USING COMPUTER SIMULATION MODELS TO AID REPLANT PLANNING AND HARVEST DECISIONS IN IRRIGATED SUGARCANE

By

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Abstract

LARGE commercial sugarcane operations face complex replant planning decisions. The replant operation is costly and limited resources must be employed where they are likely to produce the largest yield improvement. These decisions are complicated further by the need to evaluate the benefit across multiple cutting seasons. Typically, replant field selection is based on historical performance, and poorest yielding fields on poorer soils tend to be prioritised for replant. However, this approach might not maximise estate-wide productivity. The decision making process needs to consider: which fields should be selected for replant in which season; what varieties should they be replanted back to; and what long-term harvest sequence should be followed to minimise harvest age effects; to maximise sucrose production in current and future seasons. A replant planning decision support framework was developed in CanePro, a commercially available Agricultural Management System, to assist with this complex task. Field selection was made by benchmarking actual field cane yields against potential yields discounted for soil type and ratoon using a soil type/ratoon matrix. Climatic potential yields were estimated using a simplified version of the CANEGRO crop simulation model. Each field's ideal replant ratoon age was estimated by maximising the total (across all fields) of the average (across all ratoons) expected yield of each field. Fields were assigned a replant date based on their ratio of current to ideal replant ratoon age within the estate's replant capacity constraints. Replant variety selection was made by optimising overall sucrose performance in a season using variety-specific sucrose curves. The harvest sequence was adapted to maximise overall sucrose production. To evaluate the methodology, four seasons of historical field data were obtained from a commercial operation in Swaziland. Actual estate practice was compared with the replant recommendations made using the CanePro framework. The relative performance of the scenarios was evaluated by comparing the overall sucrose yield simulated for each scenario. A 0.6% improvement was attributed to the CanePro field selection algorithm and a further 0.6% to the harvest sequencing algorithm

Introduction

Large irrigated commercial sugarcane operations form the backbone of many sugar industries in Africa, Latin America and Asia. Typically, these estates comprise one or more factories supported by miller-owned and managed nucleus estates. Often these agricultural operations are responsible for the bulk of mill supply and are used to ensure rateable delivery during the milling season. Estates range in size between 10 000 and 60 000 hectares but, on average, are between 10 000 and 20 000 hectares, typically made up of 1000–5000 fields. Management is usually well structured and competent, and required to meet strict production and budgetary targets.

The management of an operation this size is inherently complex, especially long-term replant decisions and variety selection following plough-out. Yield in successive ratoons tends to decline due to reductions in stalk population and mass, and an increase in stalk mortality (Chapman, 1988). The rate of yield decline depends on a range of factors, some inherent and others due to management practices employed (King *et al.* 1965). Inherent factors include sugarcane varietal characteristics and the crop's growing environment including climate, soil structure and inherent fertility. Examples of management factors include soil compaction, nutrition, water management, disease management etc.

The decision to replant a field is principally an economic one. At some point, maintenance of a ratoon crop under a certain yield may not be profitable (Bakker, 1999). A number of methods have been proposed to establish an optimum replant ratoon age based on economic considerations (Chinloy and Shaw, 1973; Hoekstra, 1976; Keerthipala & Dharmawardene, 2001; Simms, 1982).

However, these methods are difficult to integrate into a whole estate management plan and generally fail to acknowledge the limitations imposed by an estate's capacity to replant in term of replant period(s) and capital constraints on plant and equipment. The replant decision on these estates changes from one of optimum replant age, to one of maximising estate-wide productivity given a limited replant capacity. Limited resources must be employed where they are most likely to produce the largest overall yield improvement. These decisions are further complicated by the need to consider their effect on current and future seasons.

Estate practice

Replant planning involves three primary decisions. Firstly, which fields to select for plough-out, secondly, what varieties to plant fields back to and, thirdly, an optimum harvest sequence to satisfy a plough-out calendar while maximising average harvest age and overall sucrose production.

Current estate practice tends to prioritise fields based on their absolute performance in isolation. Fields on inherently weaker soils tend to be replanted more frequently. This practice assumes that replanted fields attain a similar plant yield irrespective of inherent soil limitations. This is often not the case and more productive fields are often overlooked. Additional considerations confound field selection decisions. Probably the most important constraint to the replant operation is capital which restricts the area that can be replanted annually. Management also need to consider other issues including changes to field layout, irrigation system redesign priorities and estate variety composition which could take precedence over purely agronomic considerations.

