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PEAK-LOAD PRICING AND ON-FARM STORAGE IN THE AUSTRALIAN GRAIN HANDLING SYSTEM

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Introduction

In the last five years, attempts at improving the efficiency of the Australian agricultural sector have increasingly focused on the handling and processing of farm products after they leave the farm gate. There is a widespread perception that inefficiencies in this sector have offset gains in farm productivity and are obstructing attempts to improve Australia's economic performance. This concern was one of the factors leading to the establishment of the Royal Commission into Grain Storage, Handling and Transport.

The grain handling and transport industries have been dominated by statutory monopolies for half a century. It is natural for economists to consider whether the pricing policies adopted by these monopolies are conducive to efficiency. The present grain handling system is characterised by extensive cost-pooling, both between country receival points and among the users of a particular receival point. The general principle is that all growers are charged the same amount per tonne, regardless of the actual cost of handling their grain. There are a number of ways in which the social cost per tonne of delivery, handling and storage may vary between deliveries of grain to a given receival point. Some of the general issues associated with cost pooling have been discussed by Quiggin (1988). In this paper, the main focus will be on differences associated with delivery time.

At present, wheat growers are paid, shortly after delivery, an advance equal to the net guaranteed minimum price. The earlier the wheat is delivered, the earlier the advance is received. Since the amount received is independent of the time of delivery there is an incentive for early delivery. In addition to the charges levied by the bulk handling authority, farmers incur costs between harvesting and delivery to receival points. These include the cost of any on-farm grain storage, transport costs from farm to receival point and the opportunity cost of time spent queuing at receival points.

The operating costs of receival points are likely to be affected by the time of delivery. It seems reasonable to hypothesise that costs are lowest when the pattern of deliveries is uniform through the harvest period. Thus, deliveries at peak times would impose a higher marginal cost on the system than would deliveries at off-peak times. It also seems

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likely that there would exist some optimal operating period which would minimise operating costs.

Several questions of interest arise here. First, given the incentives under which farmers currently operate, how do their delivery patterns differ from those which would minimise total social costs? Second, is there a pattern of incentives which would minimise total social costs? Third, what pattern of incentives could be produced by alternative institutional structures (including changes within the present structure)? Finally, what is the pattern of gains and losses associated with the adoption of such a structure?

In this paper, these questions are analysed using a model of grain delivery and on-farm storage decisions. The primary objective is to examine the impact of alternative pricing structures on farmers' decisions whether to store grain on-farm or deliver it immediately and, if storage is undertaken, how long to store. A secondary objective is to estimate social costs associated with this part of the grain storage and delivery process, and the extent to which they differ from the private costs which determine decisions.

Two main sources of divergence between private and social marginal costs may be identified. The first divergence is the congestion externality associated with queuing. Congestion externalities of this kind are discussed by Baumol and Oates (1975) and Layard (1977). As in other problems involving congestion, the private marginal cost of delivering at peak times will be less than the social marginal cost. Farmers will take account of the length of the queue in deciding when to deliver. However, they will not take account of the impact of their decision on others in the queue.

The second source of divergence arises from pooling of grain handling costs across users. If delivery at particular times or in particular ways imposes greater marginal costs on the grain handling system, then the operation of cost pooling, by not reflecting this in prices charged, will create a divergence between private and social marginal costs.

The model presented here incorporates these factors and permits the derivation of estimates of the gains which may be obtained from a system of peak-load pricing. The estimates presented here are based on parameters derived from a study of grain handling in NSW (Fisher and Quiggin 1988).

Model Outline

The objective in constructing the model is to represent farmers' decisions regarding on-farm storage and grain delivery. For the purposes of the model, it is assumed that harvests are determined exogenously and stochastically. Thus, given n farms and m harvesting periods, h_{ij} denotes the harvest of farm i in period j. The total harvest in period j, H_j, is given by

$$(1) \quad H_j = \sum_{i=1}^{n} h_{ij}$$

In each time period, farmer i faces the choice of delivering grain immediately to the receival point or storing it on-farm for later delivery. The total amount, D_j, delivered in period j is given by

(2) $D_j = \sum_{i=1}^{n} d_{ij}$

The cost of on-farm storage from period j to period $j+T$ is assumed to take the form

(3) $C = c_t s_i(j,j+T)$

where $s_i(j,j+T)$ is the amount harvested by farmer i in period j and stored for T periods.

The cost incurred in delivery at time j is made up of transport costs and the opportunity cost of time spent queuing at terminals. Transport costs are assumed to be linear in the amount delivered and a concave function of distance from the receival point.

(4) $Z_{ij} = \kappa\phi(\delta_i)d_{ij}$

where δ_i is the distance, in kilometres, from the receival point.

