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► To cite this version:

Latifa Benhamou, Vincent Giard, Pierre Féliès. A Reverse Blending based supply chain for mass customization of green fertilizers. *Journal of Cleaner Production*, 2023, 415, pp.137495. <10.1016/j.jclepro.2023.137495>. <hal-04591513>

HAL Id: hal-04591513

<https://hal.science/hal-04591513v1>

Submitted on 9 Jul 2025

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A Reverse Blending based supply chain for mass customization of green fertilizers

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Reverse Blending is a new product design and manufacturing approach based on finding the optimal chemical composition of a very small number of semi-finished common products (composites) whose possible blends may satisfy a wide variety of green fertilizers. As these fertilizers are adapted to the ecological requirements of crops and soils, Reverse Blending allows for both efficient and sustainable agriculture. Its implementation involves a supply chain redesign that calls for a shift from sequential batch production of different products to a hybrid system consisting of: *i*) make-to-stock of the composites within the chemical plant and *ii*) make-to-order of customized fertilizers within small blending units to be located near the farmer. This mass customization system brings new opportunities not yet exploited in the context of continuous production (granules, liquids...). This paper aims to highlight these opportunities and demonstrate the managerial and logistical consequences of a Reverse Blending based mass customization through several analysis studies.

Keywords: Reverse blending, Mass customization, Continuous supply chain, Sustainability, Optimization.

1 Introduction

It is unfortunately established that, especially in Africa, population growth exceeds the growth of agricultural production based on current practices. The performance of agriculture depends on many factors (crop, soil, water, fertilizer, soil organic matter...). Using fertilizers is essential to allow the cultivation of certain crops on plots whose soils cannot provide the nutrients (mainly Nitrogen N, Phosphorus P, and Potassium K) necessary for optimal sustainable yield. Several tools calculate roughly these requirements (Beneduzzi et al., 2022), generally for a crop and a large territory. FERTIMAP (<http://www.fertimap.ma/>), developed in Morocco under the aegis of the Ministry of Agriculture, offers a rapid and precise diagnosis of the exact nutrient requirements once the soil composition of a plot and the crop to cultivate are known. As an existing fertilizer can rarely meet the exact requirements, it offers a solution for mixing locally available fertilizers to get as close as possible to the desired fertilizer. Hundreds of tests conducted with FERTIMAP on actual data (Benhamou et al., 2020) have shown that almost all existing solutions lead to significant deficiencies or excesses of certain nutrients, which does not allow us to obtain the desired optimal yield and compromises the achievement of sustainable agriculture. Indeed, one of the main principles of sustainable agriculture is the reasoned fertilization using green fertilizers, i.e. fertilizers manufactured and used in a way that causes the least possible damage to soil fertility. These are customized fertilizers whose nutrient composition is specifically

adapted to the soil characteristics and needs of the crops. One way to ensure nowadays that a fertilizer is exactly what a farmer needs (in terms of NPK, but also other nutrients and trace elements) is to chemically manufacture it so that each granule contains precisely the required nutrient concentrations. OCP, a world leader in the fertilizer market, occasionally produces on order this type of fertilizer and sells it at extremely high prices (especially for African farmers) because of their long and complex design and manufacturing process. The variety of green fertilizers required to cover all nutrient needs is therefore far too vast to be obtained with the industrial solutions available at acceptable costs because, on the one hand, production by chemical reaction leads to high selling prices while limiting the variety that can be produced and managed. On the other hand, blending fertilizers, although more flexible and less expensive, does not sufficiently meet the needs of sustainable agriculture.

To cope with this situation, Benhamou et al. (2020) developed an optimization approach called Reverse Blending (RB). It involves a new blending problem whose optimization model has as input the wide variety of green fertilizers to be produced and as output the number and composition of a few basic ingredients. These ingredients are common components that must be mixed (in different ways reflecting thousands of mixing recipes) to satisfy thousands of customized fertilizers. Published research on RB (Benhamou et al., 2020; Sheikh et al., 2022) mainly gave the definition of this approach, its originality compared to the existing blending problems, its quadratic optimization models and its application on a real sample of 700 requirements in N, P and K calculated with FERTIMAP. This product design is the first step. Applying a customization strategy (fertilizer customization in our case) actually involves two main steps: product design and supply chain redesign (Baud-Lavigne et al., 2012). Approaching RB from a Supply Chain (SC) perspective remains thus to be done.

This paper aims to fill this gap by analyzing the logistical implications of adopting RB, which replaces the production of existing fertilizers with the production of a very limited number of common components, before transporting them to small decentralized blending units (such as those that already exist), where they are blended according to locally defined custom recipes to precisely respect the requirements of precision agriculture (cf. Figure 1).

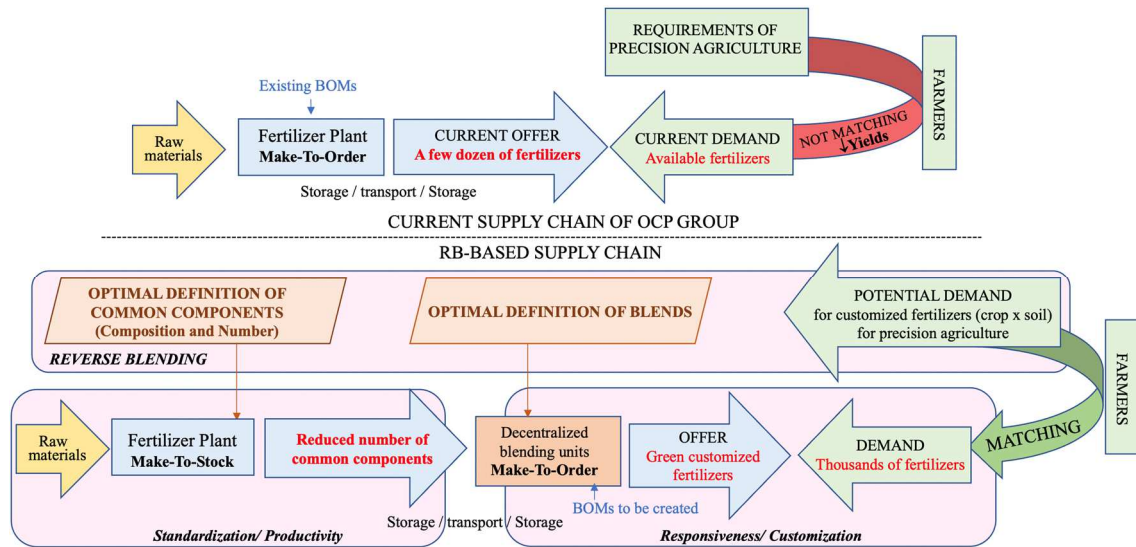


Figure 1. RB-based SC compared to OCP's current SC.

The RB-based SC involves Mass Customization (MC) and, more specifically, delayed differentiation (also known as postponement), offering both the benefits of mass production, i.e., productivity and economies of scale and those of customization, i.e., customer satisfaction and increased product value. With its ability to identify the common products set, RB can be considered a new mass customization technique bringing together different features that, in the context of continuous flow production, have, to our knowledge, never been combined before in a MC system. That said, on top of addressing a major issue of humanity's food survival, our research is motivated by the introduction of a new MC system capable of simultaneously improving customer value and sustainability, which, according to Sakao and Fargnoli (2010) and Haber and Fargnoli (2021), is essential to make the environmental value of green fertilizers appreciated by the farmers.

Before presenting the specificities of this MC system in section 3, we first present, in section 2, the main concepts and results of RB and its interest compared to classical blending. Section 4 is devoted to a brief literature review showing the originality of the RB-based MC. In section 5, we highlight the main managerial consequences of RB before concluding, in section 6, with some conclusions and perspectives.

2 Reverse Blending approach

2.1 Main concepts and results

This section does not detail the RB foundations and its original positioning in the scientific literature that can be found in Benhamou et al. (2020). Table 6 provided in the appendix of this paper, which compares four blending models (starting from the original Blending Problem (BP) model presented in the first column), allows to quickly highlight the differences between these models and to show the originality of RB. The RB model (displayed in column 2) aims, through a quadratic program, to

simultaneously define: *i*) the compositional specifications of new composites, acting as common components, belonging to a set of the smallest possible size considered as a Canonical Basis (CB) to use a classical mathematical terminology (these composites of the CB being identified by the acronym CCBs) and *ii*) the optimal BOMs of a large set of fertilizers to produce. Thousands of linear combinations resulting from mixing these CCBs should make it possible to produce a wide variety of green fertilizers, knowing that this variety is mainly explained by the combination of soil characteristics and the nutrient requirements of the crops grown in these soils. In (Benhamou et al., 2020), RB was applied to a sample of 700 requirements for N, P and K (expressed in Kg/ha), and it was found that only 8 CCBs are needed to satisfy all the 700 requirements.