Variety selection following plough-out appears to be well managed on these estates. Most estates have a clear understanding of how varieties perform during the season, have identified a long-term variety composition strategy and select varieties to satisfy seasonal differences and soil suitability within the constraints of an ideal variety plan.

Harvest planning tends to be confined to the current harvest season. Field sequencing is usually only finalised prior to the season start and the harvest age of plough-out fields is often sacrificed to ensure that harvest dates coincide with replant periods.

In an effort to address some of these limitations and improve the decision making process around replant planning, a decision support framework was developed in CanePro, a commercially available agricultural management information system (MIS) widely used in the industry.

CanePro

Decision support systems of this nature lend themselves to an MIS. An MIS can cope with the large amounts of historical data required to assess field performance and integrate the decision making process over a large area and multiple cutting seasons.

CanePro is a sugarcane-specific MIS developed by SQR Software, a software development company based in South Africa. CanePro has been adopted by a large number of commercial estates in Africa and Central America. The system provides general management functionality such as field and agronomic record keeping, resource utilisation and planning, labour control and payroll, but also more specific decision support tools including irrigation scheduling, harvest planning and field performance benchmarking functionality. These tools make use of components of CANEGRO, a crop simulation model developed in South Africa.

CANEGRO is a daily time-step model developed along the lines of the IBSNAT (International Benchmark Sites Network for Agrotechnology Transfer) models for maize, wheat and soybean (Inman-Bamber, 1991, 2001; O'Leary, 2000). CANEGRO has been incorporated into the latest DSSAT (Decision Support System for Agrotechnology Transfer) suite of crop simulation models and is being validated internationally (Singels *et al.*, 2008). Models of this nature have developed to the point that they are becoming increasingly valuable in addressing strategic and technical issues in sugarcane agriculture (Inman-Bamber *et al.,* 2001).

CANEGRO is principally climate driven. The daily inputs can be obtained from a standard meteorological station measuring rainfall, radiation (or sunhours), temperature, wind speed (or run), and a measure of vapour pressure deficit. Under irrigated conditions, potential sugarcane yields can be defined as the capacity of the crop to utilise radiation and temperature without bias (Liu and Kingston, 1995). This potential yield estimate provides a benchmark yield against which actual yield can be evaluated.

Methodology

Potential and attainable yield benchmarks

Individual field performance for a particular harvest season can be evaluated by comparing actual yield against potential yield simulated for the duration of that crop. This performance ratio can be used to compare field performance without the bias imposed by seasonal growing conditions, both within a season and between seasons. This is a useful benchmark, but fails to acknowledge the decline in yield with successive ratoons and the rate at which yield declines on poorer soils relative to more productive soils. Process-level models such as CANEGRO are calibrated and validated on well-managed small-plot experiments and are currently unable to simulate ratooning ability and some management effects which are unavoidable in a commercial operation. To cater for these effects, a soil/ratoon matrix was developed to discount potential yields based on soil type and ratoon number. Estate-specific matrices were calculated by comparing actual and potential yield by ratoon for fields within defined soil types. Potential yield, corrected for soil type and ratoon, provided a second benchmark, termed attainable yield potential, against which actual yields could be evaluated (example in Figure 1).

Replant planning

The ratio of actual to attainable yield was considered a useful tool when ranking fields to be considered for plough-out and replant, and is a key element of the replant planning framework implemented in CanePro. The average value of this ratio over the last five cycles has been adopted as an indicator of a field's performance, and is assumed to continue to apply into the future, whether the field is replanted or not. The expected cane tonnage from a given field can then be estimated as the product of

- The field area;
- The field performance ratio;
- The relevant entry in the soil/ratoon matrix; and
- The potential yield

The potential yield is determined entirely by the meteorological conditions over the growing period. For longer-term decision making on replanting, we replace the potential yield by an annual average value based on long-term mean meteorological data. Under this assumption, only the first three items in the list above are field-specific.

