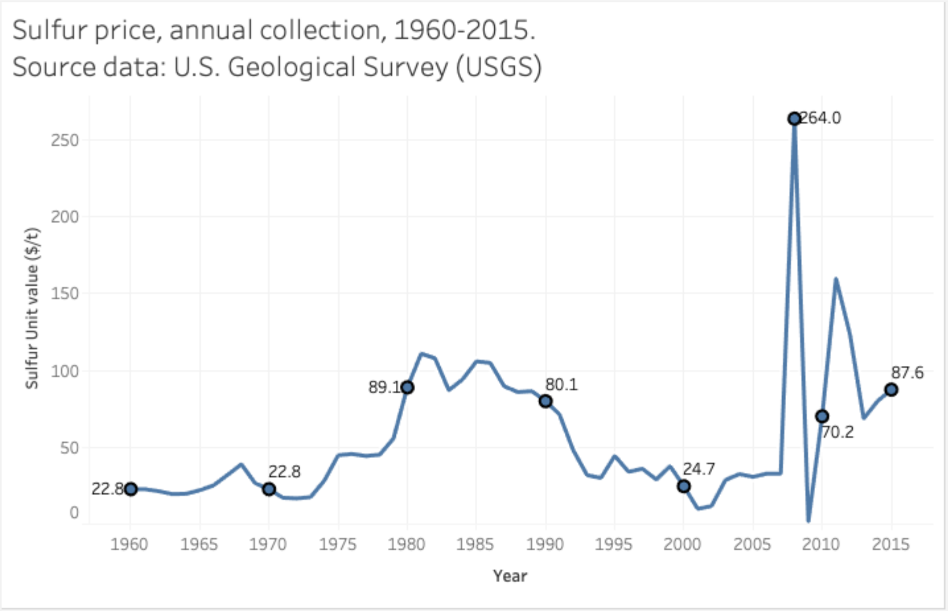

Sulfur price, annual collection, 1960-2015.
Source data: U.S. Geological Survey (USGS)

Figure 45: Annual collection of Sulfur Price from 1960 to 2015 (source: US Geological Survey).

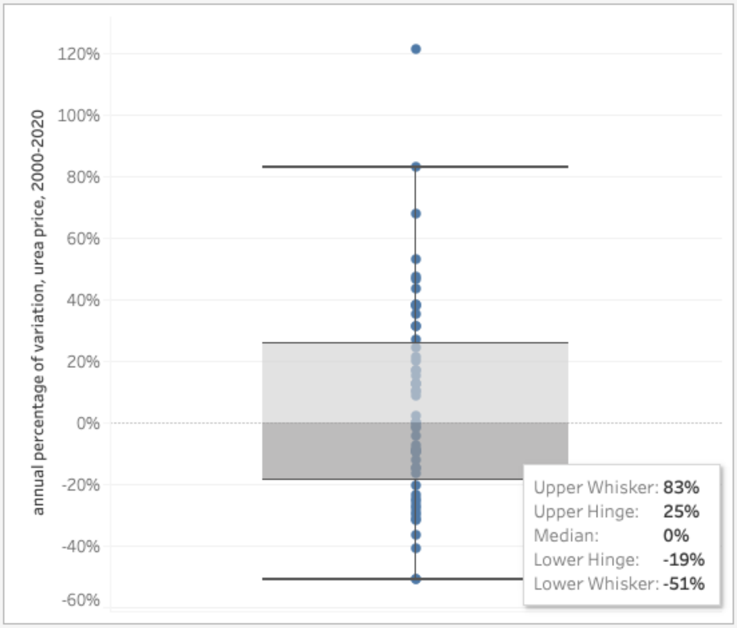


Figure 46: Annual variability of for urea price, 2000-2020 (Source data The World Bank)

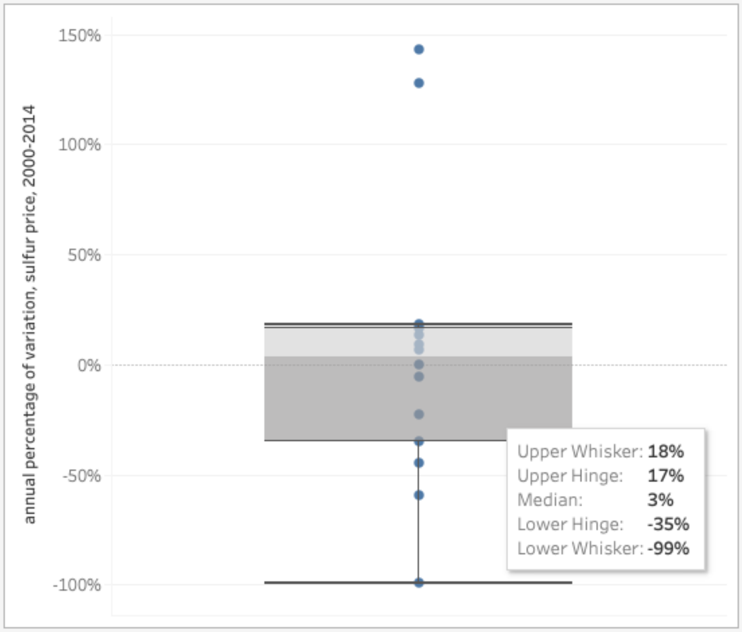


Figure 47: Annual variability of sulfur price, 2000-2014 (source data USGS)