In the present formulation, transport costs are assumed to be independent of delivery time, although it would be possible to incorporate a peak-load pricing element here.

Queuing time per unit delivered in period j, Q_j, is assumed to be an exponential function of the total amount delivered in the relevant time period.

(5) $Q_j = \theta D_j^{\alpha} d_{ij}$,

and the associated cost is $k\theta D_j^{\alpha} d_{ij}$, where k is the opportunity cost of time. Thus, the marginal private cost of queuing takes the form

(6) $\partial Q_j / \partial d_{ij} = k\theta D_j^{\alpha}$

The discounted present value of the price received for delivery at time period j is denoted p_j. The problem of maximising the present value of net returns for farmer i may be stated as

(7) $\text{Max} \sum_{j=1}^{n} (p_j - k\theta(D_j)^{\alpha} - \kappa\phi(\delta_i))d_{ij} - \sum_{j=1}^{m-1} \sum_{T=1}^{m-j} c_T s_i(j,j+T)$

subject to the conditions

(8) $d_{ij} = h_{ij} + \sum_{T<j} s_i(j-T,j) - \sum_{T=1}^{m-j} s_i(j,j+T) \quad j = 1..m$

and the inequality constraints

(9) $s_i(j,j+T) \geq 0 \qquad \forall j, T$
$d_{ij} \geq 0 \qquad \forall j$

The individual firm problem may be solved using mathematical programming techniques.

The model may also be solved for a social optimum. As noted above, social marginal costs will differ from private marginal costs because of congestion externalities associated with queues at receival points and because, under pooling, prices do not reflect variations in receival point operating costs associated with load levels. The congestion externality is illustrated in Figure 1. Within the model, it may be

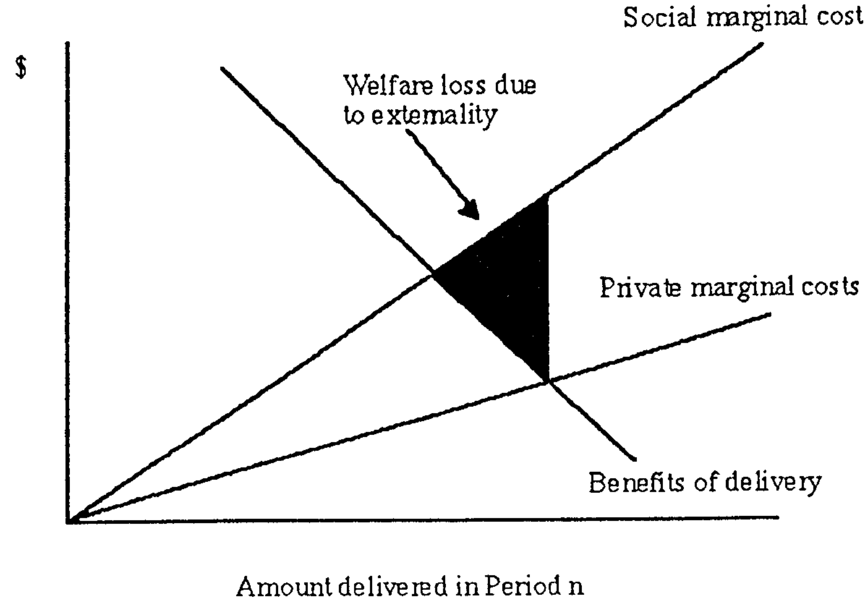

FIGURE 1—Loss Associated with Congestion Externality

analysed as follows. The total cost associated with queuing in period j is

(10) $C=(k\theta D_j^{\alpha})D_j$

and hence the marginal cost is

(11) $\partial C/\partial D_j=k\theta(\alpha+1)D_j^{\alpha}$

so that the marginal social cost is equal to $1+\alpha$ times the private marginal cost. The divergence between social and private marginal costs and the associated welfare loss are illustrated in Figure 1.

In order to analyse the congestion externality, it is necessary to replace the price with an operating cost variable and convert the problem to a minimisation problem, as well as replacing marginal private costs of queuing with marginal social costs. The new objective function is:

(12) $$\text{Min} \sum_{j=1}^{m} \text{OC}(D_j)+2k\theta(D_j)^{1+a}+\sum_{j=1}^{m-1}\sum_{T=1}^{m-j}\sum_{i=1}^{n} c_{TS_i}(j,j+T)$$

The solution to this problem is of interest in itself. It is also useful to compare the minimum value of the objective function with the value taken by the function under alternative solutions such as that obtained by maximising (7). Even if it is not possible to design an institutional structure which will yield the minimum (12), the divergence between the existing situation and the minimum gives an indication of the potential gains from change.

Model parameters and application

In converting the general algebraic model presented above into a simulation model, the primary objective was to provide an estimate of the potential gains associated with the adoption of some form of peak-load pricing. The model parameters were derived as part of a larger study (Fisher and Quiggin 1988) of grain handling, storage and transport in NSW, with a particular focus on northern NSW, and some adaptation and updating would be required before it could be applied to other regions. In particular, the benefits of peak-load pricing are obviously dependent on the severity of the peak-load problem, which in the present case depends on the distribution of the harvest over time.

The inputs required for the model are:

(a) amounts harvested (tonnes) in period i, $i=1 \ldots m$;
(b) on-farm storage costs, that is, the cost to store 1 tonne for j periods $j=1 \ldots m-1$;
(c) transport costs;
(d) relationship of queuing time (hours) per tonne delivered to the amount delivered in any period;
(e) opportunity cost of time ($/hour);
(f) receival point operating costs; and
(g) pricing structure.

The parameter settings are summarized in Table 1. Their derivation is described below.

TABLE 1

Model Parameters

Parameter	Meaning	Unit	Value
OppCost	Opportunity cost of time	$/hr	26
AveTrans	Average transport cost	$/t	5·55
StoreCost	Store entry cost	$	3
WeeklyCost	Weekly cost of storage	$/week	0·5
Int	Interest cost	$/wk	0·35
β_1	Operating cost parameter		0·5
β_1	Operating cost parameter		0·15
β_3	Operating cost parameter		4·37
β_4	Operating cost parameter		−3·06
β_5	Operating cost parameter		0·414
α	Queuing cost parameter		1·35
CAP	Receival point capacity	tonnes	90000
Harvest 0	Harvest in Period 0	tonnes	22449
Harvest 1	Harvest in Period 1	tonnes	42579
Harvest 2	Harvest in Period 2	tonnes	18097
Harvest 3	Harvest in Period 3	tonnes	4120
θ	Coefficient of Variation		0·73
ϕ	Coefficient of Skewness		0·56

The number of time-periods, m, was set equal to 4. This setting permitted the development of a model which is both analytically tractable and sufficiently rich to capture the crucial features of the problem under consideration. In particular, with 4 time periods it is possible to represent the most common peak-load pricing schemes, such as those based on peak, shoulder and off-peak periods. The total delivery period varies between sites but generally ranges from 4 to 8 weeks. Thus, the individual time-periods in the model represent a period of 1 to 2 weeks. For the present simulations the time period was set equal to 1 week.

The number of farms, n, was set equal to 80. The harvest levels used in the sample solutions are chosen to represent a medium to large receival point with an annual throughput of the order of 90,000 tonnes. It was assumed that, on each farm, harvesting was completed within 2 periods. Harvest times were assumed to be distributed randomly over the harvest period in a manner which reflected typical patterns with an early peak.

On-farm storage cost estimates were derived from Kerin (1984) who estimates an annual charge of \$6 per tonne associated with fixed capital costs and inloading and outloading costs of \$1.50 per tonne. It seems likely that farm storages are constructed primarily to cater for the possibility of harvests too large to deliver immediately, rather than as a means of permitting more flexible delivery in normal years. For this reason, the fixed capital charge attributable to flexible delivery was reduced to \$1.50, yielding a total cost of \$3 associated with the decision to store grain for later delivery. In addition, an allowance of \$0·50/tonne/week is included to cover costs associated with insect damage etc.

Finally, under the present pricing structure, storage involves an interest penalty associated with later payment. Since the price received is fixed in nominal terms (so that those who are paid later are not compensated for inflation), the appropriate cost here is the nominal interest rate, here assumed to be 18 per cent per annum (a real rate of 8 per cent plus 10 per cent inflation). The grain price is assumed to be \$100/tonne. Thus, the interest foregone is \$0·35/tonne/week.

Payment upon delivery would be appropriate if there were economic benefits from early delivery. However, in many cases, such as that of receival points operated on a 'fill and close' basis, there is clearly no difference in the final value of wheat regardless of delivery time. Only if wheat were outloaded within a short time of delivery would an interest incentive of this kind be appropriate.

Transport costs are based on contract haulage rates (derived from MacAulay, Batterham and Fisher 1988). It is assumed that farm investment decisions equilibrate the cost of self-delivery and contract delivery. Since the derivation of contract delivery costs is much more reliable than that for self-delivery, contract delivery charges are used. These take the form:

$$(13) \quad Z_{ij} = \begin{cases} 7 \cdot 00 & \delta_i < 16 \\ 7 \cdot 00 + 0 \cdot 125(\delta_i - 16) & \delta_i \geq 16 \end{cases}$$

A similar result is obtained using the cost data presented by Kerin (1984). However, in both cases, these estimated costs include allowances for time spent in queuing. Queuing costs are accounted for directly in the present model. For this reason, the fixed cost of \$7.00 was adjusted to \$4.00 to allow for an average queuing cost of \$3.00 per tonne. Distances, δ_i, from the receival point were generated randomly in line with the observed distribution for receival points in the north-west of New South Wales. The mean distance was 19·3 km and the standard deviation was 6·7 km.

Queuing time is determined by the parameter α in equation (5). Kerin (1984) examines this question, but unfortunately does not present an equation in this form. The most useful equation derived is of the form

(14) $TQC_j = \alpha_1 D_j^{\alpha_2} NHH^{-\alpha_3}$

where:

$TQC = \theta D_j T_j$ is the total queuing cost; and

NHH = number of hopper hours available at the site.

It would be preferable for the purposes of this study to have an equation which related queuing time to deliveries and a fixed measure of capacity, such as the number of hoppers available. Unfortunately, the number of hours for which hoppers are available on a given day is likely to be related to the total volume of deliveries. If hopper hours were linearly related to the number of hoppers, it would be possible to set $\alpha = \alpha_2 - 1$. However, if unloading rates are constant, so that hopper hours for a given receival point are proportional to the amount delivered, α should be set equal to $\alpha_2 - 2$. Given Kerin's estimate of $\alpha_2 = 2{\cdot}85$, this yields a range of values for α from 0·85 to 1·85. In the present simulations, a value of $\alpha = 1{\cdot}35$ has been adopted.

Opportunity cost of time is set at the rate of $26 per hour. This is based on Kerin's (1984) estimate for contract hauliers. Kerin uses the substantially lower figure of $15.09 as the weighted average opportunity cost of queuing time. However, this estimate is based on the assumption that the opportunity cost of idle time for farm trucks should be set to zero. This assumption would only be valid if the total stock of farm trucks is independent of the amount of grain hauled by farmers. In fact, grain delivery is one of the most important uses of farm vehicles, and it seems more reasonable to assume that the costs of private and contract delivery are equilibrated.

The level of operating costs is derived on the basis of the estimates of the operating cost function derived by Piggott, Coelli and Fleming (1988). The estimate of average operating costs is of the form:

(15) $AOC = \beta_0 + \beta_1/\mathbf{D} + \beta_2\,GRADES + \beta_3\,CAP + \beta_4(\mathbf{D}*CAP) + \beta_5\,\mathbf{D}^2$

where:

$\mathbf{D} = \sum_{j=1}^{m} D_j$ represents total deliveries for the season in units of 100 000 tonnes;

Grades = number of different grades of wheat received; and

CAP = capacity of the receival point in units of 100 000 tonnes.

The simulation runs presented here are based on the assumption that the capacity of the receival point is 90 000 tonnes and that there are five grades.

From (15), total operating costs take the form

(16) $$TOC(\mathbf{D}) = \beta_1 + \mathbf{D}*(\beta_0 + \beta_2\,GRADES + \beta_3\,CAP) + \beta_4(\mathbf{D}^2*CAP) + \beta_5\mathbf{D}^3$$

The problem is to derive a cost function for each period j depending on the deliveries, D_j, taking place in that period. The appropriate transformation is

(17) $$OC(D_j) = \beta_1/m + (\beta_0 + \beta_2\,GRADES + \beta_3\,CAP)*D_j + \frac{\beta_4 m}{1+\theta^2}*(D_j^2*CAP) + \frac{\beta_5 m^2}{1+\phi}D_j^3$$

where:

θ = the coefficient of variation of the D_j

$\phi = \dfrac{E[D_j^3] - (E[D_j])^3}{E[D_j]}$ is the corresponding parameter for skewness.

In order to show that this is the appropriate transformation, it is necessary to verify that:

$$(18) \quad \sum_{j=1}^{m} OC(D_j) = TOC(\mathbf{D})$$

This is immediately apparent for the first two terms in the right-hand-side of (16). For the third term, it is necessary to show that:

$$(19) \quad \sum_{j=1}^{m} \frac{m}{1+\theta^2} D_j^2 = \mathbf{D}^2$$

Observe that:

$$(20) \quad \sum_{j=1}^{M} \frac{m}{1+\theta^2} D_j^2 = \frac{m^2((E[D_j])^2 + \mathrm{var}(D_j))}{1 + \mathrm{var}(D_j)/(E[D_j])^2}$$
$$= m^2 E]D_j]^2$$
$$= \mathbf{D}^2$$

as required. The proof for the final term is similar. Reversing the chain of equalities, and treating each term separately suffices to show that (17) is the unique solution to (18).

Two polar cases are of interest. The first is the case where deliveries are evenly spread over the m time periods. In this case θ and ϕ are zero and $Dj = \mathbf{D}/m \quad j$. Verification of equation (18) is particularly easy in this case. The second polar case is where all deliveries take place in a single period, say, period 1. In this case, the coefficient of variation, θ, may be shown to be equal to $\sqrt{m-1}$, and equality (18) is once again verified. Similarly, the skewness measure, ϕ, becomes $m^2 - 1$, ensuring that $m^2/(1+\phi) = 1$. The constant term, α_1, in equation (16) requires careful treatment in this case. The procedure used here is based on the assumption that this term represents costs which are incurred regardless of the level of throughput. These costs may therefore be apportioned evenly across the m periods. However, it may be that some or all of these costs are 'flagfall' costs incurred for any positive level of deliveries but not incurred for zero deliveries. These costs would be incurred as soon as the facility opened for deliveries in a given period, but not if the facility remained idle during this period. If such costs are present, and (16) is estimated while the facility is open for only one period, then the procedure for deriving (17) from (16) must be adjusted. The 'flagfall' costs should be included in full for each period with non-zero deliveries. The costs which are incurred regardless should be spread across all periods, whether or not delivery takes place.

Pricing structures may either be imposed exogenously or derived as a consequence of some maximisation rule (for example, maximisation of social welfare or operating profit). The following exogenously determined pricing structures were considered:

(a) uniform pricing;
(b) uniform prices with all farmers being paid at a set date rather than on the basis of delivery time;
(c) as in (b) with an allowance for social costs associated with queuing;
(d) as in (c) with charges reflecting differences in receival point operating cost (assuming marginal cost pricing); and
(e) as in (c) with charges reflecting differences in receival point operating cost (assuming average cost pricing).

The model was solved algebraically, using mathematical programming techniques based on Kuhn–Tucker multipliers to derive solution conditions. The Kuhn–Tucker multipliers reflect the constraints associated with the requirement that storage be non-negative in every period. A number of potential solutions arise depending on which of these constraints are binding. For each potential solution, the conditions derived from the programming analysis were incorporated into a spreadsheet together with the equations of the model and various auxiliary computations. This permitted the derivation of numerical solutions corresponding to each algebraic solution. Since each of the potential solutions are evaluated, optimisation consists simply of selecting the potential solution which minimises private costs. The spreadsheet employed was Microsoft Excel running on a Macintosh computer.

This approach has a number of advantages. The use of spreadsheets eases many of the tasks associated with model development, particularly those relating to the management of data, documentation, respecification of the model and the reporting of results. In particular, arbitrarily complex functions of the model variables may be recalculated automatically every time the model is solved. With most mathematical programming packages, this would require either specially written code or manual entry of the solution values into a spreadsheet. Also because the entire solution process is transparent, the detection and correction of errors is easier.

More importantly, perhaps, the fact that all potential solutions are evaluated means that the use of numerical optimisation techniques is unnecessary. Since many numerical optimisation techniques (such as linear and quadratic programming) impose restrictions on the nature of the objective function and the constraints, the fact that these techniques are not used increases the flexibility of the modelling process. The objective functions employed here are generally non-linear functions of the decision variables. In addition, in solutions (d) and (e) the farmer's objective function includes an endogenously determined price variable.

This approach becomes unwieldy with large models. As the number of potential solutions becomes large, the task of deriving an algebraic specification of the associated Kuhn–Tucker conditions becomes increasingly burdensome, and the computation of the spreadsheet solution slows down. The spreadsheet approach is best adapted to the case when the model is small enough to permit the derivation of a useful algebraic solution, but not so simple that a numerical solution can be calculated manually. In many real-world problems, constraints on the availability of information, for example on parameter values, mean that extension of models beyond this size limit is of limited value.

A further, though comparatively minor, problem with the spreadsheet approach is that the techniques used by most spreadsheet programs to achieve convergence to a solution are fairly crude. If a number of variables are to be determined simultaneously, it is necessary to take care to specify the associated equations in the correct order to achieve convergence. It is to be hoped that this aspect of spreadsheet programs will be improved in the near future.

In the present case, the problems were not serious and the advantages of the spreadsheet approach were considerable. Given the steady increase in the processing power of microcomputers and the rapid improvements in software, combined with the relative stability of mainframe systems, it seems likely that the relative advantages of methods based on spreadsheets and related programs over traditional mainframe packages (even those with PC incarnations) will continue to grow.

Results

Base solution: uniform pricing

The base solution is presented in Tables 2*a* and 2*b*. This corresponds to the current situation, where farmers minimise their own transport and queuing costs, taking no account of congestion effects on other farmers or of differences in operating costs associated with peak-loads.

In Table 2*a*, the entry in position (i,j) represents the amount harvested in period i and delivered in period j. Obviously the entry can be positive only if $j \geq i$. Positive entries in off-diagonal elements, where j is strictly greater than i, represent on-farm storage. In the present solution, the only storage which takes place is from the peak harvesting period 2 to the off-peak period 4. The resulting pattern of total deliveries is substantially more uniform than the distribution in the absence of on-farm storage given by the total harvest column. Average queuing time ranges from about 1 hour to about 3·5 hours.

TABLE 2*a*

Storage and Delivery – Base Solution

Harvested in period	Amount delivered in period				Total harvest
	1	2	3	4	
1	22,449	0	0	0	22,449
2	0	33,210	0	9,370	42,580
3	0	0	18,097	0	18,097
4	0	0	0	4,120	4,120
Total deliveries (t)	22,449	33,210	18,097	13,490	87,246
Waiting time (hours)	2·02	3·42	1·51	1·01	

The various costs associated with the grain handling process up to and including delivery to a country receival point are summarised in Table 2*b*. The total cost per tonne delivered is $15.75. This solution represents a saving of about $3.20 per tonne compared with the

TABLE 2*b*

Costs – Base Solution

Costs ('000 $)	Delivered in period 1	2	3	4	Total
Storage	0	0	0	44	44
Queuing	98	246	59	30	433
Transport	125	184	100	75	484
Operating	92	206	67	48	413
Total	315	636	227	196	1,374
Average costs ($/t)	14·25	17·50	13·75	12·88	15·75

situation (not reported here) where no on-farm storage is permitted. This is made up, in approximately equal proportions, of a reduction in delivery costs (queuing and on-farm storage) and a reduction in operating costs resulting from the more even distribution of deliveries.

The private costs, in columns 1 to 4, represent the average unit cost to a farmer delivering wheat in the relevant period. This is made up of transport and queuing costs for the period concerned and operating costs pooled across the 4 periods. Although the private costs of delivery in period 4 are lower than those for period 3, the difference is not great enough to offset the costs of on-farm storage. By contrast, the difference between costs in periods 2 and 4 is large enough to encourage a significant amount of storage.

Solution (b): Uniform pricing with grower payments at a set date

Simulation (b) represents a situation where time of payment is independent of time of delivery, thereby removing the interest disincentive to storage. This leads to an increase in total storage, as indicated in Table 3*a*, from 9400 to 10 800, an increase of 15 per cent. Average queuing time in the peak period has been reduced by 0·2 or about 12 minutes. The corresponding increase in the off-peak period is only 0·15 hours or about 9 minutes. The weighted average queuing time is reduced even more since more grain is delivered in period 2 than in period 4. This gain reflects the non-linearity inherent in the congestion externality.

TABLE 3*a*

Storage and Delivery – Solution (b)

Harvested in period	Amount delivered in period 1	2	3	4	Total harvest
1	22,449	0	0	0	22,449
2	0	31,741	0	10,838	42,580
3	0	0	18,097	0	18,097
4	0	0	0	4,120	4,120
Total deliveries (t)	22,449	31,741	18,097	14,958	87,246
Waiting time (hours)	2·02	3·22	1·51	1·17	

There is a reduction in average costs of \$0·38 per tonne associated with this change. The benefits are mainly due to reduced queuing and operating costs associated with a more even pattern of delivery. The reduction in costs benefits all farmers except those harvesting and delivering in period 1, who lose because of the reduced real value of the price they receive as compared with the situation where payment is made on delivery. However, since many of these farmers also harvest in period 2, they would benefit from the reduction in congestion as well as sharing in the general reduction in operating costs. Thus, this change would be fairly close to a Pareto-improvement.

TABLE 3*b*

Costs – Solution (b)

	Delivered in period				
Costs ('000 \$)	1	2	3	4	Total
On-farm storage	0	0	0	43	43
Queuing	98	221	59	38	417
Transport	125	176	100	83	484
Operating	92	185	67	53	397
Total	315	582	227	217	1,341
Average costs (\$/t)	14·47	17·08	13·37	12·63	15·37

It may be noted that, even though the level of deliveries in Period 1 is unchanged from the previous solution, the average cost per tonne reported in Table 3*b* is increased. This reflects the fact that the model solution involves minimising private rather than social costs. The move to a fixed payment date reduces the net private returns to early delivery. Of course, for the crop as a whole, average private costs are equal to average social costs.