The administration of commercially available fertilizers necessarily leads to an excess or deficiency of certain nutrients. One of the old ways of dealing with the mismatch between these fertilizers and the needs to be met is to blend two or more fertilizers to get closer to these needs. This blend, usually defined by a simple linear program, aims to minimize a deviation indicator between the required composition and the composition obtained by the "optimal" blend of these fertilizers. Such deviations can be detrimental to sustainable agriculture. The standard European regulation (EU PE-CONS 76/18, 2019) defines the acceptable deviations in the fertilizer composition to achieve the expected performance if its composition is the one required for the « crop-soil » combination. However, although blending existing fertilizers is often used, it rarely meets the compositional requirements within the allowed tolerances. One solution would be to increase the number of fertilizers to be used as blending inputs, but to what extent?

In this sense, it is interesting first to see: *i*) to what extent classical blending of fertilizers can reduce the diversity of the commercial offer (i.e., diversity to be produced) without affecting the "potential diversity of use", and secondly, to see *ii*) whether for the same "potential diversity of use", RB can further reduce the diversity to be produced.

To show the interest of RB, we make this comparison between blending and RB based on a real-life data set composed of fertilizers currently sold by some of the largest fertilizer producers (OCP Group, Yara, Agrium, K+S, Potashcorp, Mosaic, Uralkali, Belaruskali and CF Industries). The diversity of these fertilizers is 175 compound fertilizers, but if only those with different formulas are considered, a total of $J=142$ fertilizer formulas is reached. These formulas may contain from 2 to $C = 10$ components, the first nine ones corresponding respectively to N, P, K, S, B_2O_3 , Zn, Mg (magnesium), Na (sodium) and Ca (calcium) and the last one corresponding to *filler* (an additional neutral component used for the chemical stabilization of the granules' composition). The chemical characteristics of these formulas are given in "CS3.1" sheet of the Excel file included in the link <https://data.mendeley.com/datasets/drzbzd8jw9>.

2.2 Interest of RB over classical blending

In this section, it will be shown that a significant part of the 142 formulas can be obtained by a simple mix of some of these formulas, thus showing that the diversity offered on the market is not as broad as one might think (§2.2.1). The reflection will

then go further on reducing the produced diversity for the same offered diversity by looking for the CB allowing to recreate these 142 formulas (§2.2.2).

To do so, we will start by examining to what extent certain existing fertilizers can be obtained by mixing other fertilizers, which brings us to search for the minimum set of fertilizers (inputs) from which the 142 fertilizers can be reconstituted. For this research, the absolute difference between the target value on the share of a component in the total weight and the value obtained by the solution found is tolerated to be no more than 0.0005 (for example, for fertilizer 1, N should represent 20.52% of the total weight, the solution is acceptable only if this proportion is between 20.47% and 20.57% in the proposed solution). This tolerance margin largely satisfies European regulations. We will apply the RB approach to reduce further this set of inputs allowing us to reconstitute the 142 fertilizer formulas. We will conclude this analysis by explaining the limits of the interest in reducing the commercial offer.

2.2.1 Reducing the diversity of marketed fertilizers using classical blending

Analysis method

This analysis was conducted using the Diversity Reduction (DR) model (described in column 4 of Table 6), a blending model we developed to show the added value of RB compared to the approach currently used by farmers, which consists of obtaining a fertilizer (output) by blending existing fertilizers (inputs). The solving of this model is based on parameterized mixed linear programming. Considering the constraints related to the respect of the demand and the chemical specifications of the outputs, we try to produce J fertilizers (outputs) while minimizing the number S of inputs used (S corresponding to a subset of the J fertilizers), the resolution of this model starts with $S=J-1$ then we progressively decrement S ($S = J-2, J-3\dots$) until we find the minimum number S of inputs necessary so that all the outputs can be obtained. The objective function is to maximize the number of feasible fertilizers (cf. Figure 2). In this model, the notion of tolerance is introduced to conduct a fair comparison with RB, where a very small tolerance is allowed for each output component.

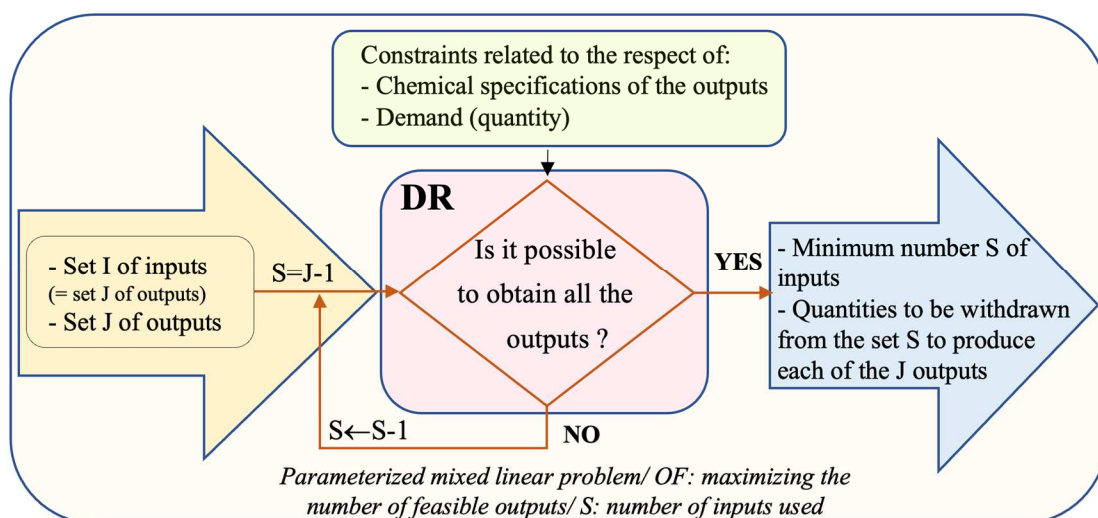


Figure 2. Descriptive diagram of the Diversity Reduction problem.

Figure 2 shows how to partition a set of fertilizers into two subsets, the first being composed of fertilizers that can be obtained by mixing fertilizers from the second. The iterative process described in this figure makes it possible to determine the first subset with the greatest possible number of fertilizers that can be obtained from the fertilizers of the second subset, which corresponds to the diversity really offered.

Analysis results

The use of the DR model reveals that instead of producing all J=142 fertilizers by chemical transformation, which is what is currently done, it is indeed possible with S=33 fertilizers to produce the remaining 109 (142-33) fertilizers. The composition of these 33 fertilizers and the quantities to be taken to meet all chemical specifications are given in the sheet "CS3.2" of the Excel file in the Mendeley link. As the tolerance to the target specifications was set to ± 0.0005 , a complementary test was carried out by decreasing the tolerance, and it turned out that an exact optimal solution exists. We preferred to keep this solution in the spreadsheet "CS3.2".

2.2.2 Reducing the diversity of marketed fertilizers using Reverse Blending

Analysis method

The objective is to determine the CCBs allowing a priori to recreate the 142 fertilizers currently sold in compliance with the European regulation (EU PE-CONS 76/18, 2019) and to satisfy a very large number of other nutritive needs. The optimization model to be used is the RB model (cf. Figure 3). Its mathematical formulation can be found in the second column of Table 6.

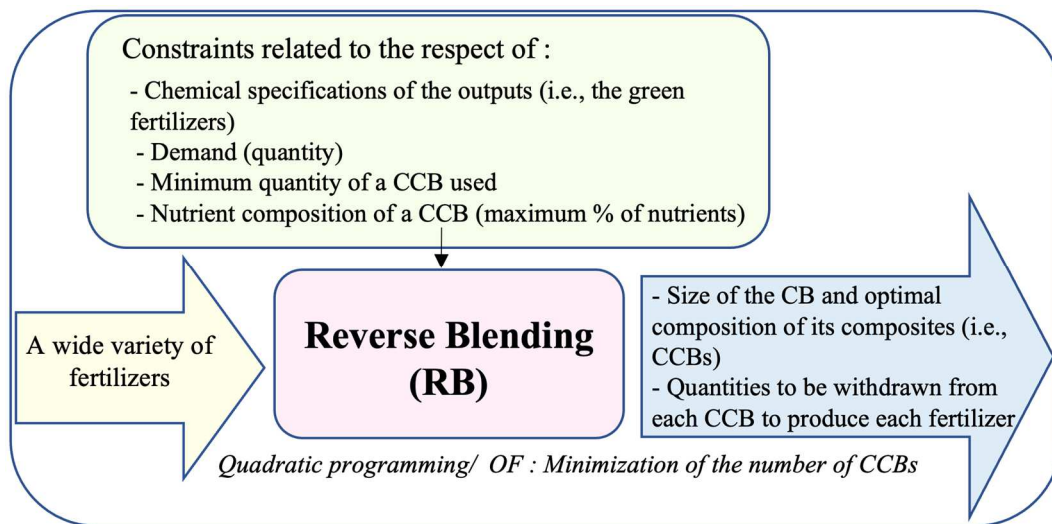


Figure 3. Descriptive diagram of the Reverse Blending problem.