9.12. First-approach analysis of correlation between costs and prices variables

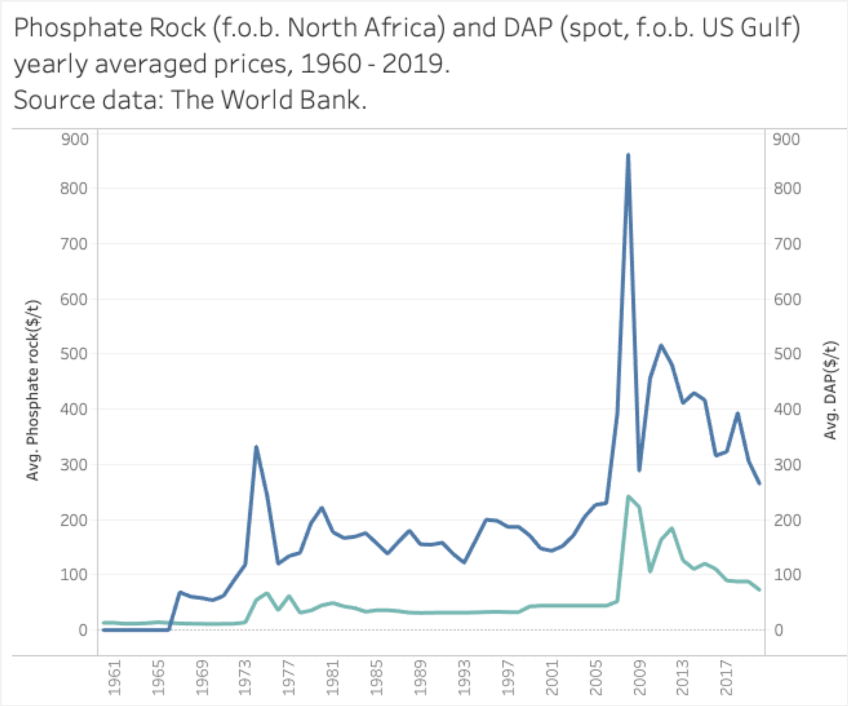

Phosphate Rock (f.o.b. North Africa) and DAP (spot, f.o.b. US Gulf) yearly averaged prices, 1960 - 2019.
Source data: The World Bank.

Figure 48: Soft synchronization of DAP and phosphate rock price variation on the commodity markets, with different magnitude of variation. Source data: The World Bank. Compiled on March 23, 2020.

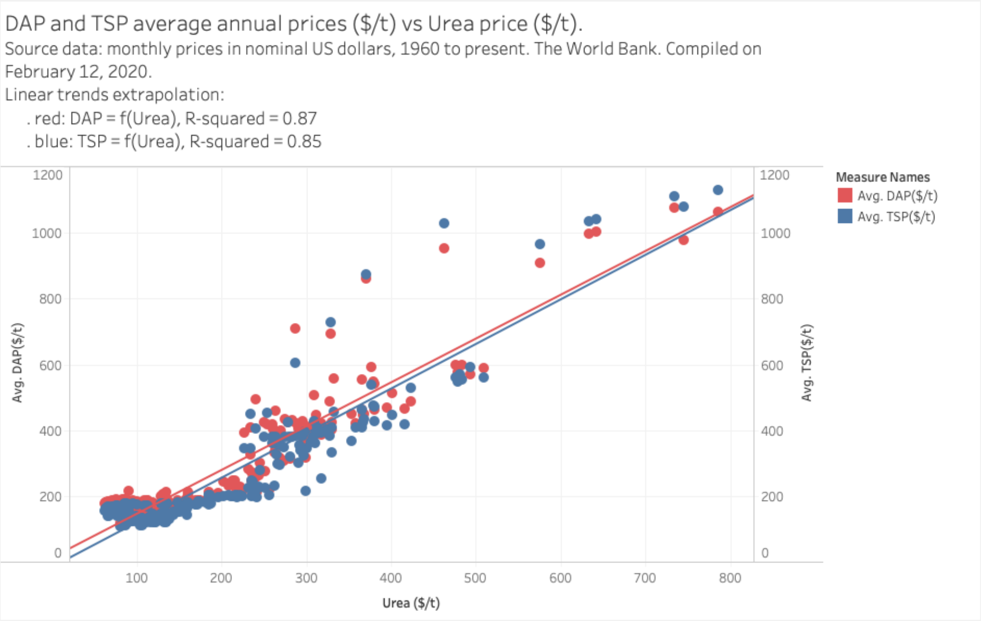

DAP and TSP average annual prices ($/t) vs Urea price ($/t).
Source data: monthly prices in nominal US dollars, 1960 to present. The World Bank. Compiled on February 12, 2020.
Linear trends extrapolation:
. red: DAP = f(Urea), R-squared = 0.87
. blue: TSP = f(Urea), R-squared = 0.85

Figure 49: Rough correlation between the price of Urea and the price of fertilizers (TSP in blue, DAP in red). Source data: The World Bank. Compiled on March 23, 2020.

9.13. Potential for phosphate recycling and impact on long-term demand

Source: [Koppelaar and Weikard, 2013] [71]

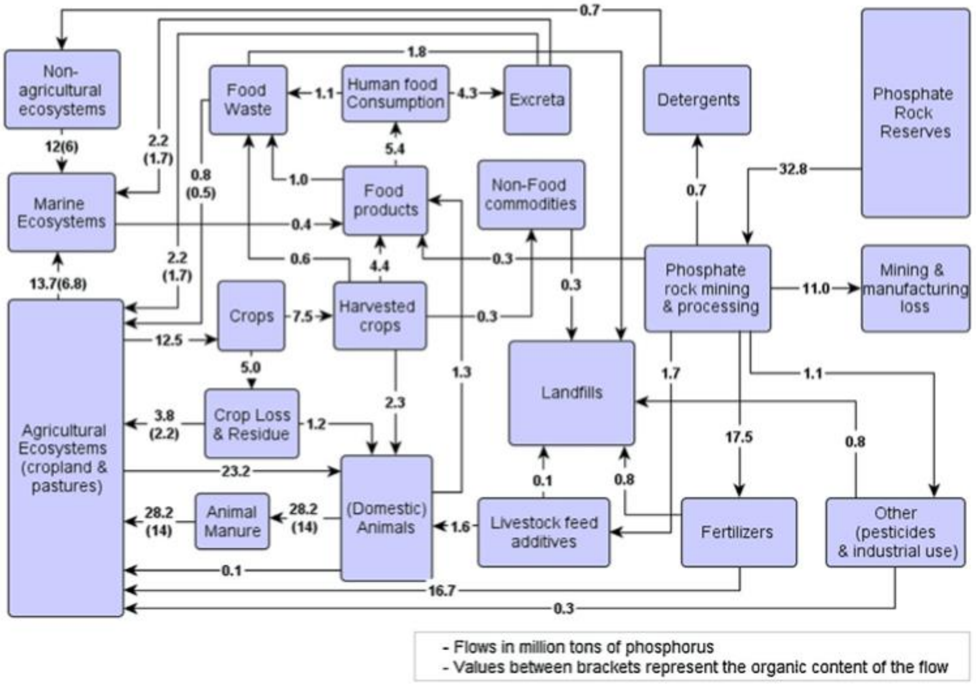


Fig. 5. Global Phosphorus flows in 2009. Total content displayed without brackets and organic content within brackets.
Source: This study based on various data sources; see Section 2.

