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Mathematical model for strategic planning optimization in the pome fruit industry

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ABSTRACT

This paper presents a strategic planning model for optimal restructuring of a pome (pears and apples) production farm concerning varieties and planting densities. The model decides the optimal investment policy for a given farm, maximizing the net present value of business while dynamically deciding its planting structure along a given time horizon under different financing scenarios. The model constraints impose restrictions on the activities to take into account risks and cultural practices. The mathematical model corresponds to a mixed integer linear programming problem, where integer decisions are related to the minimum reconversion land unit and funding requirements.

The model was applied to a realistic case study of a typical farm in the "Alto Valle de Río Negro" Argentine region. The study was conducted over a 20-year time horizon considering four varieties of apples and five of pears. The results showed the optimal investment policy for the replacement of varieties under different scenarios, with and without external financing. A sensitivity analysis was also performed on some of the most influential parameters. The model could be used either by governmental agencies to advise private sectors and to develop strategic economic policies or by companies to optimize the business profit.

1. Introduction

Supply chain planning has been intensively studied in recent years. Typically, there are three planning instances depending on the specific objectives and time horizons: operational, tactical and strategic (Shapiro, 2001). In particular, strategic planning involves long-term decisions (years) and usually considers structural aspects. Such decisions are often "irreversible" and therefore their impact should be carefully analyzed.

Depending on the specific supply chain, strategic planning can have different objectives (Shapiro, 2001). For example, in many supply chains, logistics related to the distribution of goods in a timely manner between the different system nodes is essential. Another aspect of strategic planning is related to the introduction of new products to the company portfolio.

Pome fruit (pears and apples) supply chain is a complex system involving the interaction between many production, processing, storage and distribution instances. Due to its economic importance, this system has motivated various studies from the planning viewpoint at all scales. In Masini et al. (2007, 2009) models for tactical and operational planning -short and medium term, respectively- have been proposed to study the fruit industry business in Argentina. Ortmann (2005) studied the South African fruit supply chain with emphasis in optimizing material flow within the system.

Pear and apple trees are perennial plants with a 20-to-60-year life span. However, few trees reach the end of their life span because at some stage of their productive cycle, it may be convenient to replace them by new varieties. This is essentially due to: (i) changes in consumer preferences for more widely accepted fruit varieties, and (ii) technical advances that provide better production options than those currently installed. Both factors impact on profitability and production of the different varieties.

For these reasons, strategic planning of a pome fruit farm variety structure is important to ensure an acceptable return on the activity in the long term. The basic objective of this strategic planning is to maximize some measure of profitability, typically the net present value of the system, resulting from the economic balance of removing and planting the different varieties. The trees are divided into different age groups per variety. Each age group has different productivities and, therefore, originates different cash flows. The removal of trees of different age groups has thus different effects on the objective function.

Whereas this is an important problem, very few studies have systematically addressed it from the point of view of mathematical modeling. Ward and Faris (1968) proposed a dynamic programming model based on Markov processes to study the replacement of trees of a variety of plum. The emphasis of that work was to capture the stochastic effect on the productivity of trees of different

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ages. Oppenheim (1979, 2003) presented a multi-period linear programming approach to generate replacement strategies in a typical pipfruit farm of a productive region in New Zealand. Also for New Zealand farms, Kearney (1994) proposed a multi-period linear model to replace apple varieties. In that work, a sale price profile consisting of a progressive reduction at a fixed rate for the first 10 years and then a plateau during the following decade was used for each variety. This profile was intended to reflect the increased supply of fruit, worldwide. More recently, Cittadini et al. (2008) proposed a multi-year linear modeling framework to explore options for Patagonian fruit production systems. The proposed dynamic farm-scale model optimally allocates production activities to the various land units. Their model considers several crop species (cherry, apple, plum, peach and walnut) as well as training, irrigation and frost control systems. Their model spans a 50-year time horizon and includes two different objective functions.

The present work addresses strategic planning in the pome fruit industry, specifically focused on the restructuring decisions regarding the distribution of fruit varieties in a given farm. It is considered that this aspect has a great impact on the economy of the value chain, since much of the production is devoted to the international market. The proposed model considers the simultaneous growing of apples and pears taking into account their specific developing practices. Besides removal and planting, grafting is also included as a developing option. Three typical planting densities are considered.

As a case study the model is applied to a typical farm located in the ‘‘Alto Valle de Río Negro’’ Argentine region. However, while the system under study has special features, the model was developed in general terms so that it can be applied on most production units worldwide.

2. Problem description

Pome fruit industry activity is strongly seasonal. In the southern hemisphere, apple and pear harvesting takes place between January and April. Each variety is picked in a given range of weeks within the harvest period. Pome fruit business yearly net profit is given by the sum of the sales of the different varieties minus the maintenance costs of the existing infrastructure and investments in restructuring.

In a farm, any of the different apple and pear varieties available in the market can be developed. Each variety can be set in any of three given planting densities: low, medium and high. Each density has its own setting up costs and productivities. For example, high density planting requires larger investments than low and medium density ones, but it has a sooner production entry, thus leading to larger production over the life cycle.

The farm is usually divided into land lots. The various lots have, in general, different plantings in terms of variety, age and density, and can be worked independently according to their productive history. Regarding the evolution of productivity, plants do not produce fruit during the early years of their life, then they present an intermediate period of steady productivity increase until reaching maturity, remaining at that maximum productivity level until virtually the end of their lifespan.

For all varieties, three possible market destinations are considered: export, domestic and industry. Fruit for export has the best quality in terms of appearance; i.e., damage, size and color, and pressure. Fruit for the domestic market is of intermediate quality, while the remainder is industrialized for juice production. Each fruit variety has a different price and a more or less fixed fraction of its production allocated to each destination.

The main costs of the system are related to tree maintenance, which include irrigation and fertilization, as well as cultural work, such as pruning and thinning. Since gathering is a highly intensive manpower activity, its associated costs are most important in the harvest months. On the other hand, from the point of view of investments, costs associated with the removal of existing trees and the planting of new ones are the most significant. The grafting technique; i.e., cutting down existing plantings and installing the new plants on the cut trees understocks, is also considered since it allows the developments of new varieties at lower costs and earlier production entry.