As already explained, small deviations from the target specifications are accepted in the RB and DR as long as these deviations remain within the regulated tolerances. It should be clarified that in the regulations (EU PE-CONS 76/18, 2019), the nutrient specifications of fertilizer must be met, considering a tolerance margin that varies according to the number and type of components contained in that fertilizer. For example, for secondary nutrients, the tolerances permitted with the declared values of

Ca, Mg, Na, and S are set at 1/4 of the declared contents of these elements with a maximum of 0.9% in absolute value for CaO, MgO, Na₂O, and SO₃, i.e., 0.64% for Ca, 0.55% for Mg, 0.67% for Na and 0.36% for S. In order not to complicate the models, regardless of the number of components and whether they are major, secondary or trace elements, it was decided to opt for a very low tolerance for each nutrient, so that the regulatory tolerances are always respected.

Analysis results

The application of the RB model to the 142 fertilizers shows that the totality of these fertilizers, covering 10 different components, can be satisfied with only 16 CCBs, one of which plays the *filler* role. The optimal composition of the CCBs is detailed in Table 1, and the quantities to be withdrawn from them to produce each fertilizer are given in the sheet "CS3.3".

Table 1. Optimal composition of the 16 CCBs needed to meet the 142 marketed fertilizers

			CCB <i>i</i>															
			<i>filler</i>	<i>i=2</i>	<i>i=3</i>	<i>i=4</i>	<i>i=5</i>	<i>i=6</i>	<i>i=7</i>	<i>i=8</i>	<i>i=9</i>	<i>i=10</i>	<i>i=11</i>	<i>i=12</i>	<i>i=13</i>	<i>i=14</i>	<i>i=15</i>	<i>i=16</i>
Component <i>c</i>	<i>c=1</i>	%N	0	46,0	0	11,5	0	3,7	5,5	0	40,7	9,7	0	16,5	22,8	0	0	15,7
	<i>c=2</i>	%P	0	0	46,0	56,6	0	7,0	32,8	0	0	56,0	0	26,4	23,1	0	0	0
	<i>c=3</i>	%K	0	0	0	0,0	63,9	14,0	58,6	52,0	0	0	0	0	0	0	11,0	0
	<i>c=4</i>	%S	0	0	0	0	0	0	0	45,0	56,3	31,3	45,0	7,8	0	53,2	10,0	0
	<i>c=5</i>	%B ₂ O ₃	0	0	0	0	0	0	0	0	0	0	0	1,6	0	0	0	0
	<i>c=6</i>	%Zn	0	0	0	0	0	0	0	0	0	0	0	0	5,8	0	0	0
	<i>c=7</i>	%Mg	0	0	0	0	0	0	0	0	0	0	0	0	0	26,6	5,0	0
	<i>c=8</i>	%Na	0	0	0	0	0	0	0	0	0	0	0	0	0	0	27,0	0
	<i>c=9</i>	%Ca	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26,6
	<i>c=10</i>	% <i>filler</i>	100	54,0	54,0	31,8	36,1	75,3	3,0	3,0	3,0	3,0	55,0	47,8	48,4	20,2	47,0	57,8

In analyzing these quantities, it is noticed that to produce 100 tons of outputs *j=84*, *j=109*, *j=64* and *j=59*, 100 tons of CCB *i=2*, *i=3*, *i=8* and *i=15* are needed, respectively. This means that these CCBs correspond to fertilizers, and since they are used in several other mixtures, they must be treated as both CCBs and fertilizers.

Being the three most essential nutrients for any soil, NPKs are the most produced and sold fertilizers in the world. In this example, the 79 NPK fertilizers represent about 56% of all the considered references. To produce them, the solver proposed, in addition to the *filler* (*i=1*), 6 CCBs (*i=2...7*) whose composition allows to satisfy all the nutritional needs of all 79 NPKs. In the example of the 700 NPK requirements, only one more composite (7 CCBs) was needed. This confirms that the diversity of the sample considered is not proportional to the size of the CB. Sulphur (S) is the fourth most essential soil nutrient, so NPKS account for 82% of the considered references, amounting to 117 fertilizers. For their production, RB requires a minimum number of 10 CCBs. Finally, RB makes it possible to meet all the fertilizers sold by the leaders of the fertilizer market with only 15 CCBs, and this by meeting the nutritional requirements almost exactly (within ±0.05%).

2.2.3 Discussion

In both cases, we have shown that reducing the variety to be produced is possible

without reducing the «potential diversity of use» related to the existing commercial offer. Still, we note that with only 15 CCBs, RB can satisfy an international offer of more than 140 fertilizers, whereas the current approach of blending existing fertilizers requires a minimum of 33 fertilizers, even assuming the simultaneous availability of all 142 fertilizers, which can hardly be the case. It is reasonable to think that the RB solution allows, compared to conventional blending, to increase the potential diversity of use because the CCBs contain, on average, fewer components. This being said, if this form of redundancy of the commercial offer has many economic justifications, it is necessary to question the relevance of the «potential diversity of use» of this offer. It seems necessary to us to take the problem reversely, starting from a «potential diversity of use» covering a large number of needs to determine the minimum required variety of production. This is the RB approach we recommend applying from a sustainable agriculture perspective. The application of RB to a very large representative sample of fertilizer needs enables the creation of a CB of numerical importance, probably similar to the one found for obtaining existing fertilizers by blending, but with a broader and more relevant spectrum of use. Indeed, when the set of inputs is optimally defined to cover a wide variety of products while keeping the number of these inputs as low as possible, it is obvious that \neg in terms of diversity reduction and management \neg RB achieves better results than the currently used blending where the set of inputs and outputs (whose variety is quite limited) are imposed and where the only optimality obtained is related to the blends' recipes.

3 Specificities of the RB-based mass customization

Since the 1970s, manufacturers have realized that a shift from mass production (i.e., a production method involving the manufacture of large series of standard products with consistent quality and affordable prices) to MC (i.e., a production method involving the design and manufacture of customized products with mass production efficiency and speed) is necessary to remain competitive in the market. MC has been the subject of numerous publications for more than 30 years, with the evolution of available technologies and their costs constantly bringing new opportunities (Fogliatto et al., 2012). The most efficient MC systems are found today in discrete manufacturing (automotive, textile, electronics,...), because the main approaches to MC (delayed differentiation, modularity, Assemble-To-Order (ATO), Engineer-To-Order (ETO), reconfigurable manufacturing, etc.) are not adapted to continuous flow products. Due to their fluid and homogeneous nature (liquids, granules, creams...), the latter are more challenging to handle and undergo irreversible transformations that prevent their decomposition into sub-components that can be assembled on demand (van Donk, 2001). Delaying customization using assembly processes is usually only possible for the product's packaging intended for a market, particularly for linguistic or regulatory reasons, without modifying the product's identity.

Process industries rather rely on the concept of commonality to differentiate their products. Commonality is defined as a method of product design by which several components of different finished products are replaced by a single common component

(Perera et al., 1999). This is particularly the case in the food sector, where differentiation is made to a basic formula (common component) by adding, for example, aromas and flavours (e.g., the wine industry (Van Hoek, 1997)). Nevertheless, differentiation here is not synonymous with customization; rather, it is a question of increasing variety, not developing targeted products. On the other hand, RB-based MC is characterized by pure customization, along with other features listed below:

- *Application area.* The RB has been designed to meet the challenge of sustainable soil fertilization and is therefore intended for the fertilizer industry. However, it can be applied to all process industries operating in blending contexts aiming at marketing a wide variety of products.
- *Supply chain type.* The literature classifies SCs according to the nature of their transformation processes into three types: discrete SCs, continuous SCs, and hybrid SCs that combine continuous and discrete processes by switching, at the discretization points, from continuous flows to discrete batches. RB-based MC can be applied for the last two types.
- *Degree of customization.* The Degree of Customization (DC) is one of the most cited criteria in the MC literature (Sandrin, 2016). The highest DC corresponds to 100% customized products and/or services, while the lower the DC, the more standardized the product tends to be. Depending on this degree, a distinction can be made between: *i)* pure customization, which is intended for a single customer and involves the individualization of all product features, *ii)* partial customization, which is intended for a single customer and involves the customization of certain product features and *iii)* segmented customization, which is intended for a group of customers and involves increased variety with no ability for customers to specify the product. RB-based MC involves offering farmers fertilizers with a chemical composition that exactly matches the nutrient requirements indicated in their soil test report. This is pure customization and 100% tailor-made.
- *Pre-existence of Bill Of Materials (BOMs).* This feature is about whether customization involves manufacturing an already marketed product, in which case its BOM is predetermined (ATO perspective), or whether customization involves manufacturing a new product that is not included in the product catalog, in which case its BOM is not predefined and must be created based on customer requirements (ETO perspective). In a BR-based MC, the BOM, which corresponds to a blending recipe, can only be determined after receiving the customer's soil analysis report, in which the nutrient requirements are calculated based on many variable parameters (organic matter, soil pH, available phosphorus, exchangeable potassium, target yield, crop requirements, etc.).
- *Place of customization.* In the literature, the place of customization refers to the decoupling point, i.e., the penetration point of the customer's order where product differentiation according to customer preferences begins (van Donk, 2001). This differentiation point can occur: *i)* during product design, *ii)* at one of the production stages, *iii)* during distribution, in distribution centers/outlets outside the production plant, or *iv)* at the customer's premises, where differentiation is carried out by the

customer himself at the time of or just prior to product use. In a RB-based MC, product differentiation is performed during distribution in decentralized fertilizer blending units located outside the production plant.