Figure 50: "Global Phosphorous flows in 2009"

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[71] Koppelaar and Weikard.

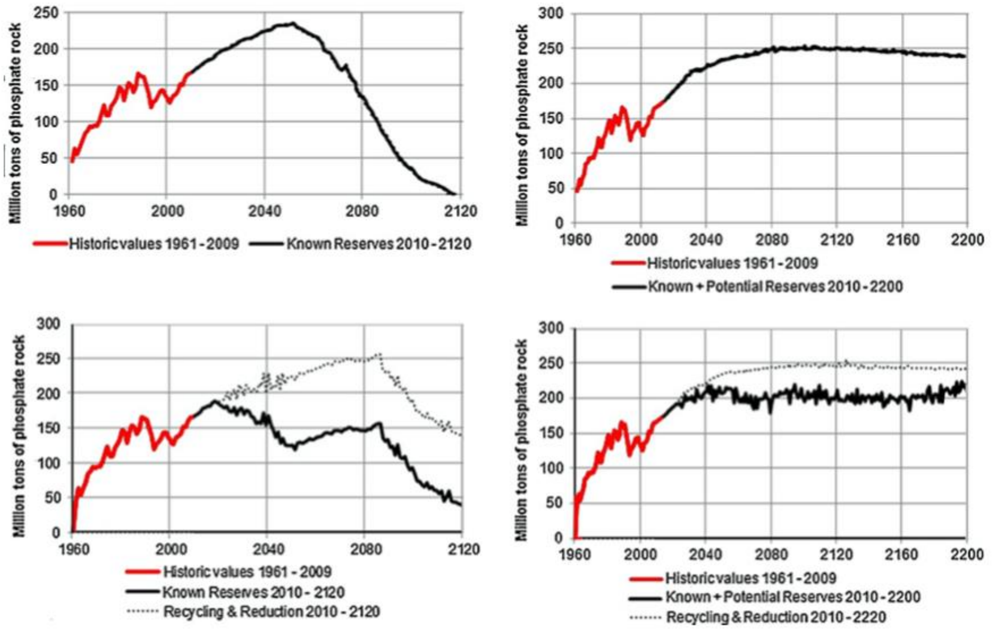

Fig. 7. Scenario results for known reserves (top left), known reserves including recycling (bottom left), known and potential reserves (top right), known and potential reserves including recycling (bottom right). Red line: historic data points (1961–2009), black line: phosphorus from produced reserves, dotted line: substitute use reduction and recycling phosphorus. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: This study.

Figure 51: Different scenario results for the mineral phosphate consumption long-term trend (2010-2120), given different assumptions for potential reserves and recycling & reduction behaviors

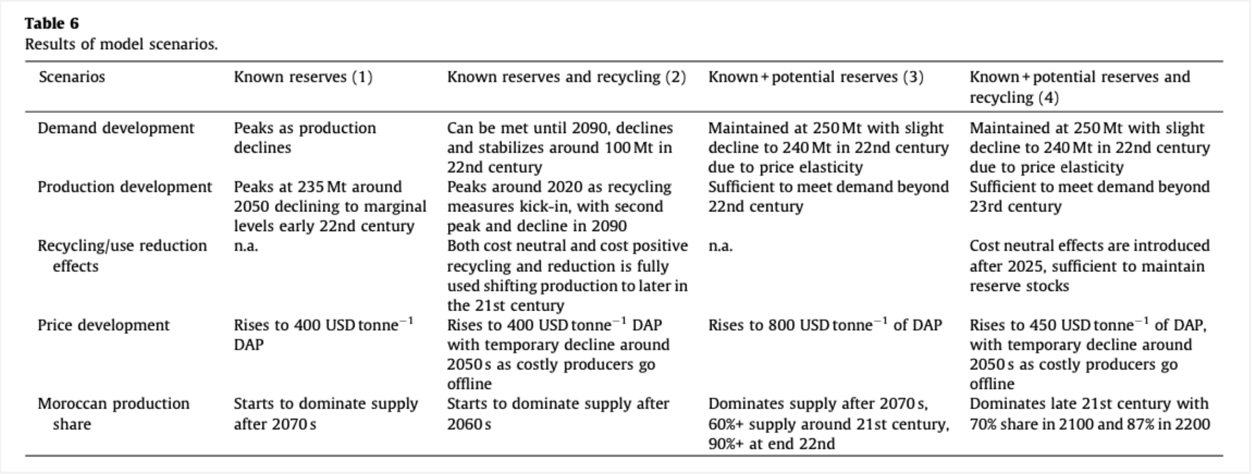

Table 6
Results of model scenarios.

Scenarios	Known reserves (1)	Known reserves and recycling (2)	Known + potential reserves (3)	Known + potential reserves and recycling (4)
Demand development	Peaks as production declines	Can be met until 2090, declines and stabilizes around 100 Mt in 22nd century	Maintained at 250 Mt with slight decline to 240 Mt in 22nd century due to price elasticity	Maintained at 250 Mt with slight decline to 240 Mt in 22nd century due to price elasticity
Production development	Peaks at 235 Mt around 2050 declining to marginal levels early 22nd century	Peaks around 2020 as recycling measures kick-in, with second peak and decline in 2090	Sufficient to meet demand beyond 22nd century	Sufficient to meet demand beyond 23rd century
Recycling/use reduction effects	n.a.	Both cost neutral and cost positive recycling and reduction is fully used shifting production to later in the 21st century	n.a.	Cost neutral effects are introduced after 2025, sufficient to maintain reserve stocks
Price development	Rises to 400 USD tonne^{-1} DAP	Rises to 400 USD tonne^{-1} DAP with temporary decline around 2050 s as costly producers go offline	Rises to 800 USD tonne^{-1} of DAP	Rises to 450 USD tonne^{-1} of DAP, with temporary decline around 2050 s as costly producers go offline
Moroccan production share	Starts to dominate supply after 2070 s	Starts to dominate supply after 2060 s	Dominates supply after 2070 s, 60%+ supply around 21st century, 90%+ at end 22nd	Dominates late 21st century with 70% share in 2100 and 87% in 2200

Figure 52: Different results of model scenarios including price development and Moroccan production share forecasts during the 21st century under different scenarios of potential reserves and recycling & reduction behaviors.

