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ECONOMIES OF THROUGHPUT AND TRANSPORT BOTTLENECKS IN GRAIN DISTRIBUTION SYSTEMS

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In this paper, a model is presented which shows the relationship between country grain storage costs and transport bottlenecks that exist in the harvest period. It is shown that transport bottlenecks limit the amount of grain that can be transported from receival points in the peak receival period. This constraint means that the cost of operating country receival points is high because the turnover of storage capacity is limited. However, system costs can be reduced by focusing the peak transport task at sites that are less intensive users of scare transport capacity. This allows more grain to be transported out of the system in the peak period, decreasing the need for costly long term storage at country sites.

In the longer term, differences in the intensity of transport use means that optimal levels of investment in storage capacity (relative to grain receivals) will differ between sites. Relatively more storage should be constructed at sites that are intensive users of transport capacity (eg. those sites that are furthest from the port). Less storage capacity is needed at sites that are less intensive users of transport because a large depot-to-port transport task will be concentrated at these sites in the peak period.

Introduction

In most studies of Australian grain distribution systems, grain storage and transport costs have been analysed from a system wide perspective (eg. MacAulay, Batterham and Fisher (1988), Blythe, Noble and Mayers (1987), Kerin (1988)). These studies examine the cost of transporting grain from farms to intermediate receival points, the cost of handling and storing grain at these intermediate nodes, and the cost of transporting the grain to the port or domestic market. One of the general results arising from past work has been that total grain system costs will be reduced if grain deliveries are concentrated at fewer sites, because the associated economies of throughput more than outweigh the extra burden placed on delivery from farms to silos. These results are determined by the shape of curves used to depict the costs of receiving grain at country receival points.

For example, MacAulay, Batterham and Fisher (1988), in their model of grain distribution in the northern New South Wales region, used U-shaped cost curves which expressed average costs as a function of throughput. The costs curves used in the model were taken from a study of grain handling costs by Piggott, Coelli and Fleming (1988a) which examined the costs of operating country receival points in New South Wales. In this study, it was found that nearly all sites were operating in the downward sloping section of their average cost curves, indicating that higher throughput would reduce costs. In fact, these cost curves showed that average costs would be minimised if the quantity of grain received were more than double the volume of storage capacity at the site. It is hardly surprising that the transhipment model based on these cost curves recommended an increased centralisation of receivals, with large amounts of grain flowing through fewer sites. However, the results of the model may be incomplete because no account was taken of the ability of the transport system to cope with these increases in turnover. For example, at one of the subterminals in the model, a large increase in turnover was achieved by doubling the amount of grain that was railed from the site during the peak period. However, it is argued in this paper that scarce transport capacity has a high shadow cost, and this implies that reallocating scarce transport capacity may impose costs elsewhere in the system. It is difficult to conclude what the benefits of increasing the transport task in a particular region will be if these opportunity costs (which may be imposed outside the region) are not accounted for.

In this article, the issue of economies of throughput is examined from the perspective of the transport bottlenecks that exist in the harvest period. Receivals at a site can only be increased above storage capacity if grain is transported out of the system during the peak period. The capacity of the transport system to move grain in this period is very limited. For example, Brennan (1992) showed that even in a system where transport capacity were allocated efficiently during the peak period, only 30% of the rail task could be undertaken in the peak period in a year of average production. In a peak production year, constraints on transport capacity were even more severe, and only 20% of the total task could be undertaken in the peak period. Failure to account for this constraint on peak rail capacity will result in models that recommend infeasible increases in turnover at selected sites. More importantly, recognition of the peak transport constraint highlights an alternative perspective of the determinants of grain handling costs. In the model presented here, grain handling costs between receival points are interdependent because they all compete for scarce transport capacity in the peak period.

Grain Handling Technologies

One of the main variable costs of storing grain is the handling cost associated with unloading the grain from transport into storage, and reloading it from storage into transport facilities. The magnitude of this handling cost depends on the technology used.

