Journal of the Operational Research Society (2006) 57, 637–642 0160-5682/06 $30.00

www.palgrave-journals.com/jors

Orange harvesting scheduling management: a case study

JV Caixeta-Filho*

University of São Paulo, Piracicaba, SP, Brazil

The competitiveness of Brazil's citrus sector is a function of quality control in the transformation of fruit into juice. The transformation process commences with the harvest, the timing of which significantly affects fruit quality. In this paper, a mathematical model is formulated that links pertinent chemical, biologic, and logistic restrictions to the quality of the fruit to be harvested, applying linear programming theory. The modelling structure was verified and validated with real data from 320 Brazilian farms involved with an annual production of approximately 7 200 000 boxes of oranges. It could be attested that the maximization of the number of boxes of oranges to be harvested (strategy that is still adopted by a representative number of Brazilian citrus farmers, based on the industry advice) does not necessarily correspond to the maximum quantity of total soluble solids (TSS). In many cases, citrus harvested at the optimum *TSS* point offered higher concentrated juice productivity. The estimated potential benefits ($) from using the proposed model reached figures over 6%.

Journal of the Operational Research Society (2006) **57,** 637–642. doi:10.1057/palgrave.jors.2602041
Published online 14 September 2005

Keywords: linear programming; agriculture; scheduling

Introduction

Since the 1970s, the Brazilian orange sector's expansion has been nearly exponential. The improvement of orange yields is especially clear in the state of São Paulo; various orchards in the state have reached average yields of five 40.8 kg-boxes per tree, quite close to yields found in the USA. Currently the world's largest orange juice exporter, Brazil has remained a major player in the world market thanks to its oranges' good quality and the adverse circumstances affecting competitors.

The use of quality control devices, as in the case of orange harvest scheduling, is justified by the importance of product quality. Harvest management can be the responsibility of the processing industry or an individual owner/producer depending on the bargaining powers involved. Industry argues that an integrated harvesting system allows fruit to be harvested at the correct point of maturation to produce high-quality juice, and that quality control would be very difficult to maintain if each of São Paulo's 20 000 producers independently determined when to harvest.

As obvious as this reasoning may be, the processors have kept the *modus operandi* of their harvest scheduling devices a great secret. Even literature, both national and international, is extremely restricted regarding the documentation of strategies or tools used by citrus industries to determine harvest scheduling.

In order to define the harvesting point of a particular orchard, the fruit's maturation characteristics must be analysed. According to Lott (1945), maturation is the process of development in which fruits reach maturity through the increased concentration of sugars and decreased amount of acids (sugars represent over 70% of the orange's soluble solids, with organic acids, specially citric acid, accounting for another 10%).

Marchi (1993) comments that the increase of sugars occurs during the entire phase of fruit growth and maturation and is directly related to the intensity of the photosynthetic process, which in turn is linked with temperature, and light intensity. Acids are formed during the Krebs cycle, at the mitochondria of juice cells, with citric acid created first. Since the harvesting point is directly related to fruit maturity and accordingly to fruit quality, a set of explanatory indexes of this state can be determined.

There are several technical studies, published by researchers from different countries, which relate some of the chemical and biological characteristics of different varieties of citrus to the question of the quality of the fruit to be harvested. Morales *et al* (1990) in Colombia, Sunarmani (1991) in Indonesia, Viegas (1991) and Marchi (1993) in Brazil, Whitney *et al* (1994) in the USA, Ragone (1996) in Argentina, Lin *et al* (1997), in China; Blanke (1997) in South Africa, among others, associate the harvesting at optimum maturity stage to several characteristics of the fruits, which

*Correspondence: JV Caixeta-Filho, Department of Agricultural Economics, 'Luiz de Queiroz' Agriculture School, University of São Paulo. Av. Pádua Dias, 11 – 13418-900, Piracicaba, SP, Brazil.
E-mail: jvcaixet@esalq.usp.br

include juice content, titratable acidity, total soluble solids (*TSS*), ratio between total soluble solids and acidity (*Ratio*), and ascorbic acid content.

Halpern and Zur (1988) confirm that most citrus varieties have an ideal harvesting time when *TSS* is optimum. Consequently, fruits harvested at the optimum *TSS* point offered higher concentrated juice productivity. The main result of this work indicates that the increased *TSS* obtained ranges from 7 to 14% if the fruit is harvested at the optimum maturation point (in comparison to the fruit harvested at a middle maturation stage). It is, then, another indicator that industrial-purpose orange harvesting must be programmed taking into account the optimum maturation points of several citrus varieties. Such a strategy would directly benefit the industries and indirectly the producers, who would plant the varieties that were more suitable for the processing.