9.14. Cadmium-limitations regulations compared to natural range of concentration

Source [Terry, 2014][72]

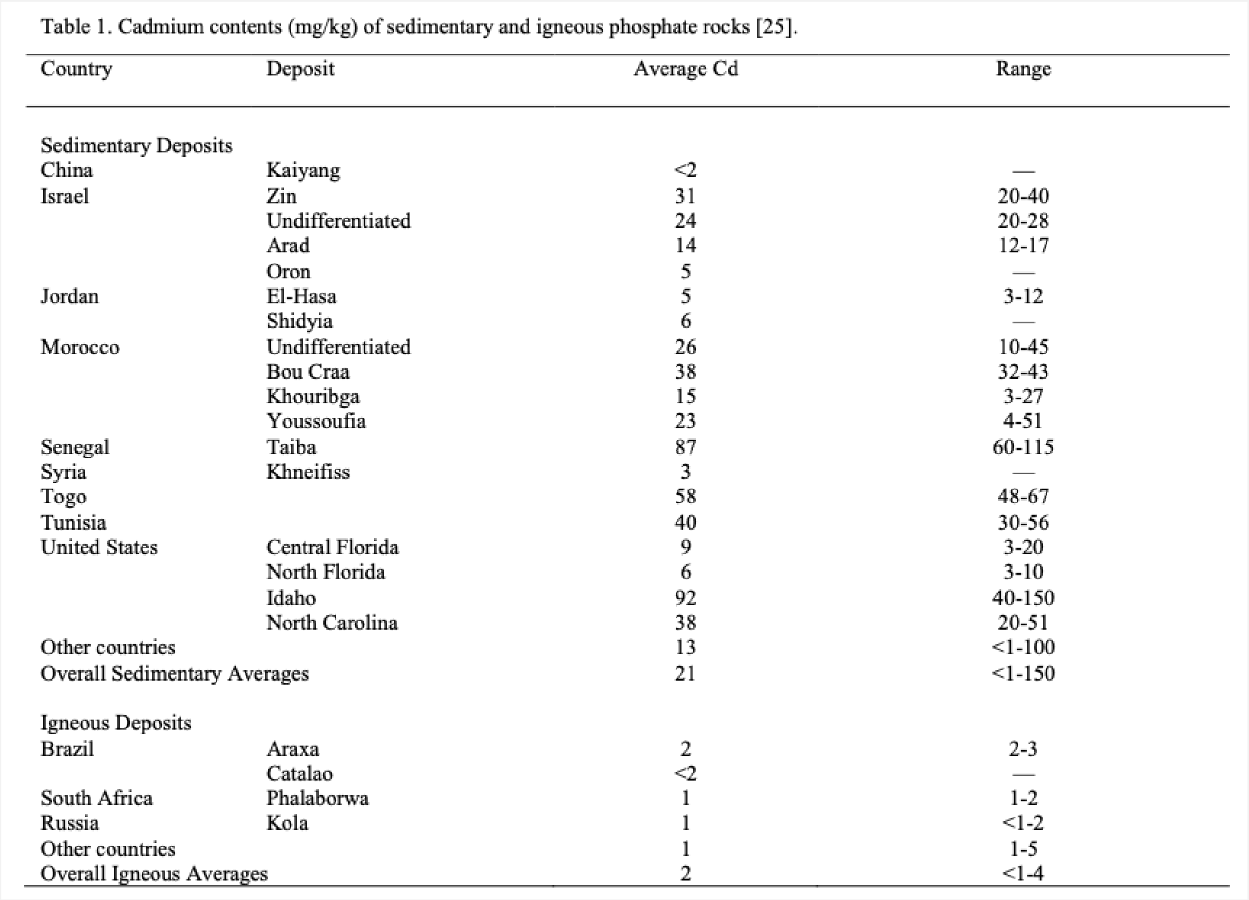

Table 1. Cadmium contents (mg/kg) of sedimentary and igneous phosphate rocks [25].

Country	Deposit	Average Cd	Range
Sedimentary Deposits			
China	Kaiyang	<2	—
Israel	Zin	31	20-40
	Undifferentiated	24	20-28
	Arad	14	12-17
	Oron	5	—
Jordan	El-Hasa	5	3-12
	Shidyia	6	—
Morocco	Undifferentiated	26	10-45
	Bou Craa	38	32-43
	Khouribga	15	3-27
	Youssoufia	23	4-51
Senegal	Taiba	87	60-115
Syria	Khneifiss	3	—
Togo		58	48-67
Tunisia		40	30-56
United States	Central Florida	9	3-20
	North Florida	6	3-10
	Idaho	92	40-150
	North Carolina	38	20-51
Other countries		13	<1-100
Overall Sedimentary Averages		21	<1-150
Igneous Deposits			
Brazil	Araxa	2	2-3
	Catalao	<2	—
South Africa	Phalaborwa	1	1-2
Russia	Kola	1	<1-2
Other countries		1	1-5
Overall Igneous Averages		2	<1-4

Figure 53: Cadmium contents of sedimentary and igneous phosphate rocks. Shows the range of variation within a same deposit.

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[72] Terry L. Robertsa, 'Cadmium and Phosphorous Fertilizers: The Issues and the Science', *Procedia Engineering*, 83 (2014), 52–59 <https://doi.org/10.1016/j.proeng.2014.09.012>.