The first objective of the replant planning algorithm presented here is to assign a maximum ratoon age (i.e. ideal long-term ratoon age at which to replant) to each field such that

- The total (across all fields) average (across all ratoons) expected cane tonnage (as defined above) is maximised; and
- The average area replanted per annum does not exceed the limit for the estate.

The replant planning module of CanePro includes an algorithm to solve this optimisation problem. It accepts as inputs: the area and field performance ratio of each field; the maximum area that can be replanted per season and the soil/ratoon matrix. The output is the ideal maximum ratoon age of each field. As one might expect, fields whose entries in the soil/ratoon matrix show a slow decline in yield with increasing ratoon are typically assigned a high maximum ratoon age, corresponding to infrequent replanting. Fields whose performance ratios are below average also tend to be replanted less frequently because the lower performance ratios will still apply after plough-out and hence reduce the benefits of replanting.

The field selection algorithm implemented in CanePro sorts the fields in decreasing order of the ratio of actual ratoon age to ideal maximum ratoon age. The fields at the top of the list are assigned the first available planting season until the replant capacity is fully utilised. A field is overlooked only if its age at the required cut date makes it a poor choice. The algorithm then proceeds to the next season in the planning period.

Variety selection following replant

The algorithm used to assign cane varieties to ploughed-out fields aims to maximise total sucrose production subject to any constraints on the variety mix. The sucrose content of cane will typically show seasonal characteristics that depend on the cane variety. A polynomial curve was fitted to historical data on sucrose content by time-of-year for each cane variety. The polynomial curves are used to estimate the performance of each variety on each day of the cutting season, and thereby determine the optimal variety mix. This is reconciled against the variety mix of fields not being replanted, and the remainder used to determine which varieties should be introduced on ploughed-out fields so as to yield the greatest benefit in sucrose production.

In practice, decisions on variety selection are often constrained by external factors. The variety selection algorithm accommodates constraints on the minimum and maximum areas of each variety that can be planted in each planting period, and these can be used to limit the overall variety mix.

Field harvest sequencing

Once fields have been identified for replanting in future seasons, the cutting plans must be modified to ensure that fields to be ploughed-out are harvested in a timely manner and at acceptable cut ages. The CanePro replant planning module incorporates a harvest planning tool that determines an appropriate cutting sequence for each season in the period of interest.

Fields identified for replant are assigned fixed cut dates in the last season before plough-out, and their cut dates in intervening seasons are assigned using a constant cut age. Fields not selected for replanting are then added to the harvest plan in such a manner that the oldest cane is cut first. In this manner, a harvest sequence that is compatible with the replant plan can be determined for each season.

An attempt was made to optimise the harvest sequence so as to maximise total sucrose production within the constraints of the replant plan. The algorithm exploits the differences in the shape of the sucrose curves by exchanging fields in the sequence where it would increase the overall sucrose yield. Fields due for imminent replanting are constrained in terms of how far they can depart from their assigned cut dates, but the cut sequence of the remaining fields is guided by the expected sucrose production. For each field, this is estimated using the cane yield from the CANEGRO model adjusted by each field's performance ratio and the sucrose polynomial for that cane variety.

Case study

A case study was conducted using data from a commercial operation in Swaziland. The purpose of the study was to evaluate and compare a number of scenarios. All scenarios were based on the same (actual) data, but differed with respect to replant decisions. All scenarios were evaluated using the same technique, viz. by estimating cane yields as described earlier and using fitted sucrose curves for sucrose yield estimation. The relative merit of the replant decisions in each scenario was gauged from the simulated total sucrose production.

Soil/ratoon matrix

The soil/ratoon matrix was calculated using field history records between 1983 and 2008. Soils were grouped into soil classes as defined by Nixon (1986). Only fields comprised of >80% of a single soil class were included in the analysis. The average performance ratio (actual/potential yield) by season was plotted against ratoon and a linear regression fitted for each soil class (Table 1).

As expected for a commercial dataset of this nature, the scatter was relatively large as indicated by the low correlation coefficients (R^2) and the large root mean squared errors (RMSE). However, all five regression models were highly significant and described the relative productivity of the soil classes in line with commercial estate experience (Figure 1).

Table 1—Soil/ratoon matrix regression analysis for the case study.