Solution (c): Social cost of queuing

The next simulation represents a situation where the congestion costs associated with queuing, derived in equation (11) are taken into account in the amount charged for deliveries and hence the net price received by farmers. The charge for deliveries in the peak period 2 is higher than in the 'shoulder' periods 1 and 3 which, in turn, are higher

TABLE 4*a*

Storage and Delivery – Solution (c)

	Amount delivered in period				
Harvested in period	1	2	3	4	Total harvest
1	22,449	0	0	0	22,449
2	0	26,063	3,799	12,718	42,580
3	0	0	18,097	0	18,097
4	0	0	0	4,120	4,120
Total deliveries (t)	22,449	26,063	21,897	16,838	87,246
Waiting time (hours)	2·02	2·47	1·95	1·37	

than those for the off-peak period 4. At the equilibrium solution, the extra charge would be of the order of $1.30 per tonne for the peak period and there would be a corresponding reduction for off-peak deliveries.

In this solution, the pattern of storage has changed with grain being stored from the peak period 2 to both the shoulder period 3 and the off-peak period 4. The result is a more even pattern of delivery than in the previous solution. Queuing time in the peak period is now reduced by almost 1 hour to approximately 2½ hours.

This change yields an overall reduction in average costs of $0·57/tonne, compared with solution (b) and $0·95/tonne compared with the base solution. Compared with solution (b), costs are reduced in every period except period 3, where increased deliveries raise congestion costs. Compared with the base solution, there are large reductions in costs in periods 2 and 4 and small increases in periods 1 and 3. Assuming that most farmers harvest and deliver in more than one period, this is likely to imply a result close to a Pareto-improvement.

TABLE 4*b*

Costs – Solution (c)

Costs ('000 $)	Delivered in period 1	2	3	4	Total
Storage	0	0	13	51	64
Queuing	98	139	93	50	380
Transport	125	145	122	93	484
Operating	92	121	89	61	363
Total	315	405	316	255	1,291
Average costs ($/t)	14·29	16·42	13·96	11·07	14·80

It may be noted that this, and the subsequent simulation runs, are equilibrium solutions in which the charges correspond to actual delivery levels. In practice, it would be necessary to announce charges in advance on the basis of expected deliveries. Given random fluctuations in harvest patterns, the charges would not match the actual pattern of congestion.

Solution (d): Average cost pricing

The next simulation (Table 5*a* and 5*b*) represents a situation where variations in average operating costs associated with delivery time are taken into account in the price charged for deliveries. The average operating cost (AOC) is given by equation (15). The spreadsheet was solved iteratively until an equilibrium delivery pattern, with prices including a storage charge equal to AOC was reached. In the equilibrium solution this implies a surcharge of about $0·70 per tonne for delivery in the peak period and a corresponding rebate in the off-peak period. However, this is offset by a reduction of about $0·30 in the peak-load charge for congestion. This offsetting reduction occurs because the policy of charging for differences in average costs reduces

TABLE 5*a*

Storage and Delivery – Solution (d)

Harvested in period	Amount delivered in period 1	2	3	4	Total harvest
1	22,449	0	0	0	22,449
2	0	25,284	3,847	13,449	42,580
3	0	0	18,097	0	18,097
4	0	0	0	4,120	4,120
Total deliveries (t)	22,449	25,284	21,944	17,569	87,246
Waiting time (hours)	2·02	2·37	1·96	1·45	

TABLE 5*b*

Costs – Solution (d)

Costs ('000 $)	Delivered in period 1	2	3	4	Total
Storage	0	0	13	54	67
Queuing	98	130	93	55	376
Transport	125	140	122	98	484
Operating	92	114	89	64	360
Total	315	384	317	271	1,287
Average costs ($/t)	14·24	15·92	13·88	10·99	14·75

the variability of deliveries and hence the level of congestion in the peak period.

This solution differs only slightly from the previous one. There is a further small decrease in the amount delivered in the peak period, and in the associated queuing time. This leads to a reduction of $0·05 per tonne in average costs.

Solution (e): Marginal cost pricing

The final simulation represents a situation where the charge for variations in operating costs is based on differences in marginal costs, derived by differentiating equation (15), rather than in average costs. This yields a usage pattern which minimises total social costs, under the solution conditions for equation (12).

TABLE 6*a*

Storage and Delivery – Solution (e)

Harvested in period	Amount delivered in period 1	2	3	4	Total harvest
1	22,449	0	0	0	22,449
2	0	25,464	3,200	13,916	42,580
3	0	0	18,097	0	18,097
4	0	0	0	4,120	4,120
Total deliveries (t)	22,449	25,464	21,297	18,036	87,246
Waiting time (hours)	2·02	2·39	1·88	1·50	

The solution is similar to that of the previous two simulations, the major difference being a decrease in the amount stored from period 2 to period 3 and a corresponding increase in the amount stored from period 2 to period 4. Costs are reduced very slightly by $0·01 per tonne. Compared to the base solution, the total gain is $1·01 per tonne, with reductions in costs accruing regardless of the period in which delivery takes place.