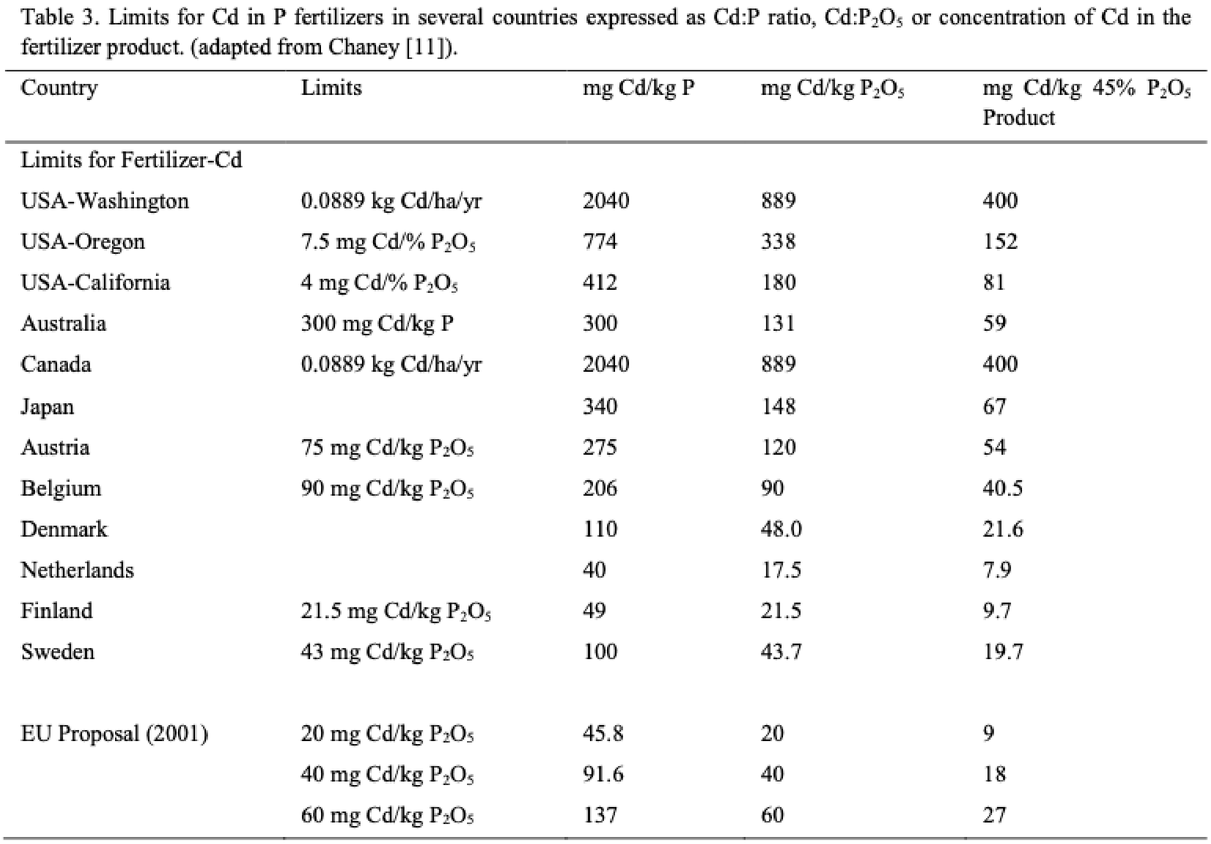

Table 3. Limits for Cd in P fertilizers in several countries expressed as Cd:P ratio, Cd:P_2O_5 or concentration of Cd in the fertilizer product. (adapted from Chaney [11]).

Country	Limits	mg Cd/kg P	mg Cd/kg P_2O_5	mg Cd/kg 45% P_2O_5 Product
Limits for Fertilizer-Cd				
USA-Washington	0.0889 kg Cd/ha/yr	2040	889	400
USA-Oregon	7.5 mg Cd/% P_2O_5	774	338	152
USA-California	4 mg Cd/% P_2O_5	412	180	81
Australia	300 mg Cd/kg P	300	131	59
Canada	0.0889 kg Cd/ha/yr	2040	889	400
Japan		340	148	67
Austria	75 mg Cd/kg P_2O_5	275	120	54
Belgium	90 mg Cd/kg P_2O_5	206	90	40.5
Denmark		110	48.0	21.6
Netherlands		40	17.5	7.9
Finland	21.5 mg Cd/kg P_2O_5	49	21.5	9.7
Sweden	43 mg Cd/kg P_2O_5	100	43.7	19.7
EU Proposal (2001)	20 mg Cd/kg P_2O_5	45.8	20	9
	40 mg Cd/kg P_2O_5	91.6	40	18
	60 mg Cd/kg P_2O_5	137	60	27

Figure 54: Limits for Cadmium in P fertilizers in several countries. Illustrates the potential differentiation of markets per region, with various "suitability" of untreated rock given the distribution of cadmium within each deposit.

9.15. OCP group’s current footprint and industrial capability

Source: IFA Agregate statistics for 9M FY2018. Fertilizers include DAP/MAP/TSP. Acid excludes purified acid coming from China.

Figure 55: OCP global presence and export volume share per region. OCP website, dec 2019.

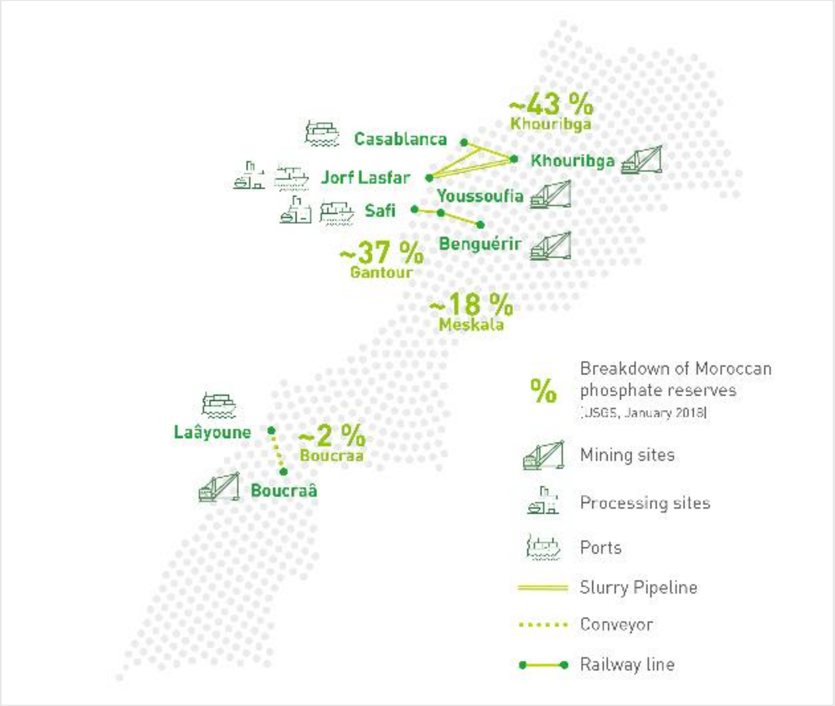

Figure 56: OCP production sites, 3 axes (Jorf, Safi, Laâyoune), with the breakdown per axe of Moroccan phosphate reserves. OCP website, dec 2019

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9.16. Screening model: Overview of the excel spreadsheet

Copy – past of the calculation tool developed on Excel. All figures have been removed to not disclose any proprietary information relative to OCP group's operations.