Soil class	No. values	Slope	Intercept	R^2	RMSE
Class I	243	0.009	0.900	0.19	0.09
Class II	65	0.010	0.811	0.10	0.11
Class III	249	0.013	0.873	0.37	0.07
Class V	80	0.018	0.870	0.27	0.11
Class VI	103	0.028	0.815	0.30	0.07

Replant plan

Four recent consecutive seasons of historical data were included in the study. No significant change in irrigation systems or field disposition had taken place during this time, and no fields had been ploughed out specifically to change their variety. Hence, all replant decisions during this time had been based on yield improvement.

A total of 1400 fields were included in the study and 538 of these (approximately one-third) had actually been replanted during this period. The replant periods within which planting took place (typically from July to November of each season) and the total areas replanted were determined from the historical data, and were used as a constraint on any alternative replant plan that was proposed. Similarly, the fallow periods following plough-out were typically between 8 and 11 weeks in duration, and were observed when determining dates of last harvest prior to planting.

Three scenarios were considered. The first was based on the actual replanting decisions during this period, and a second constructed using the plantings recommended by the field selection technique described earlier. A third scenario using no replanting was included for comparison purposes. In each scenario, a harvest plan was calculated for the four seasons of interest. The simulated tonnage of sucrose produced over the four seasons was then used as a measure of the relative benefit of each replant plan.

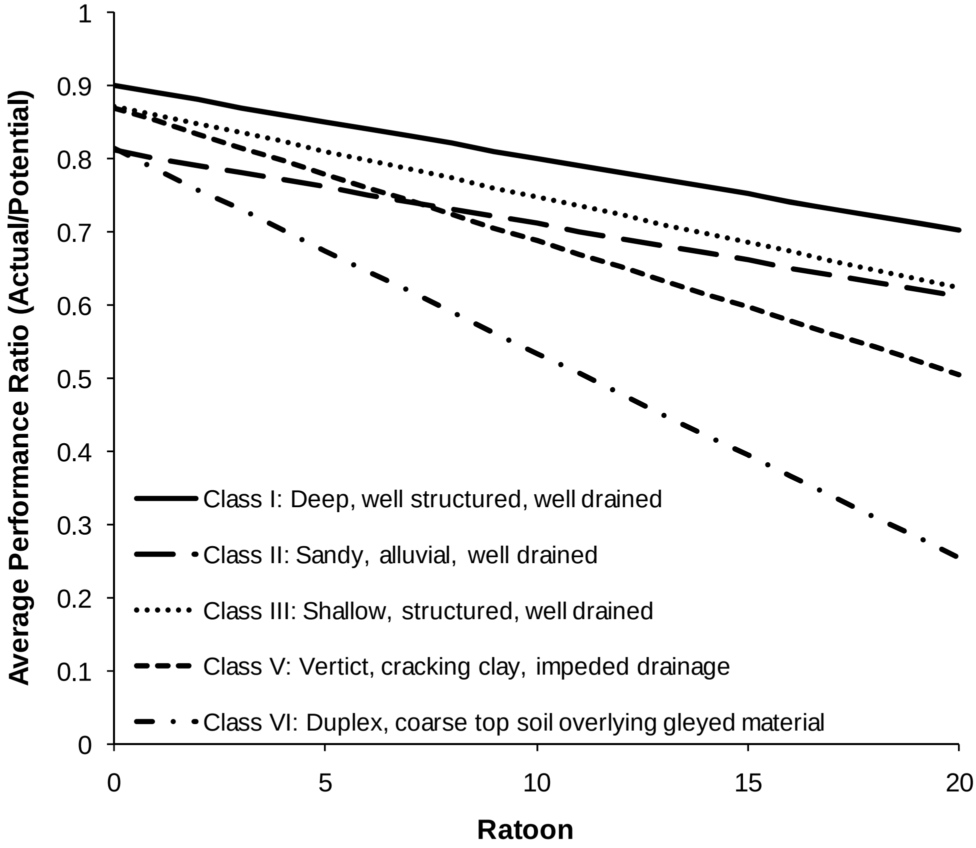

Fig. 1—Graphical representation of the soil/ratoon matrix used in the case study. Soils were grouped into land classes as defined by Nixon (1986).