Methods for harvesting scheduling

The orange harvesting scheduling can be considered as a vital phase within the juice processing system, mainly due to quality of the final product. In view of that, a series of investigations was conducted to evaluate the possible means of increasing this quality, which did not appear to be a preoccupation for the Brazilian sector industry. This can be confirmed, for instance, by the majority of the existing producer payment contracts, based on the quantity of boxes harvested by the producer, without taking into consideration any quality aspect.

Nevertheless, the harvesting scheduling problem, independent of the product, has as basic characteristic what Clarke (1989) named as '*combinatorial aspects of cropping pattern selection*'. The reviewed literature confirmed the applicability of a few rich knowledge fields to this type of problem.

Under the mathematical programming approach, linear programming techniques have been the most used in harvesting scheduling problems, for various types of agricultural products. For *grains*, models were developed by Donaldson (1968), Morey *et al* (1972), Philips and O'Callaghan (1974), Fokkens and Puylaert (1981) and Deris and Ohta (1990); for *sugar cane* the models were developed by Guise and Ryland (1969), Crane *et al* (1982), Balastreire (1987), Gualda and Tondo (1991), Barata (1992). Another analogous application can be found in *forest management problems*, with examples been documented by Dias *et al* (1984), Chaudhuri and Sem (1987), García (1990) and Bettinger *et al* (1997).

However, considering mathematical programming approaches, examples of their use for orange harvesting scheduling problems were not found in the literature, the sugar cane and forest applications being the closest ones.

Regarding the mathematical structure of the models mentioned, however, a few comments are to be outlined. First, the matter of defining the endogenous decision variable, usually associated with the area to be harvested. Since the lands have been managed through some sort of farm area zoning (groves, lots, or any other analogous terminology), the value of the solution for such a decision variable must take into account whether or not to harvest that unit within a certain period of time or, more generically, such a decision variable should assume binary characteristics, like 0–1. Such a handling unit will have to be completely harvested, since the option of harvesting only one of its fractions does not make sense. At worst, the harvesting of unit fractions could be scheduled along the year, but characterizing the exploitation of the total area, which at first does not seem to be a viable practice in logistic terms (constant displacement of hand labour and equipment, for instance), and consequently not economically advisable.

Thus, it would be interesting to use integer programming to structure the modelling of such an application, as Higgins (1999, 2002) proposed to optimize sugar cane decisions regarding harvesting date and cropping cycle length in an Australian sugar mill region. Still, the units classified within a certain zoning pattern also consider aspects of crop homogeneity as, for instance, the prevalence of a given variety. With that, the harvest scheduling will be able to eventually offer not only the harvesting schedule per land but also per variety.

As to orange, the current situation consists of the maximization of the production of boxes of orange without any reference to the quality issue, which could be modelled through the incorporation of the *TSS* and *Ratio* characteristics. In terms of differences among products, apart from the obvious ones, one should note that the harvesting point for oranges would not only be related to the quality criterion but also to the amount of fruits available on the tree. Holding back the harvest of an orchard viewing gain on soluble solids will not necessarily be a good policy if the fruit fall alone makes that eventual benefit unfeasible. In addition, economic, operational, chemical, biological, and logistical restrictions are totally distinct for orange, since it is a crop that is much more vulnerable and sensitive to inclement weathers (see Ben Mechlia and Carroll, 1989a, b) demanding certain additional care regarding handling and administrative management.

The use of linear programming to structure an orange harvesting model, viewing the applications successfully performed in analogous crops, is the best choice, although with a few basic concerns: among them, implementing such structure in microcomputers and, accordingly, with lower cost and more accessible to most of the community involved; rationalizing the processing time for large models through the analysis of computer software, incorporating converging algorithms and also interacting with friendly interfaces for data input and report printings.

A modelling structure for orange harvesting scheduling is then elaborated through the use of tools capable of considering not only logistic characteristics of the process (eg transportation distances) but also specific characteristics of orchards (eg productivity) and fruits (eg soluble solid content). In that sense, a mathematical formulation necessary to represent the problem, liable of being solved by linear programming algorithms and flexible such as to solve the problem by fractional or integer linear programming, namely, with the option of fully harvesting one grove in 1 month only or harvesting it by parts, if workable and economically viable, is proposed.