- *Object of customization.* The object of customization refers to the product substance that undergoes this customization. Three scenarios can be distinguished: *i)* a customization that acts on the form of the product without modifying its content (customization of the packaging, the labeling, the dimensions,...), *ii)* a customization that acts on the content of the product by modifying its composition and functionalities, or possibly *iii)* a customization that affects both at the same time. In RB, customization mainly concerns the content of the fertilizer, i.e. its chemical formulation, but it can also affect its packaging.
- *Environmental/ Ecological considerations.* There are several research studies that consider MC to be compatible with sustainability. Ülkü and Hsuan (2017) assert that modularity (a key technique of MC) is a strong practice for developing sustainable products. Jiang and Wu (2021) state that hybrid Make-To-Stock(MTS)/Make-To-Order (MTO) systems in which MC is achieved through the assembly of prefabricated components reduce waste and energy consumption. While MTS allows mass production and thus an optimized consumption of energy and resources, MTO allows production on demand, thus reducing waste and unsold products. RB helps to promote sustainability and environmental protection from another perspective. Indeed, by supplying farmers with customized green fertilizers at affordable prices, RB encourages green consumerism (i.e., pro-environmental individualism that protects the planet through small purchases and sober consumption (Rustam et al., 2020)) and sustainable consumption (i.e., use of green products with minimal adverse impact on the environment and its natural resources for healthy living for both current and future generations (Kumar Kar and Harichandan, 2022)).

To summarize, RB-based MC involves *i)* a customization that enable purely individualized solutions and enhanced sustainability, *ii)* new BOMs that are not predetermined, *iii)* a customization that occurs near the final consumer, and *iv)* a customization that can affect both the composition and form of the product. Referring to the postponement analysis grid introduced by Prataçviera et al. (2020), RB checks the three dimensions of postponement: *i)* time postponement (differentiation occurs at the last moment after the customer order is received), *ii)* place postponement (differentiation occurs at the end of the SC) and *iii)* form postponement (the customization provided by RB affects the identity of the product).

4 Literature review

This literature review evaluates RB-based MC in terms of the seven features presented in the previous section by exploring the MC systems considered in real-world industrial contexts. To do so, we followed the research methodology presented in Figure 4.

<p>Papers found based on keywords searched</p> <p>Science Direct & Google scholar & EBSCO : 5 351 000 papers</p> <p>Mass customization (233000 papers) Delayed differentiation (1400000 papers) Postponement (163 000 papers) Combined Make-to-stock and Make-to-order (3 555 000 papers)</p>	<p>Papers found based on the selected filters</p> <p>Mass customization (18 800 papers) Delayed differentiation (17 800 papers) Postponement (20 400 papers) Combined Make-to-stock and Make-to-order (17 800papers)</p>		
<p>Keywords</p> <p>Mass customization OR Delayed differentiation OR Postponement OR Combined Make-to-stock and Make-to-order</p>	<p>Filters</p> <p>Field: Supply Chain Management, Management & Economics, Industrial Engineering Time period: 1990 - 2023 Language: French & English</p>	<p>Papers found based on the content searched</p> <p>88 papers retenus après la lecture des titres et des résumés</p>	<p>Final list</p> <p>44 Papers retained after reading the full texts</p>
		<p>Content</p> <p>Papers dealing with the concepts of:</p> <ul style="list-style-type: none"> - Degree of customization - Point of product differentiation/ Customer Order Decoupling Point (CODP) 	<p>Empirical content</p> <p>Selection of empirical papers dealing with real industrial case studies</p>

Figure 4. Methodology of the bibliographic research

Based on the search filters indicated in the figure above, and considering the objective of this literature review, we limited ourselves to papers dealing with the concepts of "Customization Degree" and "Product differentiation point/ Customer order decoupling point", a set of 88 papers was retained. In the end, after reading these 88 articles, we eliminated from our analysis the theoretical papers that did not include real industrial case studies. This led us to a final list of 44 articles, whose analysis grid is presented in Table 2.

Table 2. Analysis grid of real MC systems

N°	Ref	Industry/ Product type	Product/ Service		Production flow type	Bill of Materials		Degree of customization		Place/Object of customization				Environmental/ Ecological considerations					
			Service	Product	Continuous/ Hybrid	Discrete	Not pre-determined (to be created)	Pre-terminated	Pure customization	Partial customization	Segmented customization	Product content	Product form	Product content	Product form	Product content	Product form	Yes	No
1	(Erens and Hegge, 1994)	Medical devices	•	•	•	•	•	•	•								•		
2	(Eastwood, 1996)	Computer products	•	•	•	•	•	•	•		•	P						•	
3	(Kotha, 1996)	Bicycle industry	•	•	•	•	•	•	•		•							•	
4	(Feitzinger and Lee, 1997)	Printers	•	•	•	•	•	•	•		•	P						•	
5	(Van Hoek, 1997)	Wine industry	•	•	•	•	•	•	•					B/ L/ P				•	
6	(Peters and Saidin, 2000)	Computer products	•	—	•	•	•	•	•		•							•	
7	(Twede et al., 2000)	Printers	•	•	•	•	•	•	•				P/ L					•	
8	(Alfnes and Strandhagen, 2000)	Swivel chairs	•	•	•	•	•	•	•		•							•	
9	(Alford et al., 2000)	Automobile industry	•	•	•	•	•	•	•		•		•					•	
10	(Thompson and Nussbaum, 2000)	Health sector	•	—	•	•	•	•	•				•					•	
11	(Myung and Han, 2001)	Mechanical products	•	•	•	•	•	•	•		•							•	
12	(Van Donk, 2001)	Food industry	•	•	•	•	•	•	•			G/ P/ L						•	
13	(Andel, 2002)	Office Products	•	•	•	•	•	•	•				P					•	
14	(Cheng et al., 2002)	Electronics	•	•	•	•	•	•	•		•							•	
15	(Chiou et al., 2002)	Computer products	•	•	•	•	•	•	•				•	P/ L				•	
16	(Drejer and Gudmundsson, 2002)	Industrial machinery	•	•	•	•	•	•	•		•							•	
17	(Salvador et al., 2002)	Motorcycle industry	•	•	•	•	•	•	•		•							•	
		Tailor-made telephony	•	•	•	•	•	•	•		•							•	
		Microwave	•	•	•	•	•	•	•	•		•						•	
		Heavy trucks	•	•	•	•	•	•	•	•		•	•					•	
		Multiplexers	•	•	•	•	•	•	•	•		•						•	
18	(Istook, 2002)	Textile	•	•	•	•	•	•	•		•							•	
19	(Ghiassi and Spera, 2003)	Bicycle industry	•	•	•	•	•	•	•		•							•	
20	(Storch and Sukapanpothara, 2003)	Shipbuilding	•	•	•	•	•	•	•		•	•						•	
21	(Yao and Carlson, 2003)	Upholstery	•	•	•	•	•	•	•		•							•	
22	(Van Vliet, 2003)	Water and electricity distribution	•	•	•	•	•	•	•		•		•					•	
23	(Caux et al., 2006)	Aluminum conversion	•	•	•	•	•	•	•			C/D						•	
24	(Sigala and Christou, 2006)	Mobile phone	•	•	•	•	•	•	•				•		•			•	
25	(Chen and Hao, 2007)	Restoration	•	•	•	•	•	•	•		•	•						•	
26	(Graziosi and Germani, 2008)	Footwear sector	•	•	•	•	•	•	•		•							•	
27	(Migas et al., 2008)	Tourism	•	—	•	•	•	•	•				•					•	
28	(Escobar-Saldivar et al., 2008)	Painted sheet metal	•	•	•	•	•	•	•		•							•	
29	(Dubey R. and Dubey J., 2009)	Pharmaceutic industry	•	•	•	•	•	•	•		•	P/ L						•	
30	(Cholette, 2009)	Wine industry	•	•	•	•	•	•	•				B/ L					•	