The harvest plans were calculated using actual mill crush rates, and the field harvest sequence was determined as described earlier. Fields were cut at the rate required to meet the demand for cane by the mill. The cane yield for each field was estimated as the product of its historical performance ratio and the attainable yield potential at the planned harvest date.

Results

The three scenarios were first evaluated using the same cane variety for all fields in all seasons. This was done to isolate the effect of the field selection by preventing small differences in the variety mix from influencing the results.

The outcomes are compared in the 'field selection' row of Table 2. The replant plan based on the field selection algorithm produced 0.6% more sucrose than the actual replant plan over the four seasons. However, both replant plans produced a benefit of less than two percent over the scenario having no planting. The results suggest that the field selection algorithm may be a reasonably good one, but that the scope for gains via field selection is rather limited.

A second set of simulations was conducted to test the effect of the modified field harvest sequence. These simulations made use of the full range of cane varieties. The harvest plan for each scenario was first calculated based on the 'oldest first' cutting sequence that is used by many estates. The scenarios were then re-evaluated using the harvest sequence optimised for sucrose production.

The results are shown in Table 2 in the 'cutting sequence' row. In each scenario, the modified cutting sequence produced an advantage over the standard sequence. The magnitude of the advantage depended partly on the degree to which the variety with the most distinctive sucrose curve had been incorporated in the replant plan. The plan recommended by the software considered this a preferred cane variety, and the modified cutting sequence produced 0.6% more sucrose than the standard cutting sequence.

In each scenario, the migration of fields within the cutting sequence towards their preferred time of harvest was clearly evident when comparing the adjusted cutting sequence from one season to the next. The total sucrose produced in the first season was typically the same regardless of which cutting sequence was used. This is because the change in each field's cutting sequence caused a departure from its ideal cut age, and this countered the benefit in sucrose yield. However, the advantage of the adjusted cut sequence increased with each season, as the cut age began to stabilise. By the fourth season, the total sucrose produced using the adjusted cutting sequence was one percent higher than when using the standard cut sequence, without any increase in cane production. These results applied equally to all three scenarios.

Table 2—Total sucrose production after four seasons estimated for the three scenarios evaluated in the case study.

	No planting	Actual plantings	Recommended plantings
Field disposition			
Total field area (ha)	20 992	20 992	20 992
Area replanted (ha)	0	7079	7029
Fields replanted	0	538	464
Field selection			
Sucrose produced with single variety (t)	1.158 m	1.174 m	1.181 m
Benefit of planting (%)		1.4	2.0
Cutting sequence			
Sucrose produced with all varieties using oldest-first sequence (t)	1.160 m	1.175 m	1.186 m
Sucrose produced with all varieties using modified cut sequence (t)	1.166 m	1.183 m	1.193 m
Benefit of sequence optimisation (%)	0.5	0.7	0.6

Conclusions

Although relatively small, this potential increase in productivity was obtained with no increase in expenditure. The increase in productivity can be attributed entirely to better decision making. In addition, it is worth noting that this estate is technically well managed and has access to reliable field records through the CanePro MIS to aid decision making. Yield benefits may well be greater for estates with limited access to technical expertise and poorer information availability. Providing access to technical expertise is one of the advantages offered by an MIS such as CanePro. Technically complex concepts, often not readily available to commercial managers, can be harnessed in a user-friendly interface as part of an MIS to aid commercial decision making.

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UTILISATION DES MODELES DE SIMULATION PAR ORDINATEUR POUR AIDER AUX PROGRAMMES DE REPLANTATION ET DE RECOLTE DANS LA CANNE IRRIGUEE