The proposed model

Halpern and Zur (1988) argue that harvesting of citrus fruits for industrial processing should be performed by planned schedules for optimum maturity of the various orange varieties. In that sense, Rapisarda *et al* (2003) illustrate the behaviours of some chemical and biological characteristics of different varieties of citrus during fruit ripening (see Figure 1), confirming—for instance—that as oranges mature, the amount of soluble solids increases and their acid content decreases.

Therefore, ideally, farmers should pick the oranges only when the fruit contains the required levels of sugar and acid, to then send the production to the industry (see Figure 2). In practice, the industry itself should define a proper schedule for the growers that supply the oranges along the harvesting season. After the delivery of that raw material to the industry, the juice is mechanically extracted from the fruit to then be pasteurized as a means of eliminating harmful bacteria and enzymes.

Brazil, however, despite its leading position in the international market of orange juice, does not necessarily have many examples of planning systems that explicitly take

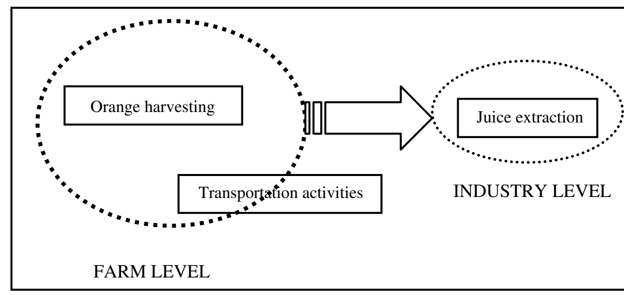

Figure 2 Schematic representation of the orange supply chain analysed in this study.

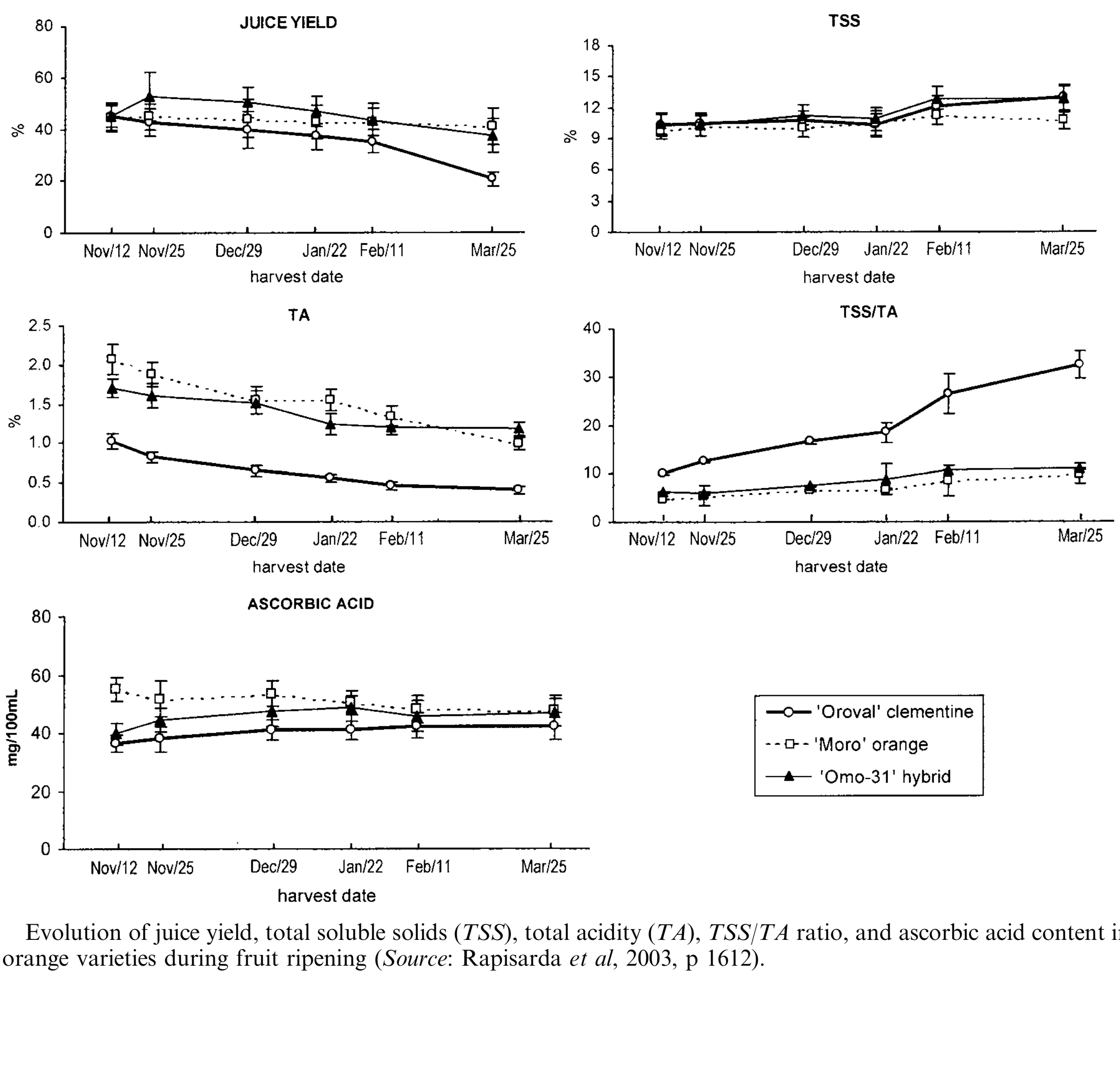

Figure 1 Evolution of juice yield, total soluble solids (*TSS*), total acidity (*TA*), *TSS*/*TA* ratio, and ascorbic acid content in juice of selected orange varieties during fruit ripening (*Source*: Rapisarda *et al*, 2003, p 1612).

into account the pertinent chemical, biological and logistical restrictions to the question of the quality of the fruit to be harvested.

In view of that, a mathematical formulation that considers as the main objective of the juice processing industry the maximization of the total soluble solids harvested, and not only the maximization of the number of boxes of orange to be harvested, is proposed. These objectives could be in conflict, since a great number of boxes could be harvested not necessarily at the peak of the citrus ripeness, affecting the quality of the extracted juice.

Also, the proposed model should consider the achievement of desirable levels of the index, simply called *Ratio*, that gives the relation between the *TSS* and the acidity level of the juice, which can reflect different levels of palatability of the juice to be processed.

Logistic restrictions are also incorporated into the model, such as the distance of the groves from the processor and the processing capacity of the industry.

The model to be proposed follows the basic structure of optimization models, with the maximization of a determined objective function, subject to several restrictions. The objective function is defined as being the *total margin towards profit* (M) to be received by the industry, that is

$$M = RSS - CTOTTR - CTOTCOLH \tag{1}$$

where RSS is the return from the commercialization of the orange juice, on account of the level of soluble solids, in US$, being

$$RSS = PSS \sum_i \sum_j PRO_{ij} TSS_{ij} T_{ij} \tag{2}$$

where PSS is the price of 1 kg of soluble solids, in US$; PRO_{ij} is the value of the production function for grove i, in month j, in boxes; TSS_{ij} is the content of soluble solids, measured from the maturation curve, for grove i, in month j, in kg/box; T_{ij} is the representative variable of the proportion of grove i to be harvested in month j.

$CTOTTR$ is the total transportation cost, in US$, being

$$CTOTTR = CUT \sum_i DIST_i \sum_j PRO_{ij} T_{ij} \tag{3}$$

where CUT is the value of the transportation cost function, in US$/box/km; $DIST_i$ is the distance of grove i from the industry, in km.

$CTOTCOLH$ is the total harvesting cost, in US$, being

$$CTOTCOLH = \sum_i \sum_j CUC_i PRO_{ij} T_{ij} \tag{4}$$

where CUC_i is the value for the harvesting cost function of grove i, in US$/box.

The alternatives for the optimization of the objective function, that is, the endogenous variables strictly speaking, are concerned with the possible harvesting scheduling combinations during the harvest season. For example, if $T_{ij} = 1$, grove i must be completely harvested during month j; if $T_{ij} = 0$, grove i should not be harvested in month j.

As to the constraints, they can be divided within three groups:

(a) Industry processing capacity, represented by

$$PROCMES_j \leqslant CAP_j \tag{5}$$

$PROCMES_j$ being the volume processed by the industry during month j, in boxes, where

$$PROCMES_j = \sum_i PRO_{ij} T_{ij}, \text{ and} \tag{6}$$

CAP_j is the industry processing capacity in month j, in boxes.

(b) Interval for the variation of the *Ratio*, represented by

$$RATIOMIN_{ij} \leqslant RATIO_{ij} \leqslant RATIOMAX_{ij} \tag{7}$$

where

$$RATIO_{ij} = R_{ij} T_{ij} \tag{8}$$

$$RATIOMIN_{ij} = RMIN_{ij} T_{ij} \tag{9}$$

$$RATIOMAX_{ij} = RMAX_{ij} T_{ij} \tag{10}$$

where Rij is the value of the *Ratio* function for grove i, in month j; $RMIN_{ij}$ is the minimum *Ratio* to be fixed by the industry to process a given type of juice from grove i in month j; $RMAX_{ij}$ is the maximum *Ratio* to be fixed by the industry to process a given type of juice from grove i in month j.

(c) Harvesting scheduling per grove, represented by

$$CRONOTAL_i = 1.0 \tag{11}$$

$CRONOTAL_i$ being the harvesting scheduling for grove i, in terms of the total proportion to be harvested within the season, where

$$CRONOTAL_i = \sum_j T_{ij} \tag{12}$$

Therefore, the basic harvesting scheduling modelling structure can be summarized as follows:

$$\text{Maximize} \quad M \tag{13}$$

subject to

$$PROCMES_j \leqslant CAP_j \tag{14}$$

$$RATIOMIN_{ij} \leqslant RATIO_{ij} \leqslant RATIOMAX_{ij} \tag{15}$$

$$CRONOTAL_i = 1.0 \tag{16}$$

To obtain an optimum schedule from the modelling structure proposed, certain management information could be achieved through auxiliary equations that will be able to be incorporated into the model. Thus, the information on revenue, costs and quantities of boxes or soluble solids can be grouped into the most convenient way for decision makers (for example, per grove, every month, according to orange variety and so on).

Application of the proposed modelling

This case study was initially motivated by the orange-juice industry which, in practice, due to its greater bargaining power over the producers, takes the main decisions related to harvesting scheduling. On the other hand, the producers, who have claimed for differentiated payments for their oranges, according to the quality of the harvested fruits, can also get important benefits through this modelling exercise.

In order to implement the modelling structure proposed by processing a set of representative data of a full season, data from a representative citrus enterprise were surveyed accounting for the production of 320 farms (most of them privately owned and some of them belonging or leased to the industry itself), with Hamlin, Pera (three distinct blooms), Natal and Valência (two blooms) as characteristic varieties. The production processed amounted to 7 200 000 boxes, with the mean productivity being 3.5 boxes/tree for Hamlin, 2.2 boxes/tree for Pera and 2.8 boxes/tree for Natal and Valência.

Each variety had distinct maturation and *Ratio* curves, depending on the bloom, with the acceptable interval for *Ratio* between 10.0 and 19.0. Notice that the data on orange production show an implicit fruit fall of 2% per month, after the farm reached *Ratio* 14. The cost of the crop varied according to the farm productivity and the transportation cost according to production and distance (in this case, US$ 0.004/box/km), with farms distributed, at most, 100 km away from the industry. Also, the processing capacity of the industry is estimated in 1 000 000 boxes/month.

The data on 320 farms were structured into a matrix of 5522 rows, 2677 columns and 46 199 nonzero elements, which was processed and solved with GAMS (Brooke *et al*, 1992) optimization package. The modelling structure proposed was then simulated—*Scenario I*—where *TSS* harvested are to be maximized. The same general modelling structure was also tested—*Scenario II*—considering that not the *TSS* but the number of boxes of oranges to be harvested are to be maximized.

From Table 1, the number of boxes obtained for *Scenario II* is always superior to the total boxes observed for *Scenario I*, with a slight variation of 0.16 to 0.75%, compared to *Scenario I*, according to the *Ratio* range. This apparent insignificant difference between the results, however, is not confirmed when the amount of soluble solids is verified for both scenarios: when assumed that the main objective of the harvesting is the maximization of *TSS*, the observed gains reached figures over 6% (see Table 2).