B : Bottling/ P : Packaging/ L : Labeling/ C/S : Cutting/Sizing/ G : Granulating

N°	Ref	Industry/ Product type	Product/ Service		Production flow type	Bill of Materials	Degree of customization		Place/Object of customization				Environmental/ Ecological considerations	
			Service	Product			Pure customization	Partial customization	Design	Manufacturing	Distribution	Customer	Yes	No
31	(Wong et al., 2011)	Soluble coffee	•	•		•	•					P/ L		•
32	(Ferreira et al., 2012)	Fruit juices and preserves sector	•	•		•	•					• B/ L/ P		•
33	(Van Kampen and Van Donk, 2014)	Dairy industry	•	•		•	•		•	P/ L				•
34	(Lu et al., 2015)	Iron and steel industry	•	•		•	•		•	C/D				•
35	(Jensen et al., 2015)	Building and construction industry	•		•	•	•		•					•
36	(Ferreira and Alcântara, 2015)	Juice industry	•	•		•	•					• B/ L/ P		•
37	(Seth and Panigrahi, 2015)	Sanitary napkin industry	•		•	•	•			P				•
38	(Ahmed, 2015)	Banking	•			•	•					•		•
39	(Ferreira and Alcântara, 2016)	Tomato products	•	•		•	•			P/ B/ L				•
40	(Larsen et al., 2019)	Building and construction industry	•		•	•	•		•					•
41	(Bandaly and Hassan, 2020)	Juice industry	•	•		•	•			B/ L				•
42	(Ben-Jebara and Modi, 2020)	Pharmaceutic Industry	•	•		•	•					•	P	•
		Compounded drugs												
		Pharmacogenomics / Biologics/ Biosimilars												
43	(Hankammer et al., 2021)	Electronics	•		•	•	•		•					•
44	(Longo et al., 2021)	Fashion industry	•		•	•	•	•						•
Us		Fertilizer industry	•	•		•	•					•	•	•

B : Bottling/ P : Packaging/ L : Labeling/ C/S : Cutting/Sizing/ G : Granulating

The papers reviewed in this table include real-life examples of MC systems in the service, manufacturing (discrete production) and process (continuous production) industries. Focusing only on continuous/hybrid SCs, we distinguish two types of papers:

1. Papers dealing with MC systems with segmented customization. For these papers, for which customization is more a matter of product diversification using known and pre-existing BOMs, we have noticed that product differentiation is usually performed during the manufacturing process within the factory. For example, Van Donk (2001) addressed a case study from the food industry where products are differentiated within the plant by separating them into several fractions that are made from the same standard recipe but differ in terms of pellet size and packaging (large or small bags of 5 to 25 kg). Here, the customization acts on the form of the product and not on its internal composition. Similarly, Ferreira and Alcantara (2016) addressed the differentiation of tomato derived products inside the factory. For these products, the standard component (tomato pulp) undergoes a series of manipulations depending on the packaging mode, which depends on the targeted clientele. In the case of drum packaging, the pulp is packed, cooled and stored. In the case of bag packaging, the pulp is cooled and stored for 12 to 30 months. Van Kampen and Van Donk (2014), on the other hand, discussed a MC system that acts on the form and content of the product but that occurs

inside the plant. They treated the case of a dairy company that, by mixing some basic components (mainly whole milk and skim milk), produces 100 milk recipes, which are transformed on 18 packaging lines into 700 finished products in different packaging formats (metal cans, bottles, cartons, cups). Lu et al. (2015) also published a case study from the metallurgical industry where customization can relate to mechanical properties (e.g., carbon grade) in which case it occurs during the primary melting process (i.e., content customization) and/or to physical dimensions (thickness, width, and length) in which case it occurs during the final process where steel plates are cut to the specified width and length (i.e., form customization). In both cases, customization constitutes one of the production processes and takes place inside the plant. In some cases (e.g., the soluble coffee industry (Wong et al., 2011)), the differentiation acting on the product's content is carried out inside the plant (e.g., by mixing different varieties of coffee beans) and that acting on the product's packaging (e.g., jars, caps, labels) is carried out outside the plant at the distribution centers.

Also, still concerning segmented customization, in some industries of the continuous/hybrid SC, customization can sometimes be performed outside the initial production site while modifying both the exterior and interior of the product. This is the case of (Van Hoek, 1997) who focused on a European wine company that produces basic wines at the production site before shipping them to distribution centers where they are blended and flavored according to predefined BOMs, then bottled and packaged according to the target markets' specifications. This type of MC - where differentiation is delayed until the distribution centers while affecting the product's content (by mixing, diluting, adding aromas and flavors) and the product's packaging (bottling, wrapping and labeling) - can also be found in the juice industry ((Ferreira et al., 2012) and (Ferreira and Alcântara, 2015)) and in the pharmaceutical industry (Ben-Jebara and Modi, 2021).

2. Papers dealing with MC systems with pure customization involve determining manufacturing BOMs. For these papers, only two could be identified. The first one (Caux et al., 2006) addressed a standardization problem in an aluminum conversion industry where aluminum plate dimensions are customized in the sawing process (form customization). The studied company offers a variety of 100 plates of different dimensions, each one being produced on specific request. This is therefore an individualized customization as the customer can always request a new dimension even though it is not included in the catalog of the 100 varieties offered. Regarding the place and object of customization, it is conducted inside the metallurgical plant and only affects the form of the plates (the dimensions), the internal composition being invariant. In this case, the BOMs to be determined is only a question of dimensioning (width, length, thickness). Biologics and biosimilars are also 100% individualized drugs whose manufacture requires materials from the patient (e.g. the patient's own blood cells) (Ben-Jebara and Modi, 2021). This type of product is personalized from the design stage.

For both types of papers, except for Van Vliet (2003), who compared the Dutch water and electricity sectors in terms of differentiation forms (e.g., green versus conventional electricity), we did not find examples in the literature of real-life continuous SCs with a MC that promotes sustainable consumption.

The literature analysis, summarized in Table 2, shows that a MC system as specified in section 3, has not yet been adopted in the process industries. Indeed, when customization is purely tailor-made, it is performed in the design phase, which occurs after the creation of the manufacturing BOMs. The only paper where customization is tailor-made and intervenes at the last stage of production in the process industry is that of (Caux et al., 2006), but here the customization acts on the product's form (dimensions of the aluminum plates). All the other papers that have dealt with MC within the context of continuous/hybrid SCs involve segmented customization with predetermined BOMs. In most of these papers, customization is one of the manufacturing steps taking place inside the production plant. If not, it is simply a matter of customizing the product's packaging without changing the internal composition.

Finally, RB-based MC provides several advantages, which, to our knowledge, have never been brought together in a continuous SC. Basically, RB offers i) an ecological differentiation that supports natural resource sustainability, ii) a last minute differentiation that is located near the final customer and that enables important savings as the more the decoupling point is delayed towards the downstream of the SC, the more it permits significant economies of scale and improved reactivity and flexibility and iii) a differentiation that, in addition to being able to customize the product's packaging, can affect the product's internal composition by defining each time the BOM enabling to exactly match the specific requirements of a single customer. This would significantly enhance the customer's perceived value of the product because, as Pine and Gilmore (1999) state, "customers don't want choice, they just want exactly what they want." This ability of RB to develop individualized products is thus a major source of competitive advantage. In principle, purely individualized customization always falls within the product design phase. In a sense, this is also true for RB, because individual requirements are considered in the product design phase, not of finished products, but of CCBs, not to meet one individual requirement specific to a single customer, but a very wide variety of requirements. This is where the originality of RB-based MC lies.

5 Managerial and logistical implications of RB

As shown in Figure 1, if OCP were to apply RB, it would adopt a hybrid MTS/MTO system, with MTS occurring in the plant for the mass production of CCBs and MTO in the blending units for the fertilizers' customization. In this section, we take the OCP's SC as an example to examine the implications of RB in the plant (§5.1) and then in the blending units (§5.2).

5.1 At the plant level

Between 2000 and 2023, OCP increased the variety of its products from 5 to about 50

fertilizers. OCP is still pursuing this strategy of increasing diversity, which enables it to meet needs better and win new customers. The counterpart is increasing complexity in the management of production and storage. This analysis focuses on the implications of RB by examining how production and storage would be organized if OCP's production in 2019 had been achieved using RB. Our aim is not to replace the existing fertilizers but to define a plausible scenario of a CB technically responding to an existing commercial supply of fertilizers.

Analysis method

The OCP's backlog of 2019 covers 28 fertilizer references whose monthly produced volumes on seven production lines are given in "CS2.1". Figure 5 shows the shares of these fertilizers in the total production of each month. It can be observed that the diversity of products (illustrated by the different colors in each stick) and the produced volumes vary from one month to another and that these volumes correspond to small batches.

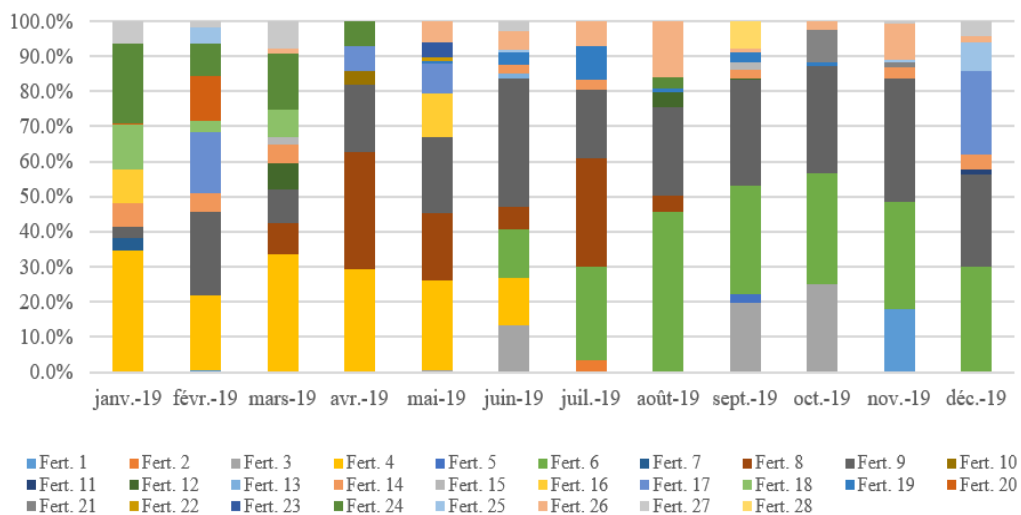


Figure 5. Individual shares of fertilizers in each month's production

This figure illustrates the considerable number of fertilizer reference changes that had to be made each month. A more detailed analysis, on a daily basis, shows that over this year, 175 changes of references were made on the 7 production lines. Even considering the shortest launch time of about two hours (it can reach more than eight hours), production had to be stopped for at least 350 hours (175*2). Given the production rates of each line, this translates into a minimum loss of production capacity of 33,783 tons. At its 9 storage sheds, this production method, which relies on the irregular launching of small batches, leads to space allocation problems and fertilizer contamination due to improper separation between the different references.

To analyze how replacing the current OCP organization with CCBs production can address these issues, we use the RB model (column 2 in Table 6 and descriptive diagram in Figure 3) and find the CB for achieving OCP's 2019 backlog.

Analysis results

Using the model of RB, we found the CB whose composites can satisfy the OCP's backlog. These are 8 in number, and their optimal composition in terms of N, P, K, B₂O₃ (boron), Zn (zinc) and *filler* is described in Table 3.

Table 3. Optimal Composition of CCBs allowing the production of the 28 fertilizers produced in 2019

		Composites of Canonical Basis (CCB <i>i</i>)								
		CCB 1	CCB 2	CCB 3	CCB 4	CCB 5	CCB 6	CCB 7	CCB 8	<i>filler</i>
Component <i>c</i>	N(<i>c</i> =1)	46.00%	11.86%	12.70%	19.00%	0%	2.34%	2.14%	0%	0%
	P(<i>c</i> =2)	0%	56.08%	16.11%	38.00%	0%	56.00%	56.00%	51.24%	0%
	K(<i>c</i> =3)	0%	0%	16.11%	0%	63.60%	0%	0%	0%	0%
	S(<i>c</i> =4)	0%	0%	0%	7.00%	25.27%	11.78%	7.06%	19.67%	0%
	B ₂ O ₃ (<i>c</i> =5)	0%	0%	0%	0%	6.13%	3.15%	0%	0%	0%
	Zn(<i>c</i> =6)	0%	0%	0%	0%	0%	0.00%	0%	7.79%	0%
	<i>filler</i> (<i>c</i> =7)	54.00%	32.06%	55.07%	36.00%	5.00%	26.72%	34.81%	21.30%	100%

The quantities to be withdrawn from them to obtain the exact monthly volume produced for each fertilizer are presented in "CS2.2". These quantities are represented differently in Figure 6 to indicate the share of each CCB in the production of each month.

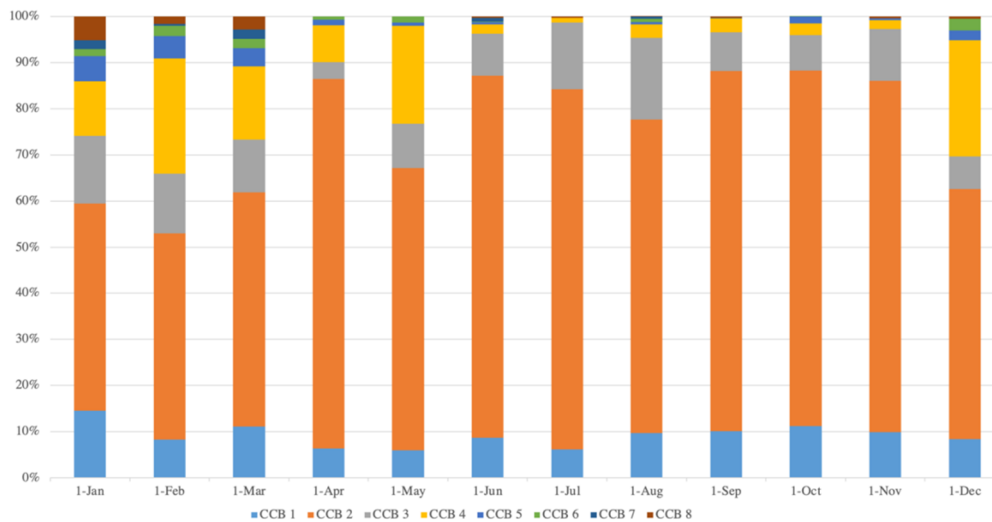


Figure 6. CCBs shares in each month's production

A comparison of Figures 5 and 6 shows how this transformation considerably simplifies the production management since, with only 8 CCBs, the monthly production of the OCP can be ensured exactly. Moreover, at least 90% of this production each month involves only the first 4 CCBs, with CCB 2 (orange color) representing more than 60%.

Discussion

This flows consolidation, which would have been even more significant if the processed variety had been greater than 28 fertilizers, shows the opportunity to design a new production system based on a Make-to-stock Production. Indeed, with seven production lines, three of which have an annual throughput of about 897,000 tons and four of which

have an annual throughput of about 669,000 tons, managing the production of 8 CCBs is relatively simple. Given the total quantity needed from each CCB and the throughputs of these production lines, it is chosen to arbitrarily assign the most demanded CCBs to the most productive (and, incidentally, the most economical) lines. Therefore, since CCB 2 represents more than 66% of the annual production volume, three production lines can be entirely devoted to it. For CCB 1, 3 and 4, each representing about 10%, there should be one production line for each of them. Finally, the rest of the CCBs, representing less than 4% of the total production, can all be assigned to one production line.

The "mono-product" lines would eliminate downtime resulting from launch times by producing in a continuous flow, thus increasing the production capacity. As for the single "multi-product" production line, it could maintain an order point production approach (production starts when a specific stock level is reached) to produce CCB 5, which represents nearly 2% of total production. For CCB 6, 7 and 8 (each representing less than 1% of total production), production could be started when the stock falls below the safety stock and be stopped when the storage capacity is fully used.

Storage shed management would also become much easier since, since OCP has 9 sheds, the storage of 8 CCBs, as opposed to 28 fertilizers will not be a problem. Each shed could indeed be assigned to one/two CCBs which would eliminate storage problems caused mainly by high diversity, such as vacant space due to small production batches and production stoppage due to stock saturation.

From an economic point of view, the RB solution, by significantly limiting the variety produced, leading to a strong flow massification, allows for reducing production costs and simplifies storage and transport.

Finally, one can note that *i*) the found CB can meet the requirements of a very much larger set of fertilizers, and *ii*) with the same number of CCBs, it is possible to define another CB able to satisfy a huge set of fertilizers.

5.2 At the blending unit level

Morocco is one of the few African countries with a reasonably extensive fertilizer distribution network, consisting of 16 local blending units. We visited one of these units and found that, in general, the produced fertilizers correspond to fixed formulas, commercially popular and commonly used by farmers, regardless of their soils and crops. Indeed, a survey of 100 Moroccan farmers conducted in early 2019 by Naamane et al. (2020) reveals that the same fertilizers (the most popular ones on the market) are applied every year using the same proportions. This is common almost everywhere in Africa and also in other countries such as India (Rajani, 2019). On rare occasions, this blending unit produces new fertilizer formulas at the request of some of its customers, but due to the limited number of its blending inputs (3 phosphate fertilizers, 2 nitrogen fertilizers and 2 potash fertilizers), these formulas usually do not match the specified needs sufficiently well and are also more expensive.

With RB, this is unlikely to happen. A blending unit that uses optimally designed CCBs as blending inputs can better customize its fertilizers to match nutrient

requirements. One might think, however, that this exact match can only be guaranteed for the fertilizers included in the initial sample used to define the CB. Proving the contrary requires an analysis of whether a CB obtained on a sufficiently large sample can be used to satisfactorily meet needs that were not considered in the initial sample. The CB we use for this analysis is the one found in (Benhamou et al., 2020), whose composition of its CCBs is recalled in Table 4.