It is necessary to consider a long time horizon to pose the economic analysis and decide on investments because plantings require several years to grow and start producing. From a financial standpoint, the system manager usually has the option of applying for loans to make major investments related to the installation of new trees. Therefore, the economic analysis must consider the loan payments in the cash flow formulation.

Based on the above considerations, a mathematical model to generate optimal strategies for the restructuring of farms producing apples and pears was formulated. The proposed deterministic multi-period mixed integer linear programming (MILP) model provides the area per year to remove and plant each variety in each land lot of the farm. Considering that long term investments are involved, the net present value (NPV) has been adopted as the objective function of the optimization model.

The general structure of the model corresponds to the following multi-period mixed-integer program formulation (see Appendix for details):

$$\max \quad NPV = -Budget_0 + \sum_{t\in T} \frac{Fc_t(\mathbf{x}_t, \boldsymbol{\theta}_t)}{(1+rd)^t} \tag{1}$$

$$\text{s.t.} \quad \mathbf{h}_t(\mathbf{x}_t, \mathbf{x}_{t-1}, \boldsymbol{\theta}_t) = 0, \quad \forall t \in T \tag{2}$$

$$\mathbf{g}_t(\mathbf{x}_t, \mathbf{x}_{t-1}, \mathbf{y}_t, \boldsymbol{\theta}_t) \leqslant 0, \quad \forall t \in T \tag{3}$$

$$\mathbf{x}_t \geqslant 0, \quad \forall t \in T \tag{4}$$

$$\mathbf{x}_t = \mathbf{x}_0, \quad t = 0 \tag{5}$$

$$\mathbf{x}_t \in \mathbf{X}_t, \quad \mathbf{y}_t \in \{0,1\}$$

$\mathbf{x}_t$ are the continuous decision variables that define the structure of the farm and related quantities. These variables involve the areas to be planted, removed, grafted and cut down; the economic variables and the production levels generated by the previous replacement activities. They are identified by a combination of indices: land lots (i), planting densities (s), fruit varieties (j), trees age in years (e). $\boldsymbol{\theta}_t$ is the input data vector, which includes: the planting productivity per variety, density and age; the harvest calendar; costs and sale prices data; market distribution per variety; etc.

Eq. (1) is the objective function of the model. It is calculated as the sum of the discounted annual cash flows ($Fc_t(\mathbf{x}_t, \boldsymbol{\theta}_t)$) over the planning horizon, using the discount rate (rd), minus the initial budget ($Budget_0$).

Eq. (2) represents area balances and economic calculations. In Fig. 1 area balances are described. The model decides if the planting present in a given time (*Occupied Area*$_{t-1}$), remains as part of the farm (*Occupied Area*$_t$), is cut down (*Cut Down Area*$_t$), or removed (*Removed Area*$_t$) in the following period. If removed, it can be replaced immediately by a new planting (*Planted Area*$_t$) or the area remains available (*Available Area*$_t$). If the planting is cut down, grafting must take place immediately (*Grafted Area*$_t$). On the other hand, if there was available area in the previous period (*Available Area*$_{t-1}$), it can be either allocated for new planting (*Planted Area*$_t$), or remain available for the following period (*Available Area*$_t$). Finally, if the planting reaches its maximum lifespan, must be removed.

It is possible to calculate the annual production levels per variety knowing the planting density and age. The economic balances include: overall income by fruit sale; operative fixed costs due to

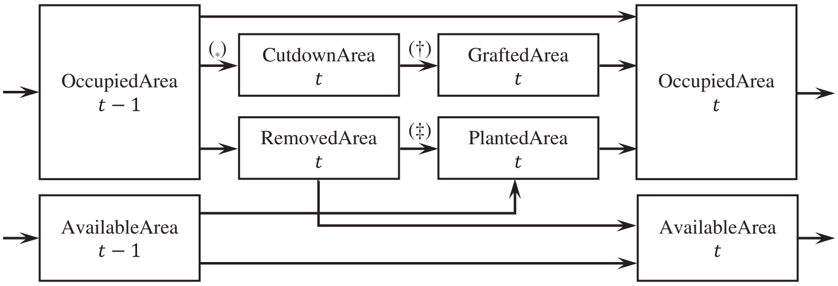

Fig. 1. Scheme of area balances. Outside blocks characterize the farm structure in a given time. Middle blocks are the replacement activities considered. Arrows connect the allowed possibilities. (∗) It can only be performed on high density young plantings. (†) It is only possible to graft an apple on an apple understock; idem for pears. (‡) Only allowed if the replacement involved plantings of different species (remove apple/plant pear and vice versa).

cultural labors; overhead costs which are function of the farm size-including management activities, technical consulting, taxes and services-; variable costs corresponding to picking fruit costs-including manpower and transportation-; the planting removal costs; the annual investment costs, calculated considering the investments for both conversion methods: new plantings, and cut down and grafting. Planting depreciation is calculated using the straight line method (Blank and Tarquin, 2002). The rescue value is calculated considering that the project continues beyond the planning horizon. Then, it is modeled as the income that the final structure of the farm would generate until all their plantings reach the maximum lifespan. It has been considered that the farm owner/manager has access to external financing for investments in restructuring, using the French repayment system for loans to be paid in equal installments (Blank and Tarquin, 2002).

Eq. (3) represents the set of inequality constraints. One set of constraints ensures that at least 1 year must elapse between removal and planting activities if the same species is installed (remove apple/plant apple; idem for pear) in a given land lot, due to sanitary reasons. Otherwise, when both the removed and new species are different, removal and planting activities can take place in the same period.

An additional requirement modeled as inequalities is the uniform distribution of the production along the harvest period; namely, harvest control. Basically, the goal is to ensure a weekly volume of fruit production between set minimum and maximum values each year. A uniform distribution throughout the season necessarily requires a minimum number of varieties set-up. This practice aims primarily to reduce risks. It may happen that the farm's maximum benefit is achieved by planting a single variety preferred by the market. However, this is a risky strategy because either the market preference can suddenly change or the productivity of such variety can be scarce due to weather or sanitary reasons. Moreover, a uniform distribution of production throughout the harvest period also facilitates manpower recruitment since it is easier to attract temporary workers for the entire harvest period than for a shorter period (a few weeks for the harvest of only one variety). The equations used in this work for the harvest control are a modified version of those presented in Kearney (1994). Harvest control is activated from a given year on of the planning horizon defined by the user. The model allows for an adaptation lapse in case the initial farm structure is not balanced and several years are needed to achieve the desired balance.

A budget control limiting the allowable expense for each period has also been implemented. The technique adopted to model the budget control is a modified version of that presented in Cittadini et al. (2008). In this work, the possibility of accessing external financing is also considered. The modeled budget control scheme, basically considers that the cash outflow in period t must be less or equal to the budget of the previous period plus the amount of borrowed money.

To avoid the removal and planting of too small areas, constraints which makes use of binary variables ($\mathbf{y}_t$) have been included to force the occupied and available areas to lay within a range or to be zero. The same strategy was adopted in the financing section. Binary variables are used to model if money is borrowed or not. If a loan is taken out, its amount should be within a certain range.

Eq. (4) are the non-negative constraints and Eq. (5) defines the farm's initial state.

The described MILP model was implemented in the modeling and optimization platform GAMS 23.0 (GAMS, 2009a) and solved with the CPLEX 11.2 solver (GAMS, 2009b). An Intel© Core™ 2 Quad Q8200 @ 2.33 GHz computer with 2.96 GB of RAM, was used to solve the case study to be considered below. A user interface for data entry and results visualization was developed using MS Excel©. The MILP model has 527.307 equations, 535.847 continuous variables and 97.300 binary variables.

3. Case study

In order to illustrate the performance of the proposed model, a typical pome fruit production farm in the "Alto Valle de Río Negro" Argentine region has been considered as case study.

The required information is provided in the Appendix. In all cases the data were obtained from official sources when available (Leskovar et al., 2010; Rodriguez et al., 2009; Villarreal et al., 2008), and from personal communications with stakeholders otherwise. Table 1 provides the initial state of the farm under study. The farm has 52 ha and it is divided into five land lots. The number of hectares planted per variety and the available area are provided for each lot, in which a given variety may have different densities and ages. Each specific planting is thus described in the table by a triad: area/age/tree density. The considered varieties of pears and apples are the most typical in the region under study.

3.1. Financing scenario analyses

In order to show the influence of different financing policies, an analysis on three financing scenarios is performed; namely:

(i) "No loan": no access to external financing.
(ii) "Loan 5": availability of external financing with a 5-year repayment term.
(iii) "Loan 10": availability of external financing with a 10-year repayment term.

3.2. Sensitivity analyses

In order to illustrate how variation on specific items impact on the optimal solution, a sensitivity analysis of three parameters on the "No loan" scenario is performed; namely:

Table 1
Farm's initial state.

L[a]	Area[b]	Free	Variety[c]								
			G	GS	CP	RD	AF	BD	PT	RB	W
1	10	1.2	1.9/5/H[d]	1.1/15/M	0.5/3/H	2.7/8/H	0.9/3/H	0.7/1/H	1.0/6/H		
2	8	0.6		2.0/30/L		3.6/31/L					1.8/30/L
3	12	0.7		0.6/20/M		2.3/21/M		0.6/21/M	1.6/13/M	1.8/15/M	1.0/18/L
				0.6/26/L		2.0/27/L					0.8/23/M
4	10	0.7	0.9/14/M			3.5/16/M					1.3/13/M
											3.6/5/H
5	12	8.8						0.8/12/M	0.7/25/L		
									1.1/30/L		
									0.6/20/M		
Total area	52	12	2.8	4.3	0.5	14.1	0.9	2.1	5	1.8	8.5

G: Gala; GS: Granny Smith; CP: Cripps Pink; RD: Red Delicious; AF: Abate Fetel; BD: Beurre Danjou; PT: Packams Triumph; RB: Red Bartlet; W: Williams; L: Low; M: Medium; H: High.

[a] Land lots.

[b] All area values are in ha.

[c] Varieties.

[d] Area in ha/age in years/tree density.

(i) *Harvest constraints*: The maximum (Q_{max}) and minimum feasible weekly capacity (Q_{min}) value have been modified. As in the base case scenario, in all cases, Q_{max} is 25% larger than Q_{min}. Q_{min} was changed from a low value (40 ton/week) to the maximum value allowed before the problem become infeasible (134 ton/week). Thus, low values of these parameters represent low labor availability, while larger figures model both less restrictive manpower activity and larger productivity levels requested.

(ii) *Initial budget*: To see how the solutions proposed by the model are affected by the initial budget, its value was changed from U$S 327.000 to U$S 575.000.

(iii) *Discount rate*: In order to illustrate the risk aversion factor influence into the decisions taken by the model, a sensitivity analysis on the discount rate was performed. This parameter was changed from 0% to 25% in 1% increments.

4. Results and discussion

4.1. Financing scenario analysis

Fig. 2 shows the evolution of the area occupied by apple and pear plantings, integrating all the varieties of each species, together with the free area for the "No loan" case. Regarding apple and pear plantings, data are discriminated by tree density. Total annual production of each species is reported on the right axis.

It can be seen that the free area vanishes in year 8, after passing through a maximum in year 3. It is also evident that the model proposes a transition from low and medium densities to high density plantings. Low density apple plantings are entirely removed in the third period, while the total removal of low density pears is reached in year 7. Medium density plantings are maintained until year 11 and then a gentle decline follows until the end of the time horizon. Most of the medium density apple plantings are removed from the orchard at the end of the planning horizon, whereas medium density pear plantings remain. When investments in new plantings are made, high density ones are always adopted. Although the investment cost is higher in this case, it is clear that the earlier production entry and the lower operating costs favor this productive option.

Finally, it can be noticed that in the first part of the time horizon, there is a production decrease for both species. This is due to the removal of old plantings still in production and the setting of new ones that do not produce fruit in earlier periods. Moving in the timeline, the new plantings become productive and their production stabilizes at high values in the final part of the study horizon.

Fig. 3a and b shows the evolution of the area of two selected apple varieties. The different gray scales represent plantings of different ages within the variety structure of the farm. The data are disaggregated in each period per planting density. On the right axis, the annual production is reported (solid line).