At the port, where very capital intensive automated facilities are available, the costs of handling and storage are cheaper than at country sites. These capital intensive, low operating cost facilities are justified at the port because grain is received throughout the year, so high turnover rates are achieved. At the country receival points, grain is only received during a short (six week) harvest period, and as a result less capital intensive facilities are generally used. For example, a commonly used facility is permanent horizontal storage, where the handling process is less automated than the vertical types often used at the port. Grain is elevated into horizontal storage (incurring a handling cost which is common to all forms of storage), but then has to be re-handled when it is loaded onto trains. This labour intensive outloading process involves carting the grain back to the grid by front end loader, then re-elevating it onto trains. This double handling cost means that grain that is put into long term horizontal storage has higher handling costs than grain that is elevated directly onto trains as soon as it is received. An alternative type of technology for handling grain is the use of bunker storage. This type of technology is the most labour intensive and has the highest variable costs. A combination of technologies with different capital/labour intensities is optimal because of the variability in the amount of grain harvested between years (Brennan and Lindner 1991).

Describing Average Cost Curves

In previous studies of grain handling costs, the method of measuring throughput has varied. For example, Kerin (1987) and Piggott *et al* (1988a and b) used a simple average of inloadings and outloadings. In contrast, Blyth *et al* (1987) used the volume of grain received. The use of grain receivals as the independent variable is considered a more appropriate choice in this article. Using an average of inloadings and outloadings confuses two opposing factors. An increase in inloadings (receivals) would be expected to increase costs if high cost storage were being used at the margin, whereas an increase in outloadings will always decrease average costs because costly long term storage is avoided.

Based on the above discussion of grain handling and storage technologies, the shape of average operating costs (per unit of grain received at country receival points) can be predicted. The double handling associated with long term storage at country sites implies that the cheapest option for handling grain may be to transport it directly to the port. For grain that is stored at country sites, the marginal cost of storage will depend on the technology used, and can be expected to be an increasing function of the amount of grain stored, as the technology with the lowest operating cost will be used first. There are also significant fixed costs associated with operating country receival points (Kerin 1988). It follows that average operating costs as a function of grain received will be U-shaped, as the effect of declining average fixed costs are eventually outweighed by the increasing marginal costs of storage. The point where average costs begin to increase will depend on how much low cost storage capacity there is and how much grain is railed from the site in the receival period.

Piggott *et al* (1988a) hypothesised that average cost curves for country receival points would be U-shaped, and estimated equations that expressed average costs as a function of turnover, where turnover was described as the throughput divided by permanent storage capacity. They arrived at an optimal turnover rate of 2.1 for country receival points in New South Wales. However, they noted that 75% of sites had average turnover rates of less than 1.3, and concluded:

> 'in order to operate at the optimal ratio, there would need to be flexibility in timing of deliveries and outloadings so that these could be matched optimally with the technical capabilities of the storage facility' (Piggott *et al* (1988a) p13)

However, the costs of increasing turnover would involve either investing in more rail capacity or in extending the delivery period, and these extra costs would detract from the benefits of increasing the rail task in the peak period. Optimal turnover rates cannot be determined independently of these peak transport constraints that limit turnover in the peak period.

In this paper, the relationship between grain handling costs and peak transport constraints is modelled explicitly, to examine the practical achievement of economies of throughput.

It is argued there grain handling costs at one site are related to grain handling costs at other sites because they all compete for scarce capacity in the receival period. It is shown that there is no unique optimal turnover level for country receival points. Rather, an important issue that needs to be considered in order to minimise grain handling costs is the allocation of transport capacity between sites in the peak period.

A Model of Peak Transport-Storage Trade-offs

This model focuses on country receival points which receive grain from farms, and which do not carryover grain from year to year. Let the total amount of grain received at site j, delivered from surrounding farms, be represented by D_j. Deliveries will depend on farm-to-silo transport costs, silo-to-port transport costs and the pricing practices used by the receival points. In this simple exposition we abstract away from depot pricing issues by treating the amount delivered to each site as exogenous.

The amount of grain transported directly out of site j in the peak period is represented by Tj, and it depends on how much total transport capacity there is as well as how this capacity is rationed in providing services to the n sites in the peak period. Define the total amount of transport capacity

[1] This constraint on transport capacity may be efficient in the longer term. Research by Brennan (1992) on the Western Australian system showed that the shadow cost of peak transport capacity was not high enough to justify purchasing extra rollingstock capacity to alleviate this peak load problem if off peak uses could not be found for the trains.

that is available in the peak period as W[1]. The use of this capacity in the peak period, is defined by the constraint:

$$(1) \qquad \sum_{j=1}^{n} \alpha_j T_j \leq W$$

The α_j's are technical coefficients relating the amount of transport capacity used up by transporting a tonne of grain from site j to the port (hours per tonne). In the limited peak period it is the total operating hours of transport facilities that is in limited supply. In the case of rail transport, time spent loading grain onto trains, and unloading grain at the port use up valuable train time, as does the time spent travelling from the country depot to the port. Transport intensity α_j is determined by train turnaround time. For example, trains travelling from sites that are further from the port take longer to complete a round trip, so are more intensive users of scarce rail capacity, where intensity is measured in terms of the train time needed to transport a tonne of grain to the port. Similarly, sites that have slow loading rates will be more transport intensive.

All grain delivered to a site incurs a minimum handling cost, for receival and transfer onto trains. For simplicity this is set to zero. Grain that is stored at the site incurs extra costs associated with putting the grain into storage facilities, and retrieving it, plus any costs of protection from the weather and insect attack. This storage cost is assumed to be increasing at the margin, as more labour-intensive grain handling methods are used as the cheaper storage facilities are filled. It is assumed that the marginal cost curve is continuous.

The total cost of storage at the jth site is described in Equation 2:

$$(2) \qquad S_j(X_j);\ \text{with}\ S'_j(X_j) > 0\ \text{and}\ S''_j(X_j) > 0$$

where X_j is the amount stored at site j. But the amount of grain stored at each site is defined as the amount of grain delivered to the site, less the amount that is transported directly to the port in the peak period. Hence, X_j can also be represented by $(Dj - Tj)$.

Thus the total costs of storing grain at N country receival points is given by:

$$(3) \qquad C(T_j) = \sum_{j}^{n} S_j(D_j - T_j)$$

which must be minimised subject to the constraint in Equation 1, and non-negativity constraints.

The relevant first order conditions show how the scarce transport capacity should be allocated in the peak period. These can be represented by the complementary inequalities:

$$(4a) \qquad S'_j = \lambda\alpha_j; \qquad T_j > 0$$

(4b) $\quad S'_j < \lambda\alpha_j \qquad T_j = 0.$

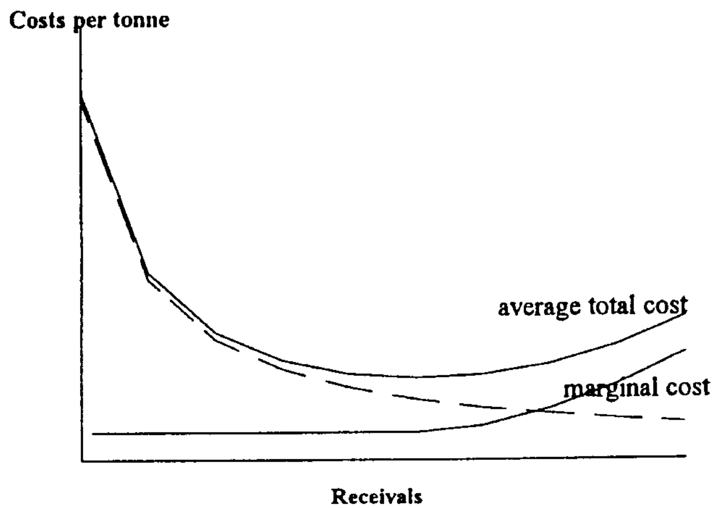
The Lagrangian multiplier λ shