MONITORING AND DECISION-MAKING PROCESSES FOR OPERATING AGRICULTURAL PRODUCTION SYSTEMS

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SUMMARY

Agricultural systems contain many inter-relationship factors which are uncertain or even unknown. Forecasting future situations is a difficult task under these uncertain conditions. Agricultural systems, however, are relatively flexible and can be adapted to new and unforeseen situations. Therefore, it is of importance to operate agricultural systems in such a way as to use their flexibility as a means of compensating for possible losses, and to take advantage of unforeseen events.

One of the models which might be suitable for operating real agricultural systems under uncertainties is the Sequential Ad-hoc Linear Model. Detailed descriptions of two of the basic processes of this model, namely those of monitoring and decision making, are given in this paper. Examples taken from a real agricultural system are presented to demonstrate the application of the methodology.

INTRODUCTION

The planning and operation of agricultural systems are strongly affected by the unique properties of these systems. The basic production functions are not fully known quantitatively. Natural resources are widely used as inputs imposing their stochastic behaviour on the systems. Consequently, forecasting future situations, especially for multi-activity systems, is a difficult task and, as a result, deviations from the plan are often necessary even when the plan is based on the best data available at the planning time. The unforeseen deviations might cause losses but might also be of advantage when adequate steps are taken.

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Fortunately, agricultural systems have another property—flexibility—which might be expected to compensate for the losses if and when this property is properly used. Especially in multi-activity systems (several crops, livestock, orchards, etc.), it is possible to change crops and modify activities even during the growing season using almost the same resources and know-how. On the other hand, the flexibility might bring about unpredicted and uncontrolled processes if the farmer or the decision-maker does not act to control the changes.

Time is another main factor that affects the management of agricultural systems. Almost all of the agricultural factors and processes are time dependent. Time has two contradictory influences on planning and operating agricultural systems: (a) it usually enables improvements to be made in the estimation of most of the factors such as crop yields, climate factors, market prices and resource availability and (b) it reduces the flexibility of the system, i.e. reduces the number of possible alternatives which are both feasible and economically justified. In other words, any delay in making a decision enables one to use more accurate data for planning but, at the same time, diminishes the capacity of the planner to adapt the system to the new data.

In order to be able to act optimally in situations which change frequently, the decision-maker has to be equipped with an appropriate managerial tool. Such a tool should comprise the following three elements: (a) planning—a method for selecting the best plan based on the data available at the planning time; (b) monitoring—a means of collecting current data in order to diagnose changes and to process the information in a way suitable for further decisions and (c) a dynamic decision-making process—a means for adapting the system to the diagnosed changes in order to keep it optimal.

Amir & Shamir (1972) have suggested the Sequential Ad-hoc Linear Model as a suitable concept and as a model which includes the above three elements.

The purpose of this paper is to present this model in general and to present in detail two of these three elements, namely, the monitoring and the dynamic decision-making processes. It contains the mathematical background, the agricultural management considerations involved, examples and an application for a real situation in Israel.

THE SEQUENTIAL AD-HOC LINEAR MODEL—SALM

SALM comprises the three elements mentioned above, where the planning and the dynamic decision-making processes are carried out at specified time intervals while the monitoring process is performed continuously.

The planning process

This process is based on the following linear programming (LP) formulation:

$$\max.\ z = \mathbf{cx} \tag{1}$$

subject to:

$$\mathbf{Ax} \leq \mathbf{b}; \qquad \mathbf{x} \geq \mathbf{0}$$

where: z is the objective function value which is the net income of the system; $\mathbf{c} = \{c_j\}$ is the vector of net income coefficients, $j = 1, \ldots, n$; $\mathbf{x} = \{x_j\}$ is the vector of activities which are the decision variables, $j = 1, \ldots, n$; $\mathbf{A} = \{a_{ij}\}$ is the technological $n \times m$ matrix, the elements of which are the demand of the ith resource by a unit of the jth activity; and $\mathbf{b} = \{b_i\}$ is the vector of the resources levels, $i = 1, \ldots, m$.

The elements b_i and c_j are usually random variables, for each of which the planner selects a value at the planning time. The planning values of b_i and c_j are statistical expectations when their probability distribution functions are known, or any other subjective estimation when the statistical expectation is unknown. The arguments for preferring the expectations as the planning values are given by Madansky (1960). The existing state of the system is introduced into the linear programming formulation by appropriate constraints and the decision variables are the possible activities. At the planning time, the allocation of the resources of the system is fixed. The resulting deterministic linear programming is then solved to yield the values of the decision variables such that the expected net income is maximised. A post-optimality analysis yields the range of validity of the optimal solution for variation in the values of the random prices and resources.

The monitoring process

Two different types of monitoring process need to be carried out in agricultural systems: comprehensive monitoring and operational monitoring.

The comprehensive monitoring process handles all of the activities in the system—production, marketing, stocking, manpower management, finances, social and municipal activities, book-keeping, contracts, etc. This process is essential in achieving an accurate balance of the whole system and the feasibility of every activity in it. Because of its comprehensive nature, this process takes a long time to develop reports, summaries and conclusions—longer than can be allowed by the decision-maker who needs to adapt his decision rapidly to follow changing conditions.

A process more suitable for dynamic decision making is the operational monitoring process which has to respond within a short time. This process is a part of the comprehensive monitoring process and deals only with data directly concerned with the production functions such as land areas, water, labour, mechanical equipment, agronomic data, expenditures, etc. This limited process collects frequently the latest information available and brings all of the activities to a common economic denominator at that point in time where the system is re-evaluated and new decisions are considered. The common denominator is essential since the various activities are at different stages of execution and, therefore, without using it decisions might be biased.

The operational monitoring process will now be described.

Consider first the updating of a net income element c_j:

$$c_{jk} = D_{jk} - E_{jk} \qquad (2)$$

where: c_{jk} is the net future income for the jth activity calculated at the kth point in time; D_{jk} is the gross income for the jth activity estimated at the kth point in time; E_{jk} is the input to be invested for the jth activity from the kth point in time to the end of the growing season when the income is materialised; and k is a point in time (herein expressed in months).

Figure 1 presents graphically the elements of eqn. (2) for a typical crop activity.

At the beginning of the growing season of the jth activity, where $k = 0$, the expected gross income is D_{j0} and E_{j0} is the amount for inputs required to materialise D_{j0}. Since $k = 0$, E_{j0} is the total input and includes the inputs which are distributed over the growing season. c_{j0} is the net income according to eqn. (2).

For the kth decision-making period, another estimation of the gross income results is a new D_{jk}. Since several inputs have already been invested, E_{jk} is usually smaller than E_{j0}, expressing that amount of inputs still to be invested in order to materialise the new D_{jk}. c_{jk} is the current net income which is generally greater than c_{j0}.

Similar procedures are applied for all the activities. As a result, each activity has its own c_{jk} value expressing its net income at the kth decision-making period.

These c_{jk}'s, for all of the activities, are the requested economic common

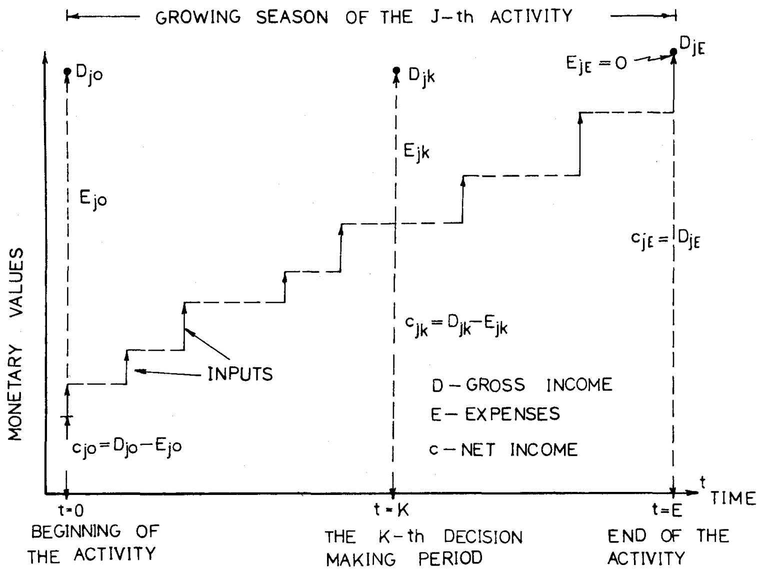

Fig. 1. Graphical presentation of the net income c_{jk} of the jth activity as a function of time.

denominator where its economic value is the expected incomes minus the inputs to be invested in order to materialise them.

In multi-activity systems, there usually exist three types of crop activities at any point in time: (a) crops which have been planted, (b) planned crops which are in the optimal solution but still waiting for execution and (c) those which have been rejected from the optimal solution but are still feasible. When re-evaluation of the entire system is required, all of these types have to be brought to a common economic denominator, otherwise the choice between them is distorted. (Such an economic common denominator is the c_{jk}—for all of the types, c_{jk} expresses the expected net income or the final income minus the inputs needed to achieve it.) For the planted crops, where $k > 0$, c_{jk} is usually greater than the original value since some expenditures have already taken place, the b_{jk} is shrinking over time and the relevant crop gets a 'premium', which is $c_{jk} - c_{j0}$. The other two types of crop activities either remain with the original c_{jk} value, c_{j0}, or are changed to new ones due to new information available.

The term 'premium' requires additional explanation. This premium rises from the fact that the expenses which have been invested prior to the decision-making time are neglected. This is done in order to reflect the decision-maker's main concern in maximising the future net income at every point in time. Accordingly, the remainder of the inputs required to materialise the income at harvest time is shrinking over the time and thus the future net income increases. Therefore, if D_{j0} has not changed significantly the planted crop has a higher future net income value compared with its original value and has an additional economic advantage—a 'premium'.

An example taken from the application of the monitoring process will clarify this notion of the 'premium' and the considerations involved. Cotton, in Israel, is seeded during April and harvested during October. In our case, the expected yield was 400 kg/dunam (1 dunam = 0·1 ha = 1000 m^2) and the expected income, D_{c0}, was 400 × 1·80 IL/kg or 720 IL/dunam (where IL = Israeli pound = approximately 0·24 US dollars). The expenses are distributed over the growing season and consist of agromechanical treatments, water, labour, sprays and other materials. The total expense, B_{c0}, was 490 IL/dunam. Therefore, $c_{c0} = D_{c0} - E_{c0} = 720 - 490 = 230$ IL/dunam, where the subscript c stands for cotton and the subscript 0 denotes that the evaluation was carried out at time $k = 0$ (October) before the cotton growing season. In June (where $k = 8$), one learned from the operational monitoring process that 358 IL/dunam had already been spent on the cotton, and, by checking the field, the farmer estimated the yield to be 270 kg/dunam due to a severe attack of pests in May. (This attack was the reason for re-evaluation.) The calculations according to eqn. (2) are:

$$D_{c8} = 270 \times 1{\cdot}80 = 486 \text{ IL/dunam}$$

and

$$C_{c8} = D_{c8} - E_{c8} = 486 - (490 - 358) = 486 - 132 = 354 \text{ IL/dunam}$$

where 132 IL/dunam were the expenses needed until the end of the growing season to achieve the gross income of 486 IL/dunam. (In practice, in most cases, the remainder of the expenses would not be 132 IL/dunam because of the low yield. These figures are given to show the considerations involved in principle.)

If the decision-maker had known this situation in advance he would not have seeded the cotton at all since under such conditions the cotton would not be profitable: the gross income is 486 IL/dunam and the expenses 490 IL/dunam. Since the new evaluation is in June, the cotton received a 'premium' and the expected net income of 354 IL/dunam is even larger than the original value of 230 IL/dunam. This is because only an additional 132 IL/dunam are required to achieve the new gross income of 486 IL/dunam. Terminating the cotton crop at this time would be irrational unless there was a better alternative. Such an alternative to the existing cotton should have an initial c_{j0} equal to or greater than 354 IL/dunam. In this case, an alternative could not be found.

The farmer still had the possibility of deciding whether to harvest the cotton during October in a single harvest, thus losing approximately 15% of the yield, or to harvest it a second time in November, when he would have the additional yield but lose the possibility of preparing the field for wheat (wheat is seeded during early December). Such considerations are evaluated by the last process of the Sequential Ad-hoc Linear Model—the decision-making process.

The decision-making process

This process is the means for interpreting the variations in the data diagnosed by the monitoring process and for determining the optimal actions to be taken in the future. The mathematical background of the decision-making process is based on duality theorems (Dantzig, 1963; Hadley, 1962 and many others). From these theorems, one can derive two conditions for continued optimality of the solution in cases where changes in the original data occur:

$$\mathbf{B}^{-1}\hat{\mathbf{b}} \geq \mathbf{0} \tag{3}$$

and:

$$\hat{\mathbf{c}}_B\mathbf{B}^{-1} \geq \mathbf{0} \tag{4}$$

where: $\mathbf{B}^{-1}$ is the inverse basis matrix of the optimal solution ($\mathbf{B} \in \mathbf{A}$); $\hat{\mathbf{b}}$ is the updated restraint vector $\mathbf{b}$; and $\hat{\mathbf{c}}_B$ are the updated net income vector $\mathbf{c}$ for the basic variables.

If eqns. (3) and (4) are met in spite of the changes included in $\hat{\mathbf{b}}$ and $\hat{\mathbf{c}}_B$, the optimality of the solution is maintained. While adopting these conditions to decision-making in crop systems, two main cases arise: (a) all of the planned crops have already been planted and (b) not all the planned crops have been planted, i.e. some have still to be started. It is usually impossible to increase the area of a planted crop. If an increase is possible, the time interval between two successive decision-making times (say a month) is large enough to justify calling the addition a different activity with a new c_{jk}. On the other hand, there still exists the possibility of reducing the area of an existing crop and of changing the purpose of the crops.

The policy in case (a) involves the following consideration. As indicated above, it is possible to reduce the area of an existing crop but not to increase the area of another existing crop. Therefore, while reducing the jth activity by Δx_j, one forgoes in advance the income of this land area—which is $\Delta z_{jk} = c_{jk} \Delta x_j$. Since $c_{jk} > 0$ (otherwise this jth activity would not be relevant), the previous income will be at least as large as the new one. However, one might change the previous purpose of the existing crop by harvesting it earlier than had been planned, maintaining eqn. (4). This situation allows a feasible alternative in which a new crop can be seeded earlier than had been planned but, at the same time, it means that a new activity enters the optimal basis. Thus, the previous basis is no longer valid. Therefore, the choice in case (a) is *laissez-faire* if the basis stays optimal or to change the non-optimal basis to a new optimal solution based on the new vectors up-dated by the monitoring process.

More complicated considerations are involved in the policy regarding case (b). In this case, the decision-maker has several choices: (1) to change a planned crop to be planted on a particular field, and/or (2) to reduce or to expand land areas of some planned crops without any exchange and/or (3) to change the purpose of both executed and planned crops. All the above possibilities must maintain the validity of the mathematical conditions expressed in eqns. (3) and (4).

The relevant considerations in these three choices are as follows: Regarding possibility (1), changing the land areas of planned crops must be performed such that the validity of the optimal basis is maintained. The admissible ranges for such changes are obtained through a post-optimal sensitivity analysis of the solution of planning time. A reason for change might arise due to variations in prices and/or resources. In such cases, there is no reason for a partial change in area unless at least one constraint forces it. Therefore, this constraint is no longer on the basis of the optimal solution. Regarding possibility (2), decreasing areas without an exchange means that the decision-maker forgoes at least part of the expected income. Although this is mathematically permitted, it is irrational. On the other hand, expanding the planned activities' areas is both possible and mathematically permissible, on the condition that the decision-maker must examine the ranges of the validity of the optimality of all the factors involved. Regarding possibility (3), changing the purpose of existing activities yields the same considerations as in case (a). For the planned activities (those which have not yet been executed), there might be alternatives which involve changes in the area of land and/or crop yields, maintaining the conditions of optimality valid. In practice, such alternatives, however, would be very limited in size. They have to be economically justified in addition to maintaining the two conditions for optimality.

Consequently, except in a few situations, the decision-maker has one clear choice: *laissez-faire* when the criteria of the optimality (eqns. (3) and (4)) are maintained, or solving a new LP problem, based on current information, for the next planning horizon. The duration of the next horizon still remains a subject to be dealt with. From experience in this application, it is recommended that the horizon be that of the planning process starting at the decision-making time (in this case, 12 monthly periods).

As far as the agricultural engineer is concerned, the main problem is how the conditions for optimality can be calculated. In other words, is the suggested theoretical approach one that can be applied? In order to carry it out, a post-optimal sensitivity analysis is required. In this study the 'TRANCOL' option of IBM's linear programming package—MPSX (IBM, 1971) was used. TRANCOL transforms specific columns of the matrix to create a presentation of these columns in terms of the current basis. Each selected vector is transformed by premultiplying it by the inverse of the basis.

By premultiplying 'TRANCOL' values by $\hat{\mathbf{c}}_B$, which is the updated net income coefficient for the activities in the optimal basis, one obtains the calculated eqn. (4). By multiplying by $\hat{\mathbf{b}}$, the vector of the updated restraints, eqn. (3) is determined (Hadley, 1962; Gass, 1964; Amir & Shamir, 1972).

Case study

An application of the procedure using TRANCOL for a real irrigated area of 730 dunams (73 ha) will now be presented. (This area was only a part of a kibbutz, a large co-operative farm, which operated, in addition, orchard, livestock and industry activities.) Nineteen possible crops were the decision variables to be chosen under more than eighty constraints dealing with land area, labour crop rotation practices, mechanical equipment and administrative instructions to yield the objective function which is the maximal expectation of the net income.

This planning process was carried out in October, 1971 for the twelve following months. The optimal solution, which comprises only five crops, obtained by the linear programming formulation, is shown in Table 1.

The last column in Table 1 gives the relevant data for the optimal activities achieved by the operational monitoring process for February, 1972.

In February, 1972, the decision-maker had to decide whether or not the

TABLE 1
THE OPTIMAL SOLUTION (OCTOBER, 1971) AND ITS UPDATING (FEBRUARY, 1972)

Crop	*Symbol*	*Land area*[a] *(dunam)*	*Net income*, c_{j0} *IL/dunam*[a] *(estimated Oct.,* 1971)	*Net income*, c_{j4} *IL/dunam* *(estimated Feb.,* 1972)
Irrigated cotton	KUTSH11E	360	210·50	230·15
Unirrigated cotton	KUTBA11E	125	115·00	130·04
Mangel	SELEK11E	55	339·09	339·09[b]
Wheat	CHITA11E	60	103·35	135·84
Potatoes	TAPUD11E	130	418·48	418·48[b]
Oats	SHIBA11E	0	62·20	62·20

[a] IL = 0·24 US dollars. Dunam = 0·1 ha = 1000 m^2.
[b] The crop had not yet been seeded in February, 1972.

optimality of the system was maintained. The TRANCOL output had been created at the planning time by the planning process. Its values under the optimal crops are listed in Table 2 (*T* columns). These values are multiplied by the updated vector $\hat{\mathbf{c}}_B$ (*M* columns). The total indicates whether or not eqn. (4) is met. (The sign of the TRANCOL values depends on whether the objective function is to be maximised or minimised and on the types of non-basic constraints, namely 'greater than or equal to' or 'smaller than or equal to'.)

The results of Table 2 show that the condition for optimality does not exist (see the minus sign of the constraint ROTKUTNA). Therefore, the solution is not optimal and a new solution is required. Obviously, in the new solution, the planted crops will enter with their new $\hat{c}_{jk}$'s while the other crops—the planned as well as the rejected ones—will enter with their previous c_{j0}'s.

By further analysis of Table 2 it was found that the reason for rendering the solution non-optimal was the relatively high input expenses of wheat (CHITALIE—Table 2). Due to an unexpectedly large amount of rainfall, frequent insecticide sprayings were required.

Rainfall amounted to 520 mm while the average annual precipitation was 435 mm. (The rainy season in Israel is from early November until early April.) Due to the non-optimality of the solution, a new LP problem had been solved containing the information of rain and the new c_{jk} of wheat, which had been collected and arranged by the operational monitoring process. The solution indicated that wheat should be replaced by unirrigated sorghum having a net income of 141·30 IL/dunam. However, sorghum is seeded during April while wheat is harvested for grain only in June. Furthermore, unirrigated sorghum requires a certain depth of wetted soil which could be achieved only by 500 mm or more of rain for the given soil. Thus, unirrigated sorghum had been rejected from the first solution in spite of its relatively high income, since in October this amount of precipitation could not be assured. In February, when the last checking of the optimal plan had been considered, one could estimate more accurately the total amount of rain and could even measure the depth of the wetted soil in the given field. Thus, the rain which caused the reduction in net income from wheat made the sorghum a feasible alternative. The decision was to harvest the wheat for fodder as silage in April and to seed the sorghum immediately after harvesting the wheat. This decision was justified by the following calculations:

Wheat for silage 58·50 IL per dunam × 60 dunams =	3510·00 IL
Sorghum 141·30 IL per dunam × 60 dunams =	8478·00 IL
	11988·00 IL
Minus wheat for grains 135·84 IL per dunam × 60 dunams =	8150·40 IL
Additional expected net income	3837·60 IL

As a result, the suggested processes enabled the decision-maker to use the flexibility

TABLE 2
THE EVALUATION OF THE OPTIMALITY CONDITIONS

Crops[a] *in the optimal basis*	$\hat{c}_{j4}$[b] (*IL/dunam*)	*Constraints not in the optimal basis*											
		AREADEC		*AREAJUN*		*ROTKUTNA*		*ROTTAPUD*		*ROTSOLAN*		*ROTIBUSH*	
		T	M	T	M	T	M	T	M	T	M	T	M
KUTSH11E	230·15	0	0	1	230·15	0	0	0	0	−1	−230·15	1	230·15
KUTBA11E	130·04	0	0	−1	−130·04	1	130·04	−1	0	1	130·04	−1	−130·04
SELEK11E	339·09	0	0	0	0		0	−1	−330·09	1	330·09	0	0
CHITA11E	135·84	0	0	1	135·84	−1	−135·84	0	0	−1	−135·84	0	0
TAPUD11E	418·48	0	0	0	0	0	0	1	418·48	0	0	0	0
SHIBA11E	62·20	1	62·20	−1	−62·20	0	0	0	0	0	0	0	0
TOTAL	—		62·20		173·75		−5·80		79·39		103·14		100·09

[a] See explanations of the symbols in Table 1.
[b] $\hat{c}_{j4}$ is the updated net income for the *j*th crop at the fourth decision period namely, February, 1972.
AREADEC—ROTIBUSH are names of constraints not in the optimal basis.
T is the value of the above columns in 'TRANCOL' under the activities in the basis ($\mathbf{c}_B$).
M is the multiplication of *T* by $\hat{c}_{j4}$.

of the agricultural system while adapting the system to unforeseen events. It was possible to compensate for the wheat damage due to heavy rains and even to improve the outcome by taking advantage of the very same event.

DISCUSSION

The model, especially its two processes—monitoring and dynamic decision making—can be useful for operating intensive multi-activity farming systems. In these systems the farmer generally has various possibilities of changing the production plan even during execution. Obviously, for one crop-unirrigated farms, such a model would not improve the management because of lack of alternatives.

The case study presented was carried out in order to examine the concept of the model and to evaluate its usefulness: this case study demonstrated that the model is applicable. However, in order to use it widely in practice the model needs to be comprehensive, including the entire system, and computerised: this has now been done on a very large scale. The economic advantages are estimated to increase on average the means of multi-activity irrigated farms to the order of 15–20%.

One of the advantages of the model immediately aimed at was the enlargement of the familiarity of the decision-maker with both his system and the outside constraints. Since the monitoring process requires continuous updating, it forces the farmer to know the data at almost every point in time.

Using such a model, however, requires computer facilities and skilled manpower for carrying out its processes. From experience, this additional manpower is very significantly reduced once the model is set up and made operational.

CONCLUSIONS

Since real agricultural systems are difficult to control, one of the most suitable approaches for operating them is to alter them to new and unforseen situations. Fortunately, most of these systems can be altered, which is of economic importance to the well equipped manager. The Sequential Ad-hoc Linear Model, described in this paper, might be a suitable tool for such a manager.

This model has the following advantages: (1) the algorithm of LP is very efficient in handling many decision variables and constraints; (2) the suggested model enables one to overcome the difficulties imposed by the inaccuracy of the data at the planning time; (3) the model and its processes enable one to continuously control the agricultural system and thus to compensate for damage caused by uncontrollable processes and even to take advantage of the unforseen events when possible and (4) the model requires a permanent updating process which, *per se*, enlarges the familiarity of the decision-maker with his system.

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