The Cripps Pink apple variety (Fig. 3a) is one of the most profitable due to its high export price, resulting from its wide acceptance in foreign markets (see Table 2 in Appendix). Therefore, the model plans several investments in high density plantings of this variety throughout the study period. The small fraction of existing high density area at the beginning is maintained throughout the whole

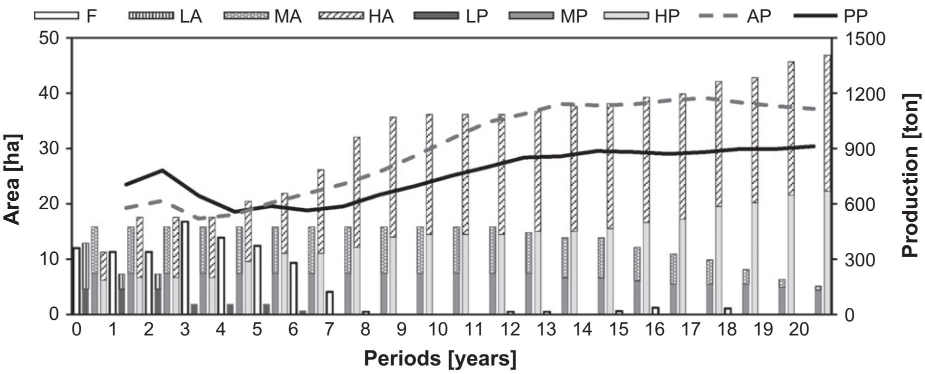

Fig. 2. Evolution of annual tree density and production level per species. F: free area, LA: low density apple plantings, MA: medium density apple plantings, HA: high density apple plantings, LP: low density pear plantings, MP: medium density pear plantings, HP: high density pear plantings, AP: apple production, PP: pear production.

planning horizon. In period 2, two additional bars appear corresponding to the grafting of this variety on the roots of other less favorable apple varieties. In period 4, another bar is added, remaining unchanged until year 8. The resulting structure of Cripps Pink is kept until year 19 when a new high density fraction is included.

In the case of the Red Delicious apple (Fig. 3b), the two existing low density plantings are removed in the first year. The existing high density planting is also cut down in order to graft a more profitable apple variety (Cripps Pink, data not shown). The two medium density plantings existing at the beginning remain on the farm until period 11. Part of one of them is removed in period 12 and is completely eliminated in year 15 due to aging (35 years). The remaining medium density planting is gradually removed from year 16. An investment in high density plantings of the Red Delicious apple is made in year 7. Despite not being one of the most profitable varieties, its presence is required to keep the weekly harvest volume balanced (Table 5 in Appendix).

Fig. 4 shows a bubble chart for the weekly harvest of fruit in each period. The bubble size represents the amount of fruit harvested in each week within the planning horizon. The dashed line after period 10 indicates the time at which the harvest control is activated. It can be observed how, from an unbalanced farm at the beginning of the time horizon, the model planifies the varieties restructuring to achieve the desired balance in terms of weekly harvested volume from year 10 onwards.

In Fig. 5, the economic results are shown. In all cases the values are discounted after taxes. Positive bars indicate income: income per fruit sales of apples and pears, depreciation, and rescue value in the last period. The negative bars correspond to the expenditure of money: fixed costs -including operative and overhead costs-, variable costs, and investment costs- considering conversion via the traditional method and the cut-down/grafting method-. The solid line shows the discounted cash flow in each period, calculated as the difference between positive and negative bars.

Fig. 5 shows that incomes from pear and apple sales are similar. Otherwise, fixed costs are even larger than investment costs, which is one of the major concerns of the growers. The optimal policy includes numerous investments, mainly during the first part of the planning horizon until period 10. It can be noted that from the fourth year on, the discounted annual cash flows become positive together with a sustained reduction towards the end of horizon due to the effect of the discount rate. The rescue value obtained from the final structure of the farm makes the last cash flow increases substantially.

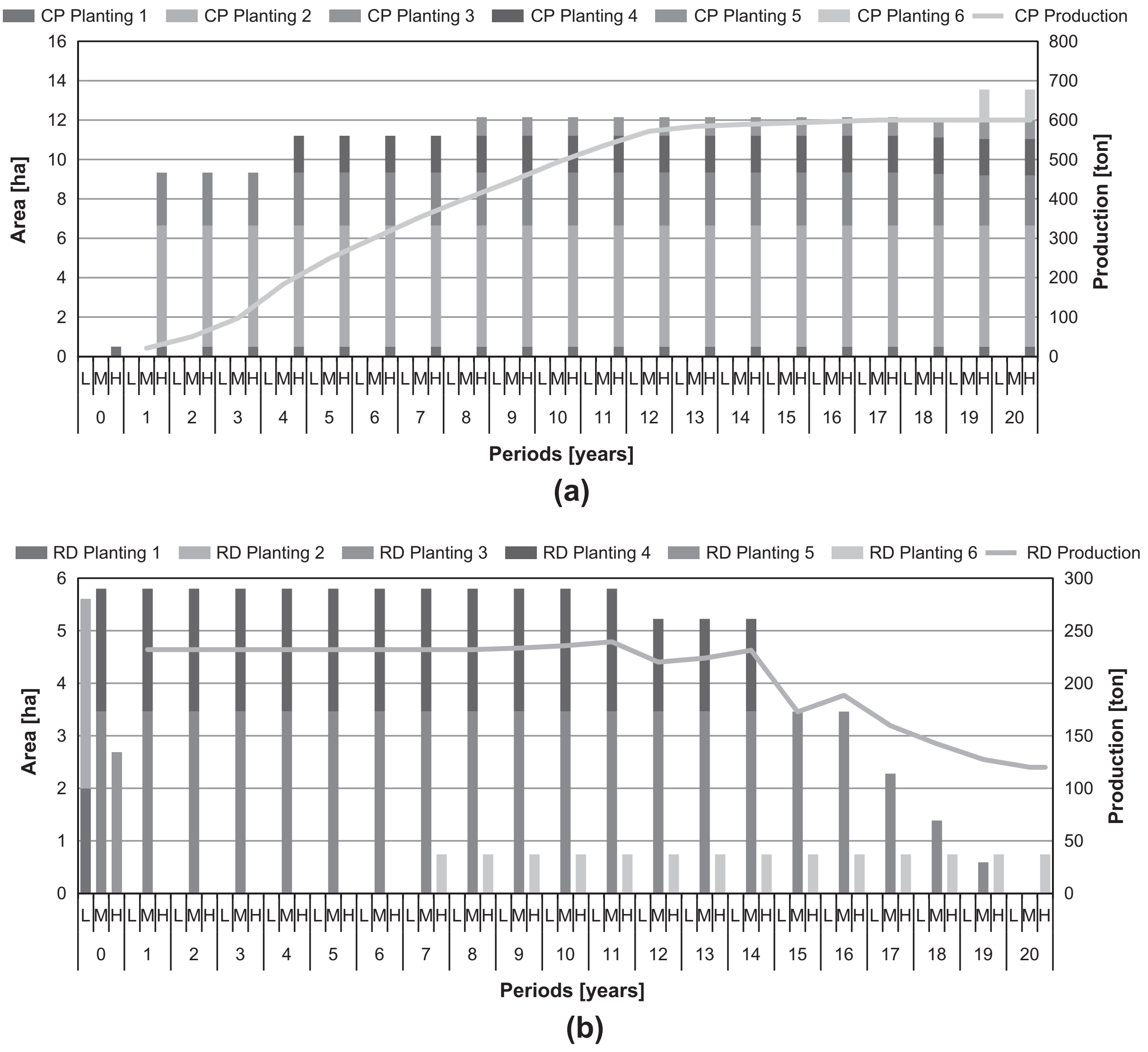

Fig. 3. Evolution of plantings disaggregated per tree density, together with annual production of: (a) Cripps Pink and (b) Red Delicious.

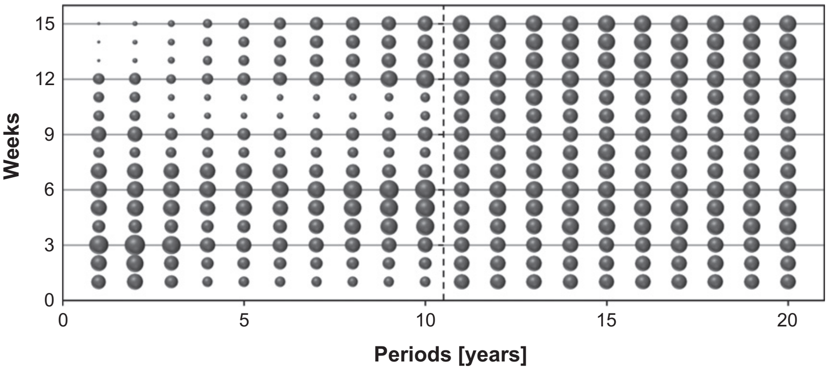

Fig. 4. Weekly harvested volume over the planning horizon. Bubble size quantifies weekly production. Harvest control is activated from year 10 on (dashed line).

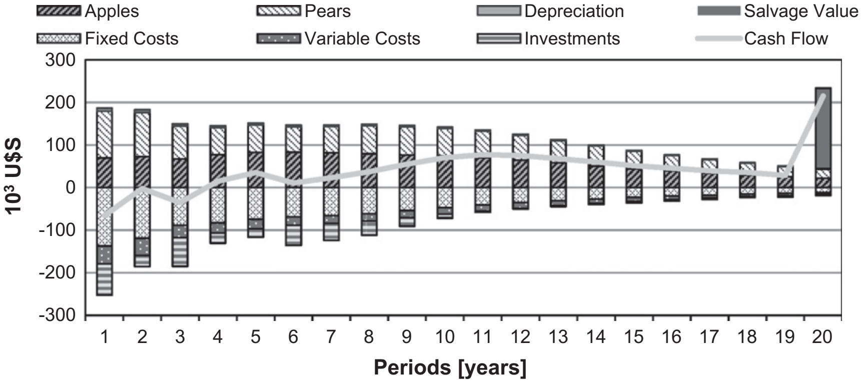

Fig. 5. Economic analysis (no external financing). Positive bars represent incomes. Negative bars represent expenditures.

A comparison of the three financing scenarios analyzed follows. Fig. 6a and b shows the cumulative discounted cash flow and the annual average tree density for each scenario, respectively. The annual average tree density is obtained from the ratio between the number of trees present in a given year and the total farm area (see Appendix for details). The values of the objective function, which correspond to the round marker in Fig. 6a, for each financing scenario analyzed are: "No loan": NPV = U$S 378.110; "Loan 5": NPV = U$S 428.657; "Loan 10": NPV = U$S 502.856. As expected it can be observed that NPV increases when access to credit is available.

In the first place, availability of external financing favors more aggressive restructuring decisions. In the case of financing at 5 years (results not shown), the model recommends a series of seven loans starting in year 2. In the first year a loan is not requested because the initial available budget does not allow covering repayment values. In the case of financing at 10 years (results not shown), the model suggests a set of six loans beginning in the first period. In this case, the initial budget is sufficient to meet the repayments for a loan taken in the first year.

Whereas Fig. 6a shows that the best the financing option, the earlier the corresponding cumulative discounted cash flow becomes positive, even allowing a 2-year shorter repayment period, Fig. 6b clearly shows that the transition speed to reach the final structure is significantly higher in the cases with access to external financing. The model with 10-year loans reached an average tree density of 900 plants per hectare in the first study period from a farm with an initial density of 500 plants/ha. Otherwise, cases with financing at 5 years and without external financing took 5 and 6 years respectively to reach such figure. It is also noted that the long term trend is the same for all financing scenarios, since the three curves are virtually superimposed at the end of the study period (from year 13 onwards). Moreover, there are no significant differences among the final structures of the farm since the optimization leads to a "unique" solution independent of the financing scheme (data not shown). As shown in Fig. 6b the difference lies mainly in the speed of transition between the two states.

The average density increase is achieved by investing in new high density plantings. The earlier the investment is made, the earlier the new plantings come into production and greater volumes of fruit are marketed during the time horizon translating into greater profitability. These results highlight the impact of the different financing policies, and therefore they can be useful for advising investors and designing promotion programs.

4.2. Sensitivity analysis

4.2.1. Harvest constraints

The general results obtained from the sensitivity analysis on the Q_{min} parameter are shown in Fig. 7a and b. In Fig. 7a the solid line shows the NPV on the left axis. The total production is represented by the dashed line on the right axis. The square marker shows the base case scenario, and the round marker corresponds to the optimum value of Q_{min}. Fig. 7b shows the final structure of the farm for values of Q_{min} near to the optimum.