Table 1 Comparison between the number of boxes (10^6 units of 40.8 kg) harvested in *Scenarios I* and *II*

Ratio range	*14–15*	*13–16*	*12–17*	*11–18*	*10–19*
Number of boxes (II)	4.275	6.703	7.213	7.213	7.213
Number of boxes (I)	4.268	6.660	7.168	7.162	7.159
% difference	0.16	0.65	0.63	0.71	0.75

Table 2 Comparison between the total soluble solid (10^4 *t*) harvested in *Scenarios I* and *II*

Ratio range	*14–15*	*13–16*	*12–17*	*11–18*	*10–19*
Soluble solids (I)	1.139	1.825	1.990	2.006	2.017
Soluble solids (II)	1.135	1.777	1.900	1.900	1.900
% difference	0.35	2.70	4.74	5.58	6.16

Therefore, assuming that

- *Scenario I* is an alternative orange harvesting strategy for the Brazilian orchards sampled in this study,
- *Scenario II* is an approximation of what has been done in the majority of orange harvesting decisions in Brazil,
- for industrial purpose, the quality and price differentials of oranges in the international market are basically measured by the *TSS*,

it seems that the maximization of the number of boxes harvested does not correspond to the maximum *TSS*, a different assumption for some agents involved in the harvesting management.

Concluding remarks

The main contribution of this study concerns structuring a model for orange harvesting scheduling, supported by the theory of mathematical programming, including information on fruit maturation through indexes such as *TSS* and *Ratio*, which, by the way, were extremely adequate for that purpose. Furthermore, this mathematical structure has been gradually introduced in the managerial systems used by representative orange-juice industries installed in Brazil.

The potential dollar benefits from using the model, specifically for this case study, seem to be very evident once, in terms of the amount of soluble solids, the observed gains reached figures over 6%. Taking as a reference the price of soluble solids during the period of the study (US$ 2.30/kg) and the results for the *Ratio* range between 10 and 19 (see Table 2), the actual dollar benefits are related to extra 1 170 000 kg of soluble solids, which account for extra US$

2 690 000.00 in a season of 7 213 000 boxes of 40.8 kg, which could mean an additional US$ 0.37 per box.

A few limitations, however, must be emphasized so that new studies may be elaborated in order to minimize them. One of them is the reliability of the information on chemical and biological characteristics of fruits, as well as the transportation and harvesting cost functions. As it was possible to have access to a very reasonable quality of data of *TSS* and *Ratio*, this limitation did not affect the main results obtained for this case study. Nevertheless, such accuracy must be always pursued carefully, planning the orchard data sampling so that the corresponding equations can effectively be estimated and validated.

In this case, continuous care should be given to the validation of the structure of the model, a task that will be easier when the industry or producers themselves discuss the characteristics of the process modelled in this study. Certainly, that is a type of process, which can confirm the relevance of the proposed model not only to Brazilian growers and industries but also to some important players of the citrus sector who are developing their businesses in other different countries.

Finally, it is worth remembering that the need for adjustments in the harvesting scheduling structure is fully justified, since the gain in efficiency regarding competitiveness in the international market will no longer be marginal, which will certainly result in increased foreign exchange for the sector as well as for the country as a whole.

References

Balastreire LA (1987). Sugar cane harvesting optimization using microcomputers. In: Zhang D (ed). *Proceedings of the First International Conference on Agricultural Systems Engineering*. China Machine Press, Changchun, China, pp 557–566.

Barata MQF (1992). *Economic optimization of harvest and crop renewal of sugar cane*. MSc thesis, ESALQ/USP (Universidade de São Paulo): Piracicaba (Brazil).

Ben Mechlia N and Carroll JJ (1989a). Agroclimatic modeling for the simulation of phenology, yield and quality of crop production. I. Citrus response formulation. *Int J Biometeorol* **33**: 36–51.

Ben Mechlia N and Carroll JJ (1989b). Agroclimatic modeling for the simulation of phenology, yield and quality of crop production. II. Citrus model implementation and verification. *Int J Biometeorol* **33**: 52–65.

Bettinger P, Sessions J and Boston K (1997). Using tabu search to schedule timber harvests subject to spatial wildlife goals for big game. *Ecol Econ* **94**: 111–123.

Blanke M (1997). Fruit quality of citrus fruit in South Africa. *Erwerbsobstbau* **39**: 21–23.

Brooke A, Kendrick D and Meeraus A (1992). *GAMS: A User's Guide, Release 2.25*. The Scientific Press: San Francisco, USA.

Chaudhuri AK and Sem KM (1987). Optimum harvesting policy for an age-structured forest. *Int J Syst Sci* **18**: 1425–1432.