Table 4. The CCBs found from the example of the 700 NPK requirements

		CCB i							
		filler	$i=2$	$i=3$	$i=4$	$i=5$	$i=6$	$i=7$	$i=8$
Component c	N ($c=1$)	0.00%	46.00%	0.00%	22.53%	29.78%	12.83%	52.20%	20.32%
	P ($c=2$)	0.00%	0.00%	46.00%	0.15%	23.53%	0.00%	42.32%	0.49%
	K ($c=3$)	0.00%	0.00%	0.00%	0.00%	0.00%	47.09%	0.49%	74.19%
	filler ($c=4$)	100%	54.00%	54.00%	77.31%	46.69%	40.08%	5.00%	5.00%

We use this CB because it was constructed to satisfy a fairly large sample of 700 NPK requirements (expressed in Kg/ha), corresponding to 482 formulas (expressed in %), defined to meet the needs of Moroccan wheat (see details of this sample in <http://dx.doi.org/10.17632/z3sbn5j9z7.1>).

Analysis method

The variety of fertilizers that can be obtained by a linear combination of these CCBs exceeds the 482 fertilizers of the sample very broadly, a vast number of these linear combinations being exactly in accordance with a requested composition, others slightly deviating from it but within the tolerance limits fixed by the European regulation. To exploit this possibility, we apply the Use of the Canonical Basis (UCB) approach whose descriptive diagram is given in Figure 7 and whose optimization model is described in column 3 of Table 6.

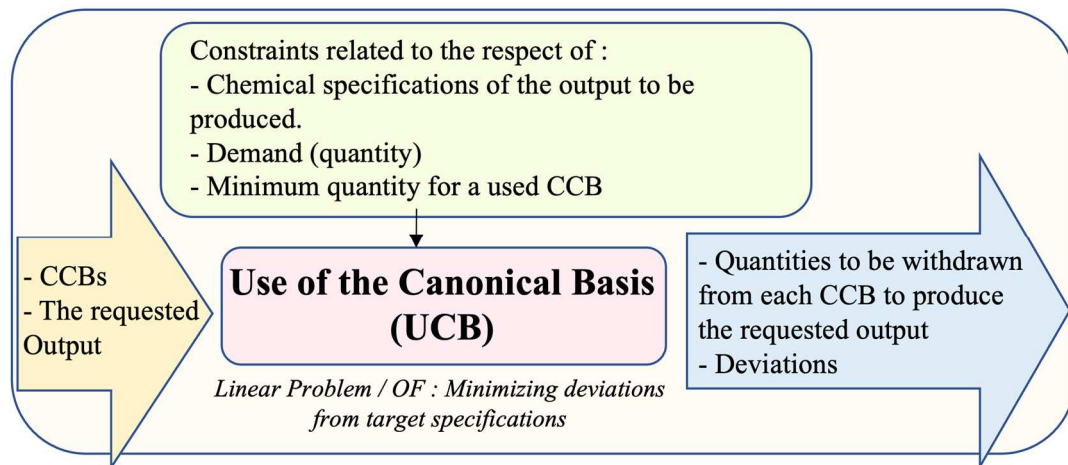


Figure 7. Descriptive diagram of CB use to create a new customized fertilizer

Through a linear program using the Excel solver, UCB aims to determine the optimal quantities to be taken from the CCBs to satisfy the specifications of a new requested fertilizer. Blending units must perform this program for each new demand to satisfy. This model : *i*) minimizes an indicator of the difference between the required composition and the optimal found composition; *ii*) allows the use of a CCB in the

BOM of the fertilizer to be produced only if it represents a sufficient percentage (1% retained by default); *iii*) considers that there are no constraints on the availability of CCBs and that the demand for the considered fertilizer is conventionally 100 tons, to facilitate the analysis of the results. The EU regulatory constraints have not been integrated, as the verification of their compliance is done from the solution. This model is implemented in Excel to allow easy use in remote blending units in response to a new fertilizer demand.

We apply this model on a new sample of 50 NPK fertilizers to verify whether each of these fertilizer can be obtained using the CB of Table 4. An extract of this sample is given in Table 5 (the complete data are provided in the sheet "CS1.1").

Analysis results

The results of these 50 optimizations (see the sheet "CS1.2"), from which an extract is given in Table 5, lead to the exact composition requested for 48 fertilizers. For the two remaining fertilizers, we observe deviations that are well below the tolerances of the European standard for fertilizer 8: 0% for N and K and +0.05% for P; for fertilizer 17: +0.01% for N and 0% for P and K.

Table 5. Extract of the optimal CCBs compositions to be used to meet the chemical characteristics of the 50 fertilizers.

	The chemical specifications β_c					Optimal quantities x_{ij} to be withdrawn from each CCB to produce each output								Demand (tons)
	%N ($c=1$)	%P ($c=2$)	%K ($c=3$)	%filler ($c=4$)		filler	$i=2$	$i=3$	$i=4$	$i=5$	$i=6$	$i=7$	$i=8$	
Fert.1	20.52%	8.94%	0.00%	70.54%	Fert.1	42.0	20.0	0.0	0.0	38.0	0.0	0.0	0.0	100
Fert.2	30.30%	9.07%	27.26%	33.38%	Fert.2	16.5	25.9	0.0	0.0	0.0	0.0	21.0	36.6	100
Fert.3	20.64%	27.15%	0.00%	52.21%	Fert.3	5.1	8.3	30.1	0.0	56.5	0.0	0.0	0.0	100
...
Fert.8	27.90%	12.00%	21.79%	38.31%	Fert.8	23.9	13.4	0.0	5.6	0.0	0.0	27.9	29.2	100
...
Fert.17	11.00%	12.87%	16.92%	59.21%	Fert.17	22.2	13.9	28.0	0.0	0.0	35.9	0.0	0.0	100
...
Fert.48	8.27%	15.93%	0.00%	75.80%	Fert.48	29.8	1.0	34.5	34.7	0.0	0.0	0.0	0.0	100
Fert.49	21.13%	19.50%	12.22%	47.15%	Fert.49	2.7	38.7	42.2	0.0	0.0	0.0	0.0	16.5	100
Fert.50	13.19%	6.70%	47.98%	32.13%	Fert.50	21.5	0.0	13.9	0.0	0.0	0.0	0.0	64.7	100

Basically, the composites of the CB in Table 4 not only provide the 482 formulas (which is a direct consequence of the use of RB) but also enable a very satisfactory and almost exact response to the specifications in terms of N, P and K of each of the new 50 fertilizers. This confirms that a well-defined CB can be used to create fertilizers other than those of the initial sample used for its determination.

Discussion

In view of these results, it is reasonable to think that the constitution of a reasoned sample of a few thousand fertilizer requirements crossing soil characteristics and those of crops could allow the creation of a CB for covering most of the NPK nutrient requirements to which other nutrients such as Sulphur S can be added. It is enough to start from the initial CB and add new composites to cover these new needs.

This being said, the adoption of RB implies, within the blending units, a shift from production for stock or on order of a limited number of blended fertilizers with standard chemical formulas to a production on order of blended fertilizers whose BOMs are to be determined at the last moment, using a simple linear program, in order to match exactly (or almost exactly) the ecological requirements of the soils and crops.

The economic consequences of the last stage of the SC, which involves the use of small blending units located close enough to the crops, are more challenging to evaluate. We can say that such units have already been set up to try, imperfectly, to obtain by mixing commercially available fertilizers a composition close to the one required. It can be assumed that the cost increase related to the final production of the custom-made fertilizer will be largely compensated by the improvement of the agricultural performance.

6 Conclusion

The contribution of this paper is to alert fertilizer producers to the major changes their SCs will have to undergo if they want to adopt RB-based MC, by answering three main questions:

- First, why is RB considered better than the conventional approach of blending existing fertilizers? The answer is that RB is able, more than conventional blending, to reduce the diversity to be produced without compromising the "potential diversity of use", and this, while satisfying both the economic and ecological requirements of agriculture, which is not the case with conventional blending.
- What changes should potential RB users expect at the chemical plant? First of all, they will need to define (via the RB model) a robust CB capable of covering all green fertilizer needs. Then, they will have to develop a planning program for the production of CCBs to stock (MTS). As the number of these CCBs is small, we have shown in this paper that the switch to MTS allows for a gain in production capacity and realizes a series of logistic simplifications (in production, storage and transport), which generates substantial savings translating eventually into lower selling prices. This MTS allows for increased productivity and economies of scale.
- What changes should potential RB users expect in blending units? The answer is that they will have to import all CCBs to use as blending inputs rather than using the most popular fertilizers on the market. Instead of marketing standard fertilizers that are contestable from an agronomic point of view, they will sell, at affordable prices, customized fertilizers whose mixing recipes will be defined at the last moment (via the UCB model), on-demand, in order to exactly match the requirements specified in the soil analysis reports. This differentiation (MTO) in blending units located close to the farmer increases flexibility and responsiveness.