At low values of Q_{min}, free area remains available at the end of the planning horizon (Fig. 7b). At first, as Q_{min} grows, an increment in the farm profit is obtained at the expense of free area occupation with new plantings, mainly of the most profitable varieties (CP and AF).

For Q_{min} from 110 to 115 ton/week, new weekly production increments also allowed investments in CP and AF. Further

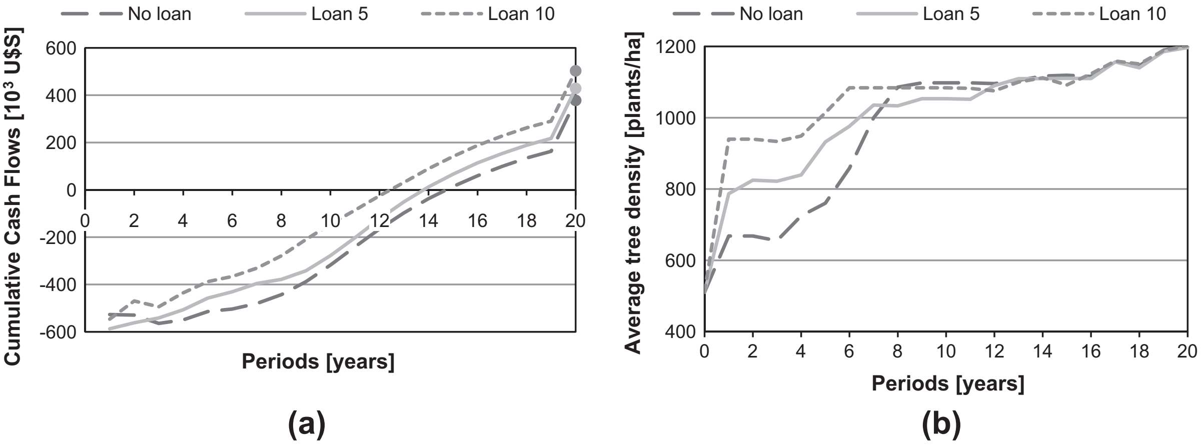

Fig. 6. Comparison among the three financing scenarios considered. (a) Cumulative discounted cash flows. (b) Annual average tree density evolution over the planning horizon.

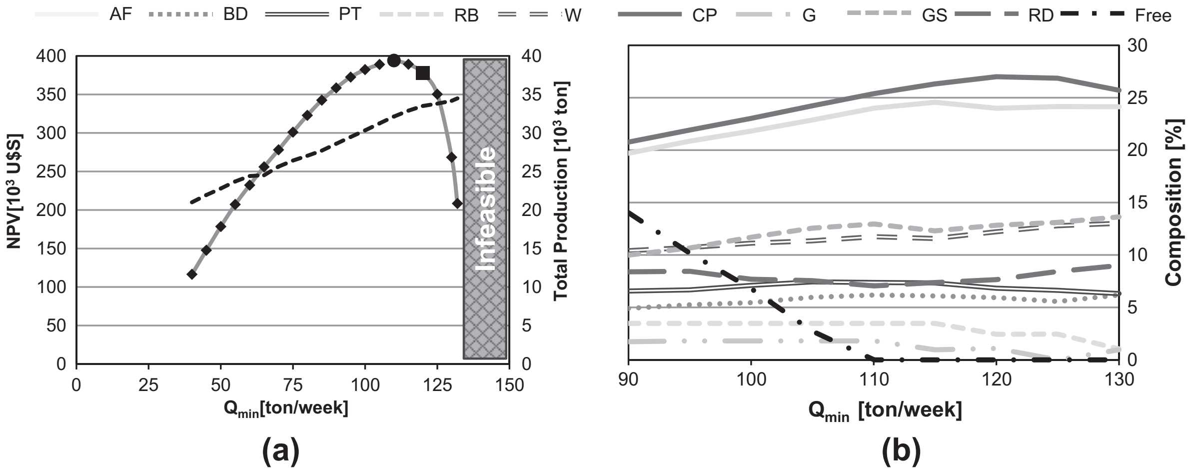

Fig. 7. Harvest constraints sensitivity analysis results. (a) NPVs (solid line) and production levels (dashed line) obtained. (b) Final farm composition regarding varieties, together with free area.

increments until 125 ton/week require the inclusion of less profitable varieties (W, GS and RD). In this segment (115–125 ton/week) CP still increases but AF reaches a plateau. From 125 on, larger weekly fruit collection levels can only be obtained by reducing the CP fraction and increasing those of W, GS and RD.

When $Q_{\min}$ is larger than 134 ton/week, the problem becomes infeasible because the total area of the farm is not enough to reach the requested weekly productivity level. It is worth noticing that the $Q_{\min}$ value adopted in the base case scenario is larger than the corresponding to the optimum profitability level (square and round marker in Fig. 7a, respectively). This situation would not have been identified without the sensitivity analysis.

4.2.2. Initial budget

A sensitivity analysis on the initial budget is reported in Fig. 8. The initial budget was changed from U$S 327.000, which is the minimum initial budget needed to reach the requested specifications, to U$S 575.000, here and beyond this value no significant changes were observed in the final solution achieved. As in the previous study, NPVs (solid line) are shown together with the corresponding total production levels (dashed line) (Fig. 8a). The square marker shows the base case scenario, and the round marker corresponds to the optimum value of $Budget_0$. Fig. 8b shows the final composition reached for the different values of $Budget_0$.

The first conclusion drawn from Fig. 8a is that there is no possibility to achieve the requested specifications if $Budget_0$ is lower than U$S 327.000 since the problem becomes infeasible. It is worth knowing beforehand the minimum initial budget necessary to address restructuring investments in a non-financing scenario.

NPV rises as $Budget_0$ increases up to U$S 401.000 and then, starts to decrease. This is due to the fact that increment of the discounted cash flows does not compensate the initial budget assigned to the project. As in the previous section, the value of $Budget_0$ of the base case scenario (square marker in Fig. 8a) is larger than the corresponding to the optimum profitability level (round marker in Fig. 8a).

It can be seen that the total production level grows almost linearly with the increase of $Budget_0$ (Fig. 8a dashed line). This is not because more investments are made (data not shown), but because they are made earlier in the planning horizon. Therefore, the transition to the optimum structure is reached faster allowing new plantings to produce over a longer period.

Fig. 8b shows that once the optimum value of $Budget_0$ is reached, there is no significant variation in the final structure of the farm. Below this value, some differences are found, mainly in RD and PT varieties.

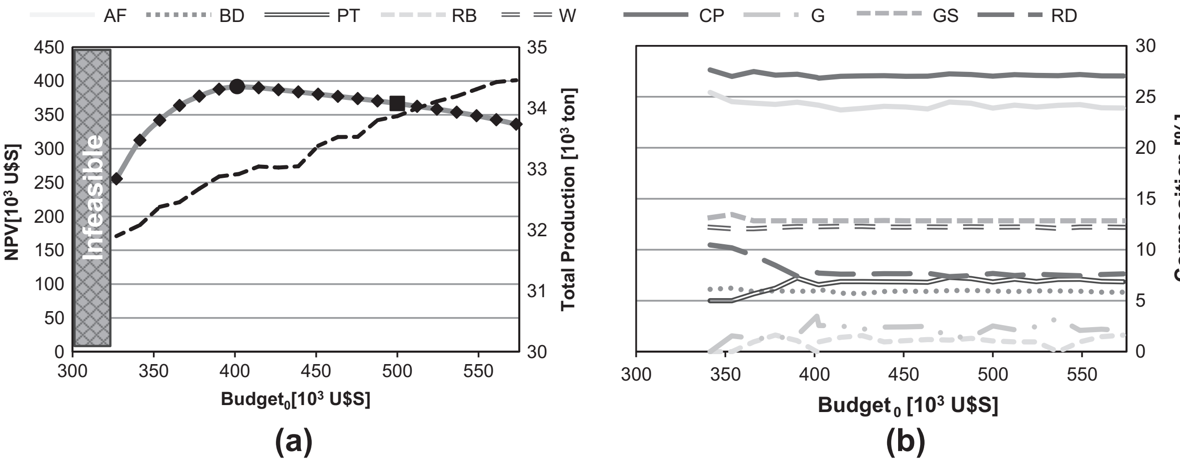

Fig. 8. Initial budget sensitivity analysis results. (a) NPVs (solid line) and production levels (dashed line) obtained. (b) Final farm composition regarding varieties.

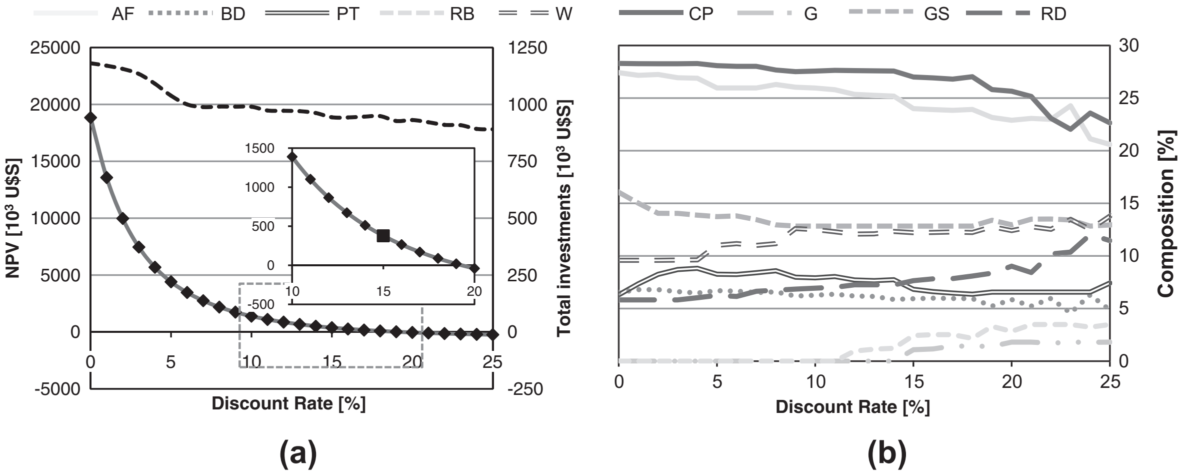

Fig. 9. Discount rate sensitivity analysis results. (a) NPVs (solid line) and total investments (dashed line). (b) Final farm composition regarding varieties.

4.2.3. Discount rate

Fig. 9a shows the influence of the discount rate on the NPV (left axis). The dashed line corresponds to the total investments planified for the different values of the discount rate (right axis). A zoomed caption near to the base case scenario is also included. Fig. 9b shows how the proposed final structure of the farm varies with *rd*.

As expected, NPV is strongly dependent on the chosen discount rate. The total investments made in the project are also affected by this parameter and decreases as *rd* increases. This is due to the fact that the opportunity cost of the investments increases with the discount rate. The money used to invest is tied up for a long time, and therefore cannot be used for other purposes, whereupon it is less convenient to assign monetary resources to the project as the risk perception increases.

The speed of transition between the initial and the final structure is also affected by the discount rate (data not shown). The lower the discount rate, the higher the speed of transition. The effect of a lower discount rate is to value later benefits more than with higher discounts. Therefore larger loses in income in earlier periods by both greater and faster replacement than with a higher discount rate become acceptable.

The caption included in Fig. 9a shows that when *rd* is larger than 19%, the project becomes unprofitable. The value of discount rate that makes the NPV equal to zero (equal discounted incomes and expenditures) is known as the Internal Rate of Return (IRR).

Fig. 9b shows how the final structure is affected by *rd*. If the risk aversion of the grower is low (low discount rate), the differences among the most profitable varieties and the others is large. If the risk perception is low, larger investments are made in those varieties which seem to be more profitable. By contrast, a much more conservative scenario is obtained when the risk perception increases.

RB and G plantings are completely removed from the initial farm and replaced by other varieties if *rd* is lower than 11%, whereas beyond this value, such plantings are conserved in the final structure. On the other hand, AF, CP and GS are varieties less favored as the risk perception increases. By contrast, on RD and W plantings the opposite behavior is observed. This is not because more investments are made in these varieties, but because their old plantings are conserved into the final structure (data not shown).