Clarke HR (1989). Combinatorial aspects of cropping pattern selection in agriculture. *Eur J Opnl Res* **40**: 70–77.

Crane DR, Spreen TH, Alvarez J and Kidder G (1982). *An analysis of the stubble replacement decision for Florida sugarcane growers*. Agricultural Experiment Station, Bulletin 822, University of Florida, Institute of Food and Agricultural Sciences: Gainesville.

Deris SB and Ohta H (1990). A machine-scheduling model for large-scale rice production in Malaysia. *J Opnl Res Soc* **41**: 713–723.

Dias GBN *et al* (1984). Integrated forest planning—Planflor. *CVRD-revista* **5**: 35–50.

Donaldson GF (1968). Allowing for weather risk in assessing harvest machinery capacity. *Am J Agri Econ* **50**: 24–40.

Fokkens B and Puylaert M (1981). A linear programming model for daily harvesting operations at the large-scale grain farm of the IJsselmeerpolders Development Authority. *J Opnl Res Soc* **32**: 535–547.

García O (1990). Linear programming and related approaches in forest planning. *N Z J Forest Sci* **20**: 307–331.

Gualda NDF and Tondo CM (1991). A large l.p. model for sugarcane crop planning. Paper presented in *TIMS XXX – SOBRAPO XXIII Joint International Meeting*, Rio de Janeiro.

Guise JWB and Ryland GJ (1969). Production scheduling and allocation: a normative decision model for sugar milling. *Aus J Agri Eco* **13**: 8–24.

Halpern D and Zur A (1988). Total soluble solids in citrus varieties harvested at various stages of ripening. In: *Proceedings of the Sixth International Citrus Congress*. Balaban Publishers, Tel Aviv, pp 1777–1783.

Higgins AJ (1999). Optimising cane supply decisions within a sugar mill region. *J Schedul* **2**: 229–244.

Higgins AJ (2002). Australian sugar mills optimize harvester rosters to improve production. *Interfaces* **32**(3): 15–25.

Lin FT, *et al* (1997). Studies on quality of 'Ma-tou' Wentan (*Citrus grandis Osbeck cv.'Ma-tou')* fruits. In: Chen YW and Chang LR (eds). *Proceedings of a Symposium on Enhancing Competitiveness of Fruit Industry*. Taichung District Agricultural Improvement Station, Taiwan, pp 77–91.

Lott RV (1945). The terminology of fruit maturation and ripening. *Proc Am Soc Horticult Sci* **46**: 166–173.

Marchi RJ (1993). *Maturation curves for orange variety 'pera' at Bebedouro region, SP*. MSc thesis, Jaboticabal (Brazil) FCAV/UNESP (Universidade Estadual Paulista).

Morales GRA, Salazar CR and Munoz FJE (1990). Production and development of nine varieties of orange *Citrus sinensis (L.) Osbeck* in the plain of the Cauca Valley. *Acta Agron* (Universidad Nacional de Colombia), **40**: 53–67.

Morey RV, Peart RM and Zachariah GL (1972). Optimal harvest policies for corn and soybeans. *J Agri Eng Res* **17**: 139–148.

Philips PR and O'Callaghan JR (1974). Cereal harvesting—a mathematical model. *J Agri Eng Res* **19**: 415–433.

Ragone ML (1996). Flowering, fruit-set and ripening in mandarin cultivars. *Horticul Argentina* **15**: 55–61.

Rapisarda P, Pannuzzo P, Romano G and Russo G (2003). Juice components of a new pigmented citrus hybrid *Citrus sinensis (L.) Osbeck* × *Citrus clementina Hort. ex Tan. J Agri Food Chem* **51**: 1611–1616.

Sunarmani S (1991). Quality assessment of fresh tangerine (*Citrus nobilis Lour.*) and its processed products. *Hortikultura* **30**: 5–11.

Viegas F (1991). Citrus product processing. In: Rodriguez O, Viegas F, Pompeu Jr J and Amaro AA (eds). *Brazilian Citrus Industry*. (Fundação Cargill), Campinas, Brazil, pp 898–921.

Whitney JD, Wheaton TA, Castle WS and Tucker DPH (1994). Optimizing orange grove factors for fruit production and harvesting. *Transact ASAE* **37**: 365–371.

Received January 2005;
accepted May 2005 after one revision