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Optimization of biodiesel supply chains based on small farmers: A case study in Brazil

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ABSTRACT

This article presents a methodology for conceiving and planning the development of an optimized supply chain of a biodiesel plant sourced from family farms and taking into consideration agricultural, logistic, industrial, and social aspects. This model was successfully applied to the production chain of biodiesel fuel from castor oil in the semi-arid region of Brazil. Results suggest important insights related to the optimal configuration of the crushing units, regarding its location, technology, and when it should be available, as well as the configuration of the production zones along the planning horizon considered. Moreover, a sensitivity analysis is performed in order to measure how possible variations in the considered conjecture can affect the robustness of the solutions.

1. Introduction

In recent years, the value of biodiesel has been highlighted in literature due to its importance both economically and environmentally. Biodiesel is derived from a renewable resource, is biodegradable and non-toxic, and has a more favorable combustion emission profile than petroleum derivatives (Zhang et al., 2003). These qualities have made biodiesel a good alternative to petroleum-based fuel and have led to its use in many countries, especially in environmentally sensitive areas (Körbitz, 1999).

The increasing production and use of biodiesel as a replacement for fossil diesel fuel is a global phenomenon, although with different motivations. The United States is mostly concerned with establishing an energy mix that is less dependent on imported oil, especially because this commodity usually comes from politically unstable countries. For Europeans, the main motivating factor is to ensure environmental sustainability in economic growth through the goals of replacing fossil fuels and reducing emissions from other fuels (Van Dyne et al., 1996).

It is very difficult to predict the behavior of biodiesel production worldwide over the next ten years. Other than the leadership of the European market, the volume of production planned by the Brazilian government, particularly the plans to diversify the supply with castor oil and palm oil, has been attracting international attention (Karmakar et al., 2010). China and India have been making efforts to promote jatropha as a raw material, while other South Asian countries are focusing on biodiesels from palm and coconut oil (Von Lampe, 2006).

The Brazilian Biodiesel Program is now six years old and has grown to the point of placing the country as one of the leading producers and consumers of biodiesel fuel in the world. Since 2010, all of the diesel fuel sold in Brazil – approximately 45 million cubic meters per year – must be mixed with 5% biodiesel. Furthermore, the federal government created the “Social Fuel Seal” (SCS), in which the industrial biodiesel producers agree to purchase minimum quotas of raw materials from small farmers, therefore promoting social inclusion. With the SCS, these companies can participate in closed biodiesel auctions and receive significant tax exemptions.

Family farming in Brazil plays a crucial economic role, accounting for about 20% of the national agricultural GDP. In most parts of the country, however, rural workers live and work in poor conditions, with low incomes and limited access to public resources. In response to this situation, the Brazilian government has singled out social benefits as the main target of the Biodiesel Program, seeking to integrate these small farmers into the production chain as suppliers of raw materials. This strategy can provide a fairer distribution of income and improve living conditions in rural regions. Studies have shown that for every 1% of fossil diesel that is replaced by biodiesel, 45,000 new jobs are created in rural areas, with an average annual income of US$ 2800.00 (Holanda, 2004).

Due to the growth forecasted for the coming years and the lack of adequate facilities, the continued success of the biodiesel

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program requires significant investments in structuring the supply chain to ensure efficient conditions for the production, transportation, and processing of raw materials.

Although several papers applying quantitative approaches to study the development of biodiesel production can be found in the literature, only a few directly apply mathematical optimization techniques (see, for example Leduc et al., 2009). These papers are generally focused on defining levels of subsidies, crops pricing, and land allocation for oilseed production (Bard et al., 2000; Rozakis and Sourie, 2005; Schmidt and Weidema, 2008; Schmidt et al., 2010; Lee et al., 2009) using economic models supported by simulation systems. Another strong research line focused on biodiesel production is concentrated in defining aspects of the production process itself, which covers questions involving the optimization of certain aspects of the chemical conversion processes used (Vasudevan and Briggs, 2008; Vicente et al., 2007). Although the Brazilian biodiesel production has been the subject of investigation in the recent literature, most of the papers are also related to the technical characteristics of the chemical processes (see, for example: Dussana et al., 2010; Fonseca et al., 2010; Da Silva et al., 2011; Costa and de Morais, 2011).