The NPV obtained with this model is then normalized, for all the results presented in this thesis.

		Y0	**Y1**	**…**	**Y10**
WORLD DEMAND					
demand rock	ton	XXXX	XXXX		XXXX
demand P-acid	ton	XXXX	XXXX		XXXX
demand P-fertilzers	ton	XXXX	XXXX		XXXX
demand P-special	ton	XXXX	XXXX		XXXX
MAX ACCESSIBLE DEMAND (MARKET SHARE)					
demand rock	ton	XXXX	XXXX		XXXX
demand P-acid	ton	XXXX	XXXX		XXXX
demand P-fertilzers	ton	XXXX	XXXX		XXXX
demand P-special	ton	XXXX	XXXX		XXXX
INITIAL CAPACITY + CONSTRUCTION OF UNITS OF PRODUCTION					
Mining and wash plants units	units	X	X		-
P acid units	units	X	X		-
Granulation unit	units	X	X		-
Granulation unit advanced (special prod)	units	X	X		-
TOTAL UNITS OF PRODUCTION					
Mining and wash plants units	units	X	X		X
P acid units	units	X	X		X
Granulation unit	units	X	X		X
Granulation unit advanced (special prod)	units	X	X		X

TOTAL CAPACITY OF PRODUCTION				
capacity rock	ton	XXXX	XXXX	XXXX
capacity P-acid	ton	XXXX	XXXX	XXXX
capacity P-fertilizers	ton	XXXX	XXXX	XXXX
capacity P-special	ton	XXXX	XXXX	XXXX
VARIABLE COSTS OF RAW MATERIALS				
Rock cost	$/ton	$XX	$XX	$XX
Sulfur Cost	$/ton	$XX	$XX	$XX
Ammonia Cost	$/ton	$XX	$XX	$XX
FIXED OPERTIONAL COSTS PER UNIT OF PRODUCTION				
labor costs and other opex – per unit of mine	$/UNIT	$ XXXX	$ XXXX	$ XXXX
labor costs and other opex - per unit of chemical	$/UNIT	$ XXXX	$ XXXX	$ XXXX
labor costs and other opex - per unit of granulation	$/UNIT	$ XXXX	$ XXXX	$ XXXX
labor costs and other opex - per unit of special	$/UNIT	$ XXXX	$ XXXX	$ XXXX
internal logistics - transfert costs, ONCF	$/UNIT	$ XXXX	$ XXXX	$ XXXX
TOTAL VARIABLE OPEX PER PRODUCT				
total variable opex rock production	$/ton	$XX	$XX	$XX
total variable opex P-acid production	$/ton	$XX	$XX	$XX
total variable opex fertilizer production	$/ton	$XX	$XX	$XX
total variable opex special production	$/ton	$XX	$XX	$XX
EXPORT SALES PRICES				
trade spot price rock	$/ton	$XX	$XX	$XX
trade spot price P-acid	$/ton	$XX	$XX	$XX
trade spot price fertilizer (DAP)	$/ton	$XX	$XX	$XX

trade spot price special	$/ton	$XX	$XX		$XX
PRODUCTION ALLOCATION					
total production allocation rock	ton	XXX	XXX		XXX
including rock for trade	*ton*	*XX*	*XX*		*XX*
including rock for acid for trade	*ton*	*XX*	*XX*		*XX*
incl. rock for fertilizers & Acid-to-fertilizer	*ton*	*XX*	*XX*		*XX*
including rock for specials & Acid-to-special	*ton*	*XX*	*XX*		*XX*
total production allocation acid	ton	XXX	XXX		XXX
including acid for trade	*ton*	*XX*	*XX*		*XX*
including acid for fertilizers	*ton*	*XX*	*XX*		*XX*
including acid for specials	*ton*	*XX*	*XX*		*XX*
production allocation fertilizers	ton	XXX	XXX		XXX
production allocation specials	ton	XXX	XXX		XXX
CAPACITY UTILIZATION					
capacity utilization rock	*%*	*97%*	*100%*		*100%*
capacity utilization acid	*%*	*77%*	*87%*		*100%*
capacity utilization fertilizer	*%*	*100%*	*100%*		*100%*
capacity utilization special	*%*	*0%*	*100%*		*100%*
TOTAL OPERATIONAL COSTS (VARIABLE + FIXED COSTS) AND REVENUE					
total fixed costs	k$	$ XXXX	$ XXXX		$ XXXX
total variable costs	k$	$ XXXX	$ XXXX		$ XXXX
total revenue	k$	$ XXXX	$ XXXX		$ XXXX
NET OPERATING PROFIT					
net operating profit	k$	$ XXXX	$ XXXX		$ XXXX
CAPITAL EXPENDITURES					
Other ("not production") investments	k$	$ XXXX	$ XXXX		$ XXXX

Capital expenditure - mine units	k$		$ XXXX	$ -
Capital expenditure - acid units	k$		$ XXXX	$ -
Capital expenditure - granulation units	k$		$ XXXX	$ -
Capital expenditure - special units	k$		$ XXXX	$ -
terminal value of the assets + investments	k$		$ XXXX	$ XXXX
DCF AND ENTERPRISE VALUE		***0***	***1***	***10***
total cash flow (CF)	k$	$ XXXX	$ XXXX	$ XXXX
total discounted CF (DCF)	k$	$ XXXX	$ XXXX	$ XXXX
NET PRESENT VALUE (NPV)	**$**	**$ XXXX**		
check proportion of the terminal value in the NPV		*XX%*		