Meanwhile, if the advantages of RB-based MC have been highlighted, it also has some limitations. Indeed, the NPK CB used in this paper was defined according to the needs of Moroccan wheat which count a few hundred fertilizers, whereas it should be designed based on a much larger sample. Also, even if the minimization of the CCBs number implicitly implies the minimization of production costs, the non-consideration of the cost factor in the conducted analyses can indeed be criticized. Economic studies must therefore be carried out using relevant cost systems to estimate the gains but also the required investments, particularly regarding CCBs manufacturing and blending units construction. These limitations bring out two lines of thought :

- First, the disruptive nature of the RB approach implies that such a transformation is only possible from a multidisciplinary approach mobilizing not only skills in industrial engineering but also in chemistry for the manufacture of CCB and that of agronomists for the analysis of potential needs to be met. This mobilization requires a strong and lasting involvement of the Executive Management. This example may encourage the management of some large groups to invest in the RB.
- The second line of thought concerns the question of the definition of the sample leading to the creation of a CB. This question is to be positioned in a global SC approach involving production centers that can serve one or more commercial areas of heterogeneous characteristics through a distribution network (that the RB contributes to consolidate). If we take the example of fertilizers, we can ask ourselves the question of the usefulness of a vast planetary sample of fertilizer needs. It is likely to be in the interest of defining a few samples corresponding to vast markets to be served from one or two plants. Since such an approach leads to so many disjointed sets of CCBs, one may ask whether it would not be wise to pool some CCBs, particularly from a risk management perspective. This reflection type must be based on economic studies using relevant cost systems.

It is by working simultaneously in these two directions that RB is likely to be adopted.

7 References

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8 Appendix

The synthetic presentation of the models of Blending Problem (BP), Reverse Blending problem (RB) , Use of a Canonical Basis (UCB), and Diversity Reduction problem (DR) is provided in Table 6; their objectives and foundations are briefly described next, the two first one being detailed in Benhamou et al. (2020).

Table 6. Comparison of one-stage blending models

BP (Blending Problem) - RB (Reverse Blending) - UCB (Use if the Canonical Base) - DR (Diversity Reduction)					
BPRBUCBDR Indexes					
X	X	-	X	j	Output ($j \in J; J = J$)
X	X	X	X	c	Chemical component ($c \in C; C = C$)
X	-	-	-	i	Existing input ($i \in I; I = I$)
-	X	-	-	i	Composite of the Canonical Basis (CCB) to be created ($i \in I; I = I$)
-	-	X	-	i	Composites of the Canonical Basis created previously ($i \in I$), used to produce the new requested output
-	-	-	X	i	Existing input (= output) ($i \in I \wedge I \subset J \wedge I = S$).
BPRBUCBDR Parameters					
X	-	-	-	β_{cj}^{\min}	Minimal proportion weight of component c in the weight of output j
X	-	-	-	β_{cj}^{\max}	Maximal proportion weight of component c in the weight of output j
-	-	X	-	β_c	Target proportion of component c in the weight of the requested output
-	X	X	X	β_{cj}	Target proportion of component c in the weight of output j
X	X	-	X	D_j	Demand for output j , expressed in weight, real for B and fictitious for RB et RD
-	-	X	-	D	Demand for the wanted output, expressed in weight
X	-	-	-	A_i	Availability of input i , expressed in weight. Guaranteed availability for RB, RD and UCB
X	-	X	X	α_{ci}	Proportion of component c in the total weight of input i (B and RD) and of CCB i (UCB)
X	-	-	-	ω_i	Unit cost of input i
-	X	-	-	τ_{ci}^{\min}	Minimal proportion weight of component c in the total weight of CCB i
-	X	-	-	τ_{ci}^{\max}	Maximal proportion weight of component c in the total weight of CCB i
-	X	-	X	η_{cj}	Maximal absolute deviation of component c in the total weight of output j
-	X	-	X	M	High constant (Big M)
-	X	X	X	κ	Minimal weight percentage of a CCB in the total weight of any output (if this CCB is to be used)
BPRBUCBDR Variables					
X	-	-	X	x_{ij}	Quantity of input i used in the production of output j
-	X	-	-	x_{ij}	Quantity of CCB i used in the production of output j
-	-	X	-	x_i	Quantity of CCB i used to produce the new requested output
-	X	-	-	α_{ci}	Proportion of component c in the total weight of CCB i
-	X	-	-	w_{ij}	Binary variable which is equal to 1 if CCB i is used to produce fertilizer j and 0 otherwise
-	-	-	X	w_j	Binary variable which is equal to 1 if output j is produced and 0 otherwise
-	X	-	X	y_i	Binary variable which is equal to 1 if input i (for DR) and CCB i (for RB) is used and 0 otherwise
-	-	X	-	η_c	Maximum absolute difference between the proportion of component c obtained in the CCBs blend and the target-proportion.
BPRBUCBDR Objective function					
X	-	-	-		$\text{Min}(\sum_i \sum_j \omega_i x_{ij})$ Minimisation of the production cost
-	X	-	-		$\text{Min}(\sum_i y_i)$ Minimisation of the number of CCBs
-	-	X	-		$\text{Min}(\sum_c \eta_c)$ Minimisation of the sum of absolute differences between the obtained composition and the target-one
-	-	-	X		$\text{Max}(\sum_j w_j)$ Maximisation of the number of outputs that can be produced with the set $I \subset J \wedge I = S$
BPRBUCBDR Satisfaction of composition constraints of an output					
X	-	-	-	$\beta_{cj}^{\min} \leq \sum_i \alpha_{ci} \cdot x_{ij} / D_j \leq \beta_{cj}^{\max}, \forall c, j$	Linear constraints
-	X	-	-	$\beta_{cj} - \eta_{cj} \leq \sum_i \alpha_{ci} \cdot x_{ij} / D_j \leq \beta_{cj} + \eta_{cj}, \forall c, j$	Quadratic constraints
-	-	X	-	$\beta_c - \eta_c \leq \sum_i \alpha_{ci} \cdot x_i / D \leq \beta_c + \eta_c, \forall c$	Linear constraints
-	-	-	X	$(\beta_c - \eta_{cj}) \cdot w_j \leq \sum_i \alpha_{ci} \cdot x_i / D_j \leq (\beta_c + \eta_{cj}) \cdot w_j, \forall c, j$	Linear constraints
BPRBUCBDR Satisfaction of demand					
X	X	-	-	$\sum_j x_{ij} = D_j, \forall j$	
-	-	X	-	$\sum_i x_i = D$	
-	-	-	X	$\sum_j x_{ij} = D_j \cdot w_j, \forall j$	
B RB UCB DR Main specific constraints					
X	-	-	-	$\sum_j x_{ij} \leq A_i, \forall i$	Constraint of inputs availability
-	X	-	-	$\sum_c \alpha_{ci} = 1, \forall i$ $\tau_{ci}^{\min} \leq \alpha_{ci} \leq \tau_{ci}^{\max}, \forall i, c$	Constraints on components' structure of CCB i
-	X	-	X	$\sum_j x_{ij} \leq M \cdot y_i, \forall i$	Determination of the binary variable for the use of CCB i
-	X	-	-	$x_{ij} \leq M \cdot w_j$ $x_{ij} \geq \kappa \cdot w_j \cdot D_j, \forall i, j$	Constraint of minimum use of CCB i in output j (if this CCB i is used)
-	-	-	X	$\sum_j x_{ij} \leq M \cdot y_i, \forall i$ $\sum_i y_i = S$	To force $y_i = 1$ if i is used Progressive decrementation of S (starting from J) until $\sum_j w_j = J$

The classical formulation of the Blending Problem determines the quantities of inputs to be mixed to produce the required quantities of several outputs whose compositional constraints must be respected. The inputs are available in limited quantities, and their unit costs are known. In the single-period problem, the solution sought is that which minimizes the total cost of production.

In the Reverse Blending formulation, the concern of cost is absent due to the lack of knowledge of the potential demands for the customized fertilizers and the CCBs production costs. In this problem, we simultaneously seek the composition of CCBs (inputs) and their blending recipes, leading to the required outputs (fertilizers) with sufficient accuracy. The lack of knowledge of demand brought us to work with identical demand fixed at an arbitrary value, and the goal of RBP is to find a technical solution to the problem at hand without being concerned, at this stage, with cost issues. This problem, which aims at satisfying all the identified demands with the smallest possible canonical basis (optimization criterion), is based on a steady-state logic. RB presents quadratic constraints involving the multiplication of the quantities of CCBs to be used with the CCBs composition parameters to be determined by the optimization process.

The formulation of the Diversity Reduction Problem aims at determining the smallest subset of outputs (fertilizers) belonging to an existing set of marketed fertilizers, allowing *i*) the production of the other outputs of the complementary subset and *ii*) the definition of their blending recipes (BOMs). Considerations of actual costs and demands are not involved, as we are only interested in the technical possibility of producing fertilizers by combining other fertilizers.

Finally, the formulation of the problem of using a Canonical Basis to produce an output that was not considered in the initial sample retained for the creation of this CB consists in searching for the CCBs mixture whose composition is the closest to that of the target output. To do so, we minimize an indicator calculated as the sum of the absolute deviations obtained in the composition found compared to the target composition.