The purpose of this article is to present an integrated analysis of the supply chain of vegetable oils for the production of biodiesel fuel sourced from family-owned farms, considering the production, transportation, and crushing of oilseeds and the transportation of vegetable oils to the biodiesel production units.

The proposition is a mathematical optimization model, which suggests multiannual investment solutions for the structure of the supply chain as an analysis tool for strategic decision making. The solution includes suggestions for: (i) investments in oilseed crushing units – quantity, location, technology, and capacity; (ii) agricultural dimensioning – geographic distribution of the production and area occupied; and (iii) logistical planning – definition of oilseed and vegetable oil transportation routes.

Finally, a practical application of the proposed model is presented. The case study was based on an analysis of the conditions required to fulfill the demand for vegetable oil of a Brazilian biodiesel plant. As a solution, a set of decisions and investments to be made over a ten year period is proposed, aiming to optimize the supply chain operation.

2. Methods

The goal of this section is to present and detail the mathematical model that was designed. Considered as a method of treating the considered problem, it may be applied to numerous different scenarios. The second part of this section is dedicated to presenting, as an example, the application of the method to a case study, considering parameters of a real decision-making situation in Brazil.

2.1. Method

The aim of the proposed model is to provide support for strategic decisions related to the definition of the logistic structure, offering a solution for decision making at two levels: the distribution of agricultural production and the specification of crushing units.

The distribution of agricultural production involves selecting specific regions for the production of each type of oilseed and defining the occupied area in each region. While observing the basic constraint of area availability for cultivating the crop in each region, the aspects considered are agricultural productivity and production costs. The distribution is determined on a yearly basis throughout the period of analysis.

It is important to emphasize that the determination of the distribution of agricultural production is sensitive to social aspects and takes into account the number of families involved in each of the regions selected. It is possible to apply additional constraints related to social inclusion strategies, such as establishing a minimum number of families included for each year of the analysis.

For the specification of crushing units, four parameters are determined: the number of facilities, the technology selected for each facility, the geographic location, and the scale of the processing capacity. The best time to make investments in each unit should also be determined, considering each year throughout the period of analysis.

The final aspect of determining the structure is indicating transport routes for the oilseeds and vegetable oils. In each year of the period under analysis, the origin and destination points are defined for the movement of all the materials necessary to supply the biodiesel production plant with vegetable oil from oilseeds produced by small farmers.

Generally, the problem of determining the best location for production zones and crushing units is to find an optimum point between the two extremes, seeking to balance logistical costs with investment costs. At one extreme, only one very large crushing unit would be built (minimum investment costs); at the other, a large number of very small units would be built (minimum logistical costs).

The mathematical formulation itself consists of an objective function to be minimized, which considers the costs involved in the operation of the chain (agricultural, industrial, and logistical) and sets of constraints associated with the demands to be fulfilled.

Initially, the sets of indices of the model, to which all the other data are referred, are determined, namely, production zones, locations of the crushers, types of crushers, oilseeds, and production plants. The production zones can be as small as the desired level of granularity for the model.

Based on these initial definitions, the data to be collected are determined. These data can be organized according to the echelon of the production chain with which they are associated: agricultural production, crushing, or transportation of oilseeds and oils. There are also some additional constraints relating to social aspects that can be controlled by the decision-maker. Depending on the scope of the case being studied, the model can, for example, determine a minimum number of families to be hired in a selected production zone in a particular year or during the whole period. For the sake of clarity, the elements that compose the mathematical model are stated below.

Sets	Index
Time period	t
Crushing plant project	k
Production zone	p
Crushing plant possible location	c
Biodiesel plant	u

Parameters	Description	Unit
α	Oil percentage in the oilseed	Unitless
β_k	Crushing efficiency of k-type crushing plant	Unitless
γ_p^t	Oilseed productivity at production zone p at period t	ton/hectare
AZ_p^t	Average land size at production	Hectare

(continued on next page)

(*continued*)