9.17. Screening model: table of assumptions for baseline, worst case, best case

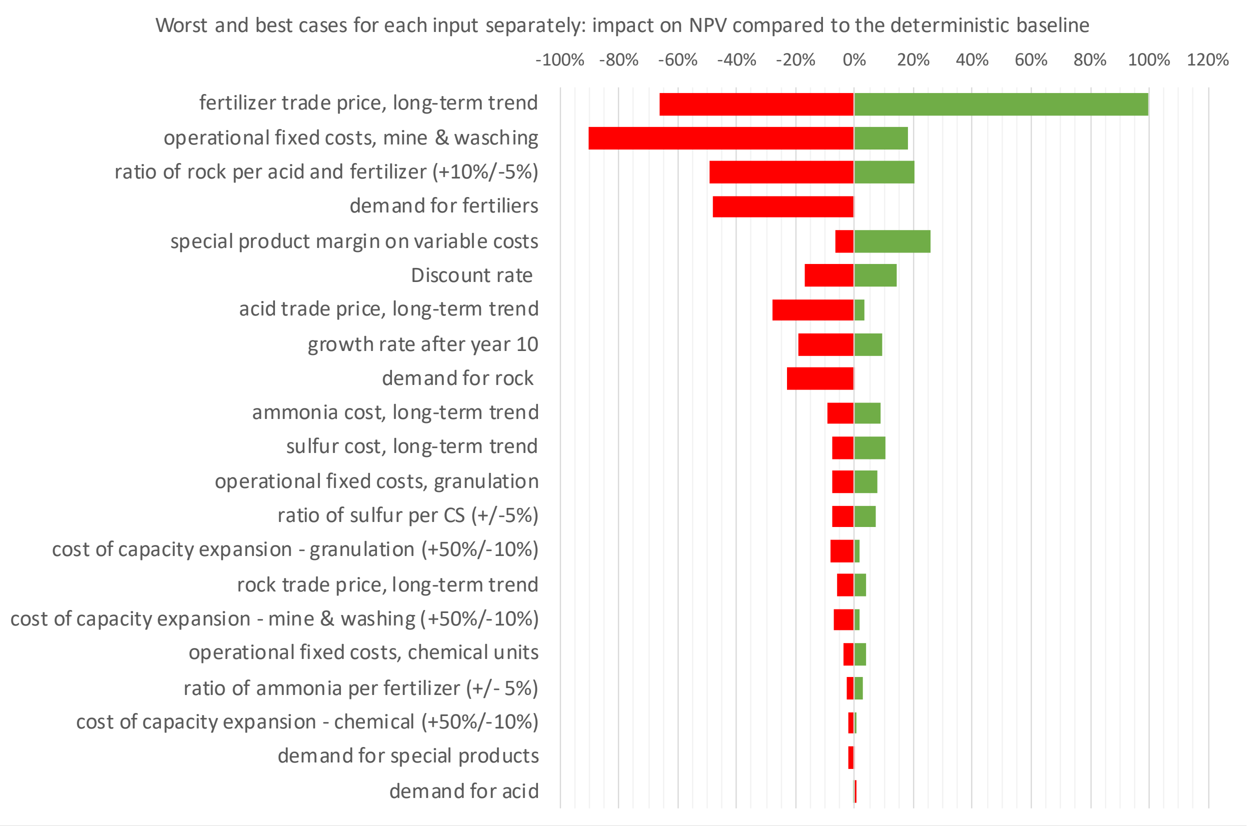

Figure 57: Full sensitivity analysis of performance to worst / best cases estimates for each variable independently

Table 15: Baseline values and best and worst cases values for the screening model's inputs, used for the tornado diagram and sensitivity analysis. Values used to match the specific case of OCP are hidden.

Variable	**units**	**base-line**	**worst case**	**best case**	**note**
Discount rate	-	moderate	higher	lower	high discount rate moderates the weight of capacity expenditures, but also minimizes mid and long-term revenues. Under our assumptions and timeline of investments, higher discount rate decreases the NPV.
Growth rate at the end of the horizon	-	slightly positive	slightly negative	moderate	this variable impacts the projection of cash-flows beyond 10-y and the terminal value.

Variable	units	base-line	worst case	best case	note
Accessible demand parameters		**base value**	**min value**	**max value**	
10-y variation in demand for rock	-	2%	-5%	10%	Baseline assumptions are related to historical trends, sources IFASTAT and The World Bank. We assume the uncertainty is higher for fertilizer and special products, given our own analysis of environmental risks.
10-y variation in demand for P-acid	-	3%	-5%	10%	
10-y variation in demand for fertilizers	-	2%	-10%	20%	
10-y variation in demand for special	-	10%	-10%	30%	
Raw material costs and trade prices		**base value**	**min value**	**max value**	
10-y variation in sulfur cost	-	3%	20%	-20%	Baseline assumptions are related to historical trends, sources IFASTAT and The World Bank.
10-y variation in ammonia cost	-	0%	25%	-25%	
10-y variation in rock price	-	3%	-5%	8%	
10-y variation in Fertilizer price	-	15%	-5%	45%	
P-acid trade price compared to DAP trade price		90%	50%	95%	Assumptions and placeholders that can be tailored differently to match any other context of production and sales.
special product trade price compared to production cost		120%	100%	200%	
costs of new facilities (capex) and costs of production		**base value**	**max increase**	**max decrease**	
cost of new unit of production mine + wash	$/unit	X	50%	-10%	Cost of building new capacity, more susceptible to go-over budget than to decrease.
cost of new S-acid + P-acid unit	$/unit	X	50%	-10%	