TABLE 6*b*

Costs – Solution (e)

	Delivered in period				
Costs ('000 $)	1	2	3	4	Total
Storage	0	0	11	56	67
Queuing	98	132	87	59	375
Transport	125	141	118	100	484
Operating	92	116	85	67	359
Total	315	389	301	281	1,286
Average costs ($/t)	14·25	16·03	13·57	11·71	14·74

The absence of further significant gains associated with the last two simulations does not imply that variations in operating costs are unimportant. Rather they reflect the fact that solution (c) is already fairly close to the global minimum for social costs. In the base situation, a small charge on peak load deliveries leads to a fairly large increase in on-farm storage and to very substantial welfare gains. As the optimum is approached the responsiveness of the level of storage declines and the gains associated with a given increase in storage decline. This is a reflection of the standard welfare triangle principle which states that welfare losses are quadratic in the size of the relevant distortion.

Sensitivity testing

Extensive sensitivity testing was undertaken to test the effect of variations in the model parameters on the outcomes. The primary variables which were considered were α, the parameter for the degree of non-linearity in the queuing time function, θ, the opportunity cost of time and $c_T(0)$, the fixed cost of on-farm storage. In addition, the effect of changes in the pattern of harvest was considered. Only the implications for the average cost per tonne are reported here and, in view of the fact that solutions (c), (d) and (e) are usually fairly similar, only the results for simulations (a), (b) and (c).

The main focus of interest here is not on the absolute cost levels but on the differences between the three solutions. In general, the differences are largest when the cost of on-farm storage is high, when the opportunity cost of time is low and when the congestion externality is severe (that is when α is large). The last of these results is unsurprising, but the first two are somewhat counter-intuitive. The explanation is that when on-farm storage is cheap and queuing is expensive, the private incentive to store yields a solution with high levels of storage. As was noted in the previous section, the first

TABLE 7

Results of Sensitivity Tests

Parameter values			Unit costs		
α	θ	C_T	Solution (a)	Solution (b)	Solution (c)
1·35	26	1·5	15·75	15·37	14·80
1·35	15	1·5	15·34	14·58	13·22
1·35	40	1·5	17·62	17·36	17·02
1·35	26	0	14·39	14·17	14·02
1·35	26	6	17·70	17·23	15·66
1·85	26	1·5	14·85	14·43	13·67
0·85	26	1·5	16·98	16·67	16·32

increments to storage yield the largest social gains. Thus, if on-farm storage is already extensive, the gains from correcting the externality effects are much smaller.

Two sensitivity tests were also undertaken with different distributions of the harvest. In the first, output in the off-peak period 4 was increased to 10 000 tonnes. This reduced the severity of the externality effect somewhat but did not alter the nature of the solution. In the second, the peak in period 2 was reduced to 30 000 tonnes. This had the effect of altering the optimum pattern of storage in solution 2. The new optimum was one in which grain was stored in periods 2 and 3 for delivery in period 4. The cost reduction from eliminating the interest incentive for early delivery was \$0·20 per tonne and the additional cost reduction from congestion charges was \$0·26 per tonne, about half the level observed in the main set of simulations. This is unsurprising since the size of the potential loss depends directly on the variability of deliveries.

Concluding Comments

The results from the model developed in this paper are consistent with the hypothesis that there are significant potential gains from adopting a pricing system which takes time of delivery into account and which eliminates the present incentives for early delivery. The total gain could be of the order of \$1 per tonne in areas where queuing is a significant problem. Even where queuing problems are unimportant, there are potential reductions in operating costs associated with a more uniform pattern of delivery.

It would be a mistake to focus primarily on the numerical estimates offered here. As the sensitivity tests presented above indicate, the actual gains will depend on a variety of parameters which will vary over time and from place to place. The primary function of the model is to illustrate some of the processes which affect farmers' decisions between on-farm storage and immediate delivery and the way in which certain pricing structures may lead to decisions which increase the costs faced by farmers as a group. It follows from the results presented above that particular attention should be paid to the structure of pricing rules for individual receival points. The policy of charging a uniform average delivery fee is sub-optimal.

The model may be used to derive optimal peak-load pricing systems. However, in practice it seems that the optimal systems devised by economists are rarely appealing to administrators. In any case, the results presented above indicate that refinements of the pricing system beyond the imposition of a charge related to congestion costs yield only marginal social welfare improvements. The major gains arise from the decision to adopt some form of peak-load pricing in the first place.

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