Parameters	Description	Unit
	zone p at period t	
CC_k	Unitary crushing cost of k-type crushing plant	\$/ton
D_u^t	Vegetable oil demand of biodiesel plant u at period t	m^3
$GTC_{p,c}$	Unitary oilseed transportation cost between the production zone p and the crushing zone c	\$/ton
IC_k^t	k-type crushing plant installation cost at period t	\$
$OTC_{c,u}$	Unitary vegetable oil transportation cost between crushing plant p and the biodiesel plant u	\$/m^3
OC_u^t	Vegetable oil cost for biodiesel plant u at period t	\$/m^3
PC_p	Unitary oilseed production cost at production zone p	\$/ton
TF^t	Minimum number of families to be allocated at period t	Dimensionless
$\overline{W}_k$	Annual capacity of k-type crushing plant	ton/year
$\overline{Z}_p^t$	Total available area of production zone p at period t	Hectare

Variables	Description	Unit	Domain
$y_{c,k}^t$	Decision of installing a k-type crushing plant at location c at period t	Unitless	{0,1}
Z_p^t	Size of area p allocated for production at period t	Hectare	$\mathbf{R}^+$
$gx_{p,c}^t$	Amount of oilseed transported from the production zone p to the crushing plant located at c at period t	ton	$\mathbf{R}^+$
$ox_{c,u}^t$	Amount of vegetable oil transported from the crushing plant c to the biodiesel plant u at period t	m^3	$\mathbf{R}^+$
$w_{c,k}^t$	Amount of oilseed crushed by the k-type crushing plant at location c at period t	ton	$\mathbf{R}^+$
v_u^t	Amount of vegetable oil bought to fulfill the biodiesel plant u at period t	m^3	$\mathbf{R}^+$

The mathematical model for the aforementioned problem can be stated as follows:

$$\min_{\substack{y\in\{0,1\}\\ gx\geqslant 0\\ ox\geqslant 0\\ z>0\\ w\geqslant 0\\ v\geqslant 0}} \sum_{c,k,t} IC_k^t y_{c,k}^t + \sum_{p,c,t} GTC_{p,c} gx_{p,c}^t + \sum_{c,u,t} OTC_{c,u} ox_{c,u}^t + \sum_{p,t} PC_p z_p^t + \sum_{c,k,t} CC_k w_{c,k}^t + \sum_{u,t} OC_u^t v_u^t \quad (1)$$

$$\text{s.t.} \quad \sum_c x_{c,u}^t + v_u^t \geqslant D_u^t, \quad \forall u,t \quad (2)$$

$$z_p^t \leqslant \overline{Z}_p^t, \quad \forall p,t \quad (3)$$

$$\sum_p z_p^t/AZ_p^t \geqslant TF^t, \quad \forall t \quad (4)$$

$$\sum_c gx_{p,c}^t = \gamma_p^{s,t} z_p^t, \quad \forall p,t \quad (5)$$

$$\sum_p gx_{p,c}^t = \sum_k w_{c,k}^t, \quad \forall c,t \quad (6)$$

$$\sum_u ox_{c,u}^t = \sum_k \alpha\beta_k w_{c,k}^t, \quad \forall c,t \quad (7)$$

$$w_{c,k}^t \leqslant \overline{W}_k \sum_{t'\leqslant t} y_{c,k}^{t'}, \quad \forall c,k,t \quad (8)$$

Eq. (1) represents the objective function, which comprises the total costs of the supply chain, including investment costs related to the installation of the unit, oilseed and oil transportation costs, agricultural production costs, oilseed processing costs at the crushing units, and the costs associated with the purchase of any additional volumes of oil in the market to meet the demand of the biodiesel plants. Constraint (2) states that the vegetable oil demand D_u^t of each biodiesel plant u must be fulfilled by the vegetable oil produced among the crushing plants, eventually acquiring v_u^t of vegetable oil from the market. Constraint (3) consists of an upper bound for the total area $Z_p^{s,t}$ to be allocated for the production of the oilseed in each production zone p. Constraint (4) states that the total number of families allocated among all the production zones p must meet an amount predefined by federal social policies, being greater than or equal to a minimum family allocation requirement TF^t It is important to point out that the number of families to be allocated at the production zone p is defined by the term $Z_p^{s,t}/AZ_p^t$, because each family must be allocated to a farm with average size AZ_p^t. Constraint (5) states that the total number of oilseeds that leave a production zone p is equal to the total area $Z_p^{s,t}$ dedicated for the production of the oilseed times the production yield per area unit $\gamma_p^{s,t}$. Constraint (6) defines that the total number of oilseeds allocated to a crushing plant located in c must be equal to the total number of oilseeds crushed at the same crushing plant located in c. Constraint (7) states that the total amount of vegetable oil produced in a certain crushing plant c is equal to the total number of oilseeds crushed times the oil percentage α of the oilseed and times the efficiency β_k of the crushing process defined in project k used by the crushing plant located in c. Constraint (8) states that the total available capacity of a crushing plant located in c is defined by the number of times a certain crushing plant project k was implemented until the time period t times the total crushing capacity $\overline{W}_k$ specified in this project.