Variable	**units**	**baseline**	**worst case**	**best case**	**note**
cost of new granulation unit for fertilizers	$/unit	X	50%	-10%	
cost of new granulation unit for special products	$/unit	X	50%	-10%	
fixed opex per unit of mining + washing	$/unit /year	X	100%	-20%	We assume a potentiality of doubling the production cost, if the rock were to need heavy additional treatment before being usable
fixed opex per (S+P acid) unit	$/unit /year	X	10%	-10%	We assume a potential variation due to technological innovation or additional, costly, requirements.
fixed opex per granulation unit	$/ton	X	10%	-10%	
production parameters		**base value**	**max increase**	**max decrease**	
rock per P-acid ratio, rock per fertilizer ratio, rock per special product ratios	-	x	10%	-5%	We assume technological change or change in the products requirements could impact these ratios. Especially for the rock, we assume potential greater increase if specific elements naturally existing in the rock had to be removed.
Ammonia N per fertilizer ratio	-	x	5%	-5%	We assume technological change or change in the products requirements could impact these ratios.
Liquid Sulfur per ACS ratio	-	x	5%	-5%	
ACS per P-acid ratio	-	x	5%	-5%	

9.18. Screening model: Allocation of production procedure, example plan A

To illustrate the allocation of production possible procedures, we describe below the example of allocation "plan A" that prioritizes 1. Special fertilizer, 2. Mainstream fertilizer, 3. Phosphoric acid, 4. Rock for trade. This procedure is directly implemented in the Excel spreadsheet (using only Excel native functions).

All variables' names are listed in Table 16 and Table 17 below.

1. Allocate the production of Special, $P_{special}$

$$P_{special} = Min\left(D_{special}\ , C_{special}, C_{acid}/\propto_{AcidToSpecial}, C_{rock}/(\propto_{RockToSpecial} + \propto_{RockToAcid} * \propto_{AcidToSpecial}\right)$$

- ***Update the production of rock and acid required:***

$$P_{RockForSpecial} = P_{special} * \propto_{RockToSpecial}$$

$$P_{AcidForSpecial} = P_{special} * \propto_{AcidToSpecial}$$

2. Allocate the production of Fertilizer, $P_{Fertilizer}$

$$P_{Fertilizer} = Min\left(D_{Fertilizer}\ , C_{Fertilizer}, (C_{acid} - P_{AcidForSpecial})/\propto_{AcidToFertilizer}, (C_{rock} - P_{RockForSpecial})\ /(\propto_{RockToFertilizer} + \propto_{RockToAcid} * \propto_{AcidToFertilizer})\ \right)$$

- ***Update the production of rock and acid required:***

$$P_{RockForFertilizer} = P_{Fertilizer} * \propto_{RockToFertilizer}$$

$$P_{AcidForFertilizer} = P_{Fertilizer} * \propto_{AcidToFertilizer}$$

3. Allocate the production of Acid for trade, $P_{AcidForTrade}$

$$P_{AcidForTrade} = Min\Big(D_{Acid}\ , C_{Acid} - P_{AcidForSpecial} - P_{AcidForFertilizer}, (C_{rock} - P_{RockForSpecial} - P_{RockForFertilizer})\ / \propto_{RockToAcid}\Big)$$

- ***Update the production of acid and rock required:***

$$P_{Acid} = P_{AcidForSpecial} + P_{AcidForFertilizer} + P_{AcidForTrade}$$

$$P_{RockForAcid} = P_{Acid} * \propto_{RockToAcid}$$

4. Finally, allocate the production of Rock for trade, $\boldsymbol{P_{RockForTrade}}$

$$P_{RockForTrade} = Min\big(D_{Rock}\ , C_{Rock} - P_{RockForSpecial} - P_{RockForFertilizer} - P_{RockForAcid}\big)$$

- ***Update the production of rock required:***

$$P_{Rock} = P_{RockForSpecial} + P_{RockForFertilizer} + P_{RockForAcid} + P_{RockForTrade}$$

Tables of variables:

Table 16: Table of input variables used in the production allocation procedure

Name	**unit**	**Input variable**
$\boldsymbol{D_{Rock}}$	Ton rock	Accessible demand of Rock on the trade market
$\boldsymbol{D_{Acid}}$	Ton acid	Accessible demand of Acid on the trade market
$\boldsymbol{D_{Fertilizer}}$	Ton fert.	Accessible demand of Fertilizer on the trade market
$\boldsymbol{D_{special}}$	Ton spe.	Accessible demand of Special Product on the trade market
$\boldsymbol{C_{Rock}}$	Ton rock	Total capacity of production of Rock
$\boldsymbol{C_{Acid}}$	Ton acid	Total capacity of production of Acid
$\boldsymbol{C_{Fertilizer}}$	Ton fert.	Total capacity of production of Fertilizer
$\boldsymbol{C_{special}}$	Ton spe.	Total capacity of production of Special Product
$\propto_{\boldsymbol{RockToAcid}}$	Ton rock / Ton acid	Ratio Rock to Acid
$\propto_{\boldsymbol{RockToFertilizer}}$	Ton rock / Ton fert.	Ratio Rock to Fertilizer

$\boldsymbol{\propto_{RockToSpecial}}$	Ton rock / Ton spe.	Ratio Rock to Special Product
$\boldsymbol{\propto_{AcidToFertilizer}}$	Ton acid / Ton fert.	Ratio Acid to Fertilizer
$\boldsymbol{\propto_{AcidToSpecial}}$	Ton acid / Ton spe.	Ratio Acid to Special Product

Table 17: Table of output variables from the production allocation procedure.

Name	**unit**	**Output variable**
$\boldsymbol{P_{RockForSpecial}}$	Ton rock	Production of rock allocated to special product fabrication
$\boldsymbol{P_{RockForFertilizer}}$	Ton rock	Production of rock allocated to fertilizer fabrication
$\boldsymbol{P_{RockForAcid}}$	Ton rock	Production of rock allocated to acid fabrication
$\boldsymbol{P_{RockForTrade}}$	Ton rock	Production of rock allocated to trade
$\boldsymbol{P_{Rock}}$	Ton rock	Total Production of rock
$\boldsymbol{P_{AcidForSpecial}}$	Ton acid	Production of acid allocated to special product fabrication
$\boldsymbol{P_{AcidForFertilizer}}$	Ton acid	Production of acid allocated to fertilizer fabrication
$\boldsymbol{P_{AcidForTrade}}$	Ton acid	Production of acid allocated to trade
$\boldsymbol{P_{Acid}}$	Ton acid	Total Production of acid
$\boldsymbol{P_{Fertilizer}}$	Ton fert.	Total Production of fertilizer (all for trade)
$\boldsymbol{P_{Special}}$	Ton spe.	Total Production of special product (all for trade)