5. Conclusions and future work

This paper presented an optimization model to aid in investment planning regarding the restructuring of pome fruit farms. From a formal point of view, the study falls within the scope of strategic planning of supply chains. The model can be considered as a general tool since it addresses a typical pome fruit farm, and considers usual practices. Moreover it can be easily adapted to become a decision making tool for similar systems (stone, grape, citrus fruit, etc.). The explicit incorporation of financial issues allows the model to be used either by governmental agencies to advise private sectors and to develop strategic economic policies, or by companies to optimize business profit.

The model was tested on a typical farm of the main pome fruit growing area in Argentina. Results showed that from the standpoint of density, there was a clear tendency to invest into high density plantings with early removal of low density ones. Medium density plantings were, in general, kept in the farm until their maximum life span was reached. Regarding varieties, the most profitable ones were planted with preference. The cut down/grafting method was employed on several occasions to allow rapid production entry of these varieties. However the harvest control constraints generated heterogeneous structures that helped to reduce the risks associated with single product business. The possibility of accessing to credit did not significantly affect the final structure of the farm, but it had a significant impact on the rate of transition between initial and final states.

Regarding sensitivity analyses, labor availability influenced both the profitability level and the final structure of the farm. Weekly productivity and profitability levels became conflicting objectives for large production requirements. Second, the sensitivity analysis on the initial budget presented an optimum beyond which no further benefits could be obtained for a given farm. Finally, the risk aversion factor showed a strong influence on taken decisions. At low discount rate values, large investments caused large changes in the farm structure. By contrast, more conservative scenarios were found at high discount rate values.

Although the scenarios considered in this article are in many senses a simplification of the reality, current general trends were reproduced satisfactorily with the proposed model. However, in order to reach definitive conclusions in specific cases, further analysis would be needed. For example, most of the parameters require long term forecasts (20 years). In particular, fruit sale price is very difficult to estimate in the long term since it depends on the worldwide fruit production and on the consumers' preference. When a new fruit variety enters the market, usually the price is large due to the combination of the high demand caused by the novelty and the relatively short supply due to limited production. As the variety begins to be produced worldwide, its price gradually decreases until it reaches an equilibrium value. In the reported studies, the fruit prices were considered constant throughout the whole planning horizon in their current values. However, the proposed model is well suited for designing the restructuring strategy of farms including varieties that are at some intermediate stage of its selling price life cycle, if such forecasts were available. This could be useful to analyze which is the best life cycle-moment to include a new variety in the farm structure.

Moreover, it should be noticed that the restructuring decisions proposed by the model over a 20-year horizon are not to be implemented in the practice in full extent. The obvious reason is that most of the parameters might significantly change in the midterm (fruit sales price, production costs, etc.) turning the original solution obsolete. Rather, it makes sense to implement the recommended solution only for the first few years and to run the model again from the resulting condition for another 20-year period with updated data. This "rolling horizon" approach is the most intuitive and straightforward way to cope with the great deal uncertainty that faces this type of industry. More sophisticated approaches are also possible, including scenario analyses and stochastic optimization.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agsy.2012.09.010.

References

Blank, L., Tarquin, A., 2002. Engineering Economy, fifth ed. Mc-Graw Hill Science/Engineering/Math, New York.

Cittadini, E.D., Lubbers, M.T.M.H., de Rider, N., van Keulen, H., Claassen, G.D.H., 2008. Exploring options for farm-level strategic and tactical decision-making in fruit production systems of South Patagonia, Argentina. Agric. Syst. 98, 189–198.

GAMS, 2009a. A Useŕs Guide. GAMS Development Corporation.

GAMS, 2009b. The Solvers Manual. GAMS Development Corporation.

Kearney, M., 1994. An Inter-Temporal Linear Programming Model for Pipfruit Orchard Replacement Decisions. MAF Policy Technical Paper 94/6.

Leskovar, M., López, A., Malaspina, M., Villarreal, P., Zubeldía, H., Bondoni, M., 2010. Costos referenciales de producción y empaque temporada 2010–2011, pera y manzana. Secretaría de Fruticultura de Río Negro, Subsecretaría de Producción y Desarrollo Económico de Neuquén, EEA Alto Valle INTA, Facultad de Ciencias Agrarias Universidad Nacional del Comahue.

Masini, G.L., Blanco, A.M., Petracci, N., Bandoni, J.A., 2007. Supply chain tactical optimization in the fruit industry. In: Papageorgiou, L., Georgiadis, M. (Eds.), Supply Chain Optimization. Wiley-VCH Book.

Masini, G.L., Blanco, A.M., Petracci, N., Bandoni, J.A., 2009. Optimal operational planning in the fruit industry supply chain. In: Erdogdu, Ferruh (Ed.), Optimization in Food Engineering. Taylor & Francis Book.

Oppenheim, P.P., 1979. A Linear Programming Approach to the Evaluation of Orchard Adjustment Strategies. Technical Discussion Paper No. 14. Department of Agricultural Economics and Farm Management, Massey University, New Zealand.

Oppenheim, P.P., 2003. The evaluation of orchard adjustment strategies: a linear programming approach to the development of rural policy in the SME sector. In: Proceedings of the 16th Annual Conference of the Small Enterprise Association of Australia and New Zealand, September 28th to October 1st, Ballarat, Australia, 2003.

Ortmann, F.G., 2005. Modeling the South African Fresh Fruit Export Supply Chain. MSc Thesis, University of Stellenbosch, South Africa.

Rodriguez, R., Villarreal, P., Romitelli, M., Lago, J., 2009. Reinjertación. Ediciones Instituto Nacional de Tecnología Agropecuaria (INTA). Estación Experimental Agropecuaria Alto Valle. Río Negro. Argentina.

Shapiro, J.F., 2001. Modeling the Supply Chain. Duxbury-Thompson Learning.

Villarreal, P., Romagnoli, S., Lago J., 2008. Economía: El valor de la inversión de una plantación de frutales de alta densidad. Ediciones Instituto Nacional de Tecnología Agropecuaria (INTA). Estación Experimental Agropecuaria Alto Valle. Río Negro. Argentina.

Ward, L.E., Faris, J.E., 1968. A Stochastic Approach to Replacement Policies for Plum Trees. Giannini Foundation Monograph No. 22. Division of Agricultural Sciences, University of California.