2.2. Case Study

Seeking to maximize the social benefits of biodiesel, the Brazilian government selected the so-called "semi-arid" region – characterized by low humidity and low rainfall – as a priority for the Brazilian Biodiesel Program (PNBP). The majority of the population of this region lives in rural areas, which have the lowest national levels of education, income, access to healthcare, and basic sanitation services. Brazil's semi-arid region covers eight of the nine states in the Northeast region and the northern part of the state of Minas Gerais, encompassing an area of around 1.0 million square kilometers.

In terms of raw materials for the production of biodiesel, the goal is to diversify, reducing the percentage of soybean in this industry. For the semi-arid region, the program encourages the production of oilseeds intercropped with grains for the food industry, such as beans and corn, thereby expanding biodiesel production without reducing food production.

Due to its hardiness, ability to withstand adverse weather conditions, good adaptation to intercropping, and the widespread knowledge about its production techniques among farmers in the region, castor seed was selected as one of the main oilseeds for biodiesel production in the scope of the PNPB.

The model elaborated in this study was applied to a group of production zones, focusing on the supply of vegetable oil to a single biodiesel plant. However, the structure of the model was designed in such a way that it can be applied to any other region, regardless of its geographic size, or to other oilseeds and biodiesel plants; the mathematical formulation does not change, and the scale can be expanded as required.

In the present study, sixteen micro-regions located in the northern area of the state of Minas Gerais, comprising around 220,000 square kilometers, were defined as production zones. Two criteria were observed: proximity to the district where the biodiesel plant is located and the geographic boundaries of the Brazilian semi-arid region.

Based on its agricultural potential for the region of interest, castor oil was selected as the only oilseed for the development of this work. The strategic alignment between incentives offered by biodiesel producers and by the Brazilian government was also taken into account.

Despite the consensus that the main obstacle to the consolidation of the biodiesel production chain in the semi-arid region consists was guaranteeing minimum supply of oilseeds to be processed, issues related to the transport logistics of raw materials and biodiesel fuels and the location of crushing and production units have not yet been resolved (Azvaradel, 2008).

The installed storage capacity and its conditions represent another weakness in the oilseed logistic chain, particularly in regions with no tradition in this area of production, as is the case of the semi-arid area of the Northeast.

Studies estimate that cost of raw materials accounts for 60% to 75% of the total cost of biodiesel fuel (Ma and Hanna, 1999). Biodiesel producers often have to travel long distances to collect small volumes of production. Moreover, almost all of the transportation takes place on roads, which usually are in poor conditions, significantly increasing the total cost of the product (Azvaradel, 2008).

Oilseed from small farmers is purchased at certain “meeting points”, which are usually located in the areas around rural properties; typically, the farms are located no more than 20 km away from these facilities. It is, therefore, a logistic operation that is characterized by high capillarity, with hundreds of origins.

The agricultural product is always acquired in the form of grains, which must then undergo a processing stage because the biodiesel plants that adopt the normal transesterification process receive raw materials in the form of vegetable oils. This stage of extracting the oil from the grain takes place in dedicated industrial plants known as crushers or extractors.

The oilseed-crushing stage is a threshold between the farmers and the processing industry and can represent a critical stage in the financial balance of the production chain. In other words, this echelon plays an essential role in the chain. Therefore, the agent entrusted with it has considerable power over the other stages. Vertical integration can translate into economic advantages and guarantee the supply of raw materials. It is therefore important to assess the level of interest among biodiesel producers – or even producers of vegetable oil derivatives – in verticalizing the process in this way.

Of the existing oilseed-crushing technologies, “mechanical press” and “solvent extraction” were selected. Additionally, different capacities were determined for each of these technologies to represent small, medium, and large units.