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Résumé

LE PROGRAMME de replantation est complexe dans les grandes exploitations commerciales de canne à sucre. La replantation coûte chère et des ressources limitées doivent être utilisées pour améliorer au maximum les rendements. Ces décisions se compliquent davantage par la nécessité d'évaluer les bénéfices sur plusieurs saisons de coupe. En général, le choix du champ à être replanté est basé sur les performances passées et les champs à faibles rendements sur les sols pauvres ont tendance à figurer parmi les priorités pour la replantation. Toutefois, cette approche n'optimise pas la productivité globale de l'exploitation. La décision prise doit prendre en compte la saison dans laquelle certains champs doivent être replantés; les variétés qui devraient être replantées; et quelle séquence de récolte à long terme doit être suivie pour minimiser les effets de l'âge de la récolte et pour optimiser la production de sucre dans la saison actuelle et future. Un programme a été développé par CanePro, un système de gestion agricole disponible sur le marché, pour aider à la décision de replantation et faciliter cette tâche complexe. La sélection des champs a été faite par l'analyse comparative des rendements actuels et les rendements potentiels en prenant compte du type de sol et de la repousse. Les rendements potentiels dus au climat ont été estimés à l'aide d'une version simplifiée du modèle de simulation de culture CANEGRO. L'âge de replantation des repousses idéal de chaque champ a été estimé en maximisant (dans tous les champs) le rendement total moyen attendu (à travers toutes les repousses) de chaque champ. Les champs ont été assignés une date de replantation en fonction de leur rapport de l'âge actuel et idéal des repousses, en prenant compte des contraintes de capacité de replantation de l'exploitation. Les variétés sélectionnées pour la replantation ont été faites pour optimiser les performances globales de sucre dans une saison à l'aide de courbes pour des variétés spécifiques. La séquence de récolte a été adaptée pour optimiser la production globale de sucre. Pour évaluer la méthodologie, quatre saisons de données historiques ont été obtenues d'une exploitation commerciale au Swaziland. La pratique actuelle a été comparée avec les recommandations pour la replantation à l'aide du programme CanePro. Les performances relatives des différents scénarios ont été évaluées en comparant le rendement global de sucre simulé pour chaque scénario. Une amélioration de 0.6% a été attribuée à l'algorithme de sélection du champ fait par CanePro et une amélioration supplémentaire de 0.6% à l'algorithme de séquence de récolte.

USO DE MODELOS DE SIMULACIÓN PARA LA PLANEACION DE RE SIEMBRA Y LA TOMA DE DECISIONES DE COSECHA EN CAÑA DE AZUCAR CON RIEGO

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Resumen

LAS OPERACIONES comerciales a gran escala en las plantaciones de caña de azúcar enfrentan complejas decisiones de resiembra. La operación de resiembra es costosa y se deben utilizar recursos limitados donde se espera que produzcan una mejora significativa en la producción. Estas decisiones se complican más aun con la necesidad de evaluar el beneficio a través de múltiples cortes. Típicamente, la selección de un campo para resiembra se basa en el rendimiento histórico, y los campos con los rendimientos más bajos en los suelos más pobres son priorizados para la resiembra. Sin embargo, es posible que esta estrategia pueda no maximizar la productividad del estado o región. Este proceso de toma de decisión necesita considerar: qué campos deben ser seleccionados para resiembra en que años, qué variedades se deben sembrar y que secuencia de corte se seguirá a largo plazo para minimizar los efectos de la edad de corte y para maximizar la producción de sacarosa en la época de corte actual y en las subsiguientes. Un marco para la toma de decisiones en re siembra se desarrolló con CanePro, un sistema de manejo agrícola comercial, para ayudar en esta tarea tan compleja. Se seleccionó el campo estudiando el rendimiento real del área contra rendimientos potenciales descontando los efectos del tipo de suelo y soca, usando una matriz tipo de suelo/soca. Rendimientos potenciales climáticos fueron estimados usando una versión simplificada del modelo agrícola CANEGRO. Se calculó la edad ideal de soca para la resiembra de cada lote, maximizando el total (a través de todos los lotes) del promedio (a través de todas las socas) del rendimiento esperado para cada lote. A cada lote se asignó una fecha de resiembra, basado en el radio de la edad actual a edad ideal de la soca para resiembra dentro de las limitantes de la capacidad de resiembra del estado. La selección de las variedades para la resiembra se hizo optimizando todo el desempeño varietal en una zafra, usando curvas de sacarosa específicas por variedad. La secuencia de corte se adaptó para maximizar la producción total de sacarosa para evaluar la metodología, se obtuvieron datos históricos de la operación comercial de 4 años para un área de Swazilandia. Las prácticas actuales se compararon con las recomendaciones de re siembra obtenidas con CanePro. El desempeño relativo de los escenarios se evaluó comparando la producción total de azúcar para cada escenario. Un 0.6% de mejora se atribuyó al algoritmo de selección de lotes de CanePro y otro 0.6% al algoritmo de secuencia de corte.