The districts considered suitable for the installation of a crushing plant were selected from those that have good infrastructure, are relatively close to the production zones, and are strategically located close to paved highways in good conditions.

3. Results and discussion

To illustrate the applicability of the models presented in this paper, tests were carried out considering the case study previously presented. The models were implemented in the optimization software AIMMS 3.10 and solved with the solver CPLEX 11.2. The experiments were performed on an Intel Core 2 Duo P8600 2.4 GHz with 4 GB RAM on a 64-bit platform. The mixed integer linear model is composed of 1186 constraints and 2331 variables (of which 360 are binary variables, which represent the investment decisions). The solution was obtained in less than 10 s using the simplex and barrier algorithms, available in the solver CPLEX.

The solution obtained from the mathematical programming model to the problem addressed defines the optimal number, location, and type of crushing units, when these crushers must start to operate, and the distribution of the agricultural production. The analysis horizon is ten years, and the solution is multi-annual in relation to all the decisions. The model was previously validated for different cases by specialists involved with the process of planning the expansion of oilseed-crushing facilities in the country. They certified the adherence of the solutions obtained from the model to the reality of the cases considered.

Optimized distribution of production is widely dispersed in the first two years, but over the long term, a tendency toward centralization around production zones is observed. The dispersion of production in the first two years is due to the lack of available area, which is insufficient to meet all the demand from the plant, resulting in lower land production yields in the first two years. Fourteen out of the sixteen zones were involved in oilseed production in the two first years. In the third year, five of them had stopped producing, and from the fifth year onwards, only four – Araçuaí, Capelinha, Pedra Azul, and Janaúba – were still part of the oilseed supply chain. The reason for the reduction in the number of production zones involved is related to the premise that the land oilseed productivity would increase due to improvements in techniques applied and economic conditions. Therefore, oilseed logistics can be gradually facilitated by concentrating the production zones closer to the crushers.

Also, an optimized solution recommends the installation of three crushers. The first crusher, with a capacity for 25,000 tons of oilseed, should be built in the district of Montes Claros in the first year of the analysis, 2009. Built in the following year, the second crusher, Araçuaí would be the site of installation of a unit with a capacity for 12,500 tons of oilseed. Finally, in 2017, a unit similar to the one in Araçuaí would be installed in the district of Capelinha. The technology adopted in all cases is the mechanical press, which has lower operating and investment costs but is also less efficient than solvent extraction units. This choice is justified by the fact that the units selected are small and medium in size, and do not provide enough economies of scale to offset the higher fixed and investment costs required for solvent extraction.

To measure the effects of possible variation in the conjecture predicted for the forthcoming years, new scenarios are simulated, considering different sets of parameters for the activities studied. The purpose of these sensitivity studies is to increase the robustness of the solutions. Some alternative scenarios for study are shown in Table 1.

Table 2 summarizes the solutions suggested for the types of crushers and installation locations over the period of analysis,

Table 1
Scenarios for sensitivity analysis.

Scenario	Justification
Variation (−50% and +50%) in agricultural yield	Yield is subject to considerable uncertainties related to climate, such as temperature and precipitation. The considered variations are historical means for this region
Variation (−50% and +50%) in freight costs	The structure of the oilseed-collecting activities is still under development, and the costs still cannot be precisely associated to market values
Variation (+50% and +100%) in demand	These variations represent the possibilities for expanding the biodiesel plant capacity
Variation (−15% and +30%) in investment costs	These are typical uncertainties involved in budget estimations during preliminary stages

referring, in each case, to mechanical press technology. Capacities are expressed in tons of oilseed per year.

In general, the crushing units would be located in regions close to where the production is distributed, thereby creating self-sufficient oilseed production and oil-crushing centers. The only exception is Montes Claros, which does not have long-term occupied areas due to their low productivity, and therefore, its crusher would be supplied with oilseeds from other production zones.

Regarding the technology, mechanical press units are the best option in every case, except when the land productivity yields are lower and it becomes necessary to use solvent extraction technology, to fulfill the vegetable oil demand. Solvent extraction crushers achieve better extraction efficiency but require higher initial investments.

Analysis of the sensitivity of the solution to freight prices clearly demonstrates the trade-off between investment costs and transport costs. The cost of transporting vegetable oil is considerably lower than it is for grains, mainly due to the difference in volumes transported. With rising freight prices, the tendency is to install more crushing units to reduce the total volume of grain transportation. Similarly, when freight prices are lower, there is the opposite tendency to centralize the crushing process, leading to a larger volume of transported grain.

Table 2
Locations and installed capacities of the crushers.

Scenario	Location of the crusher plants	2009	2010	2011	2012	2017
Base case Investment cost of 15% or lower Investment cost of 30% or higher	Montes Claros	25,000				
	Capelinha	12,500				25,000
	Janaúba					12,500
Land production yield 50% lower	Montes Claros	25,000				
	Unaí				25,000[a]	
Land production yield 50% higher	Montes Claros	25,000				
	Unaí			25,000		
Demand 50% higher	Montes Claros	62,500				
	Araçuaí					25,000
	Capelinha					12,500
Demand 100% higher	Montes Claros	62,500				
	Paracatu				12,500	
	Araçuaí					25,000
	Capelinha					12,500
Freight cost 50% lower	Montes Claros	62,500				
Freight cost 50% higher	Montes Claros	12,500				
	Araçuaí	12,500				
	Unaí		12,500			
	Capelinha				12,500	

[a] Using solvent extraction.

The objective function – the equation minimized in the solution of the model – has a total value of approximately US$ 200 million, of which around US$ 6.3 million are invested in industrial crushing facilities. The rest of the costs are related to agricultural production, transportation, and operation of the crushing units. On the whole, this gives an estimate of US$ 1630.00 per ton of castor oil produced and delivered to the biodiesel plant.

Considering the structure now available for the development of a supply chain from castor oil for biodiesel in the semi-arid region, one can notice that the actual total production cost of the oil delivered at the biodiesel plant is higher than the one estimated above. The crushing plants are distant from their optimum locations, logistical costs are high, and production is widely spread due to lack of planning in past decades.

At the same time, biodiesel plants in the semi-arid region can hardly have their oil supply based on main crops such as soybeans and cotton seeds because these are not available in that part of the country. In Brazil, production and crushing units are concentrated in western and southern states, so the transportation costs rise considerably.

Relying on local supply chains means survival for a biodiesel plant in the semi-arid region, where a poorly developed industrial and logistics structure is established. This is exactly where the importance of a model such as the one proposed in this paper resides. The scenario suggests that there is a unique chance for decision makers to use the model as a tool for planning and implementing an optimized supply-chain structure. The necessary investments involved in new crushing plants and other echelons are low when compared to total savings that will determine the economic sustainability of the whole business.

Brazil has been attracting worldwide attention as a major producer of biodiesel, achieving considerable growth in the last years. The Brazilian government has established social benefits as one of the pillars of its biodiesel program, attempting to reduce poverty and transfer income to rural areas by including small farmers as oilseed suppliers in the biofuel production chain.

The continued success of this program requires considerable investments in production and logistical structures. The key link in this supply chain is the oilseed-crushing units, particularly due to the current poor conditions of these facilities in the country.

Consolidated agricultural production chains or those related to large farming operations have been the object of a considerable number of publications. Less-structured production chains, such as those for castor oil, however, are at most the object of qualitative analyses or studies restricted to sociological or macro-economical aspects.

The use of mathematical tools to support decision-making at a strategic level plays an important role in ensuring the economic feasibility of the investments and the sustainability of the business as a whole.

In this case study, there is a noticeable tendency to centralize the agricultural production and crushing process, preferably combining both stages in the same region. There is also a tendency to centralize the crushing process in the region close to the biodiesel plant. In each case, the solution provided by the model is to invest in mechanical press units rather than solvent extraction technology due to the high initial investment of the latter, for which the superior efficiency would only compensate with a higher economy of scale.

4. Conclusions

This article proposes a mathematical model to help determine an optimized structure for the supply of vegetable oils to biodiesel plants. A practical application is described for a real case study in Brazil.

The authors encourage other academics to work on production chains that employ small farmers. Having in mind the recent nature of the Brazilian Biodiesel Program, any idea that economic feasibility and family farming are unrelated must be firmly rejected. Thus, academic work on this subject can play a fundamental role in ensuring that the strategic goals for social inclusion and income distribution to rural areas are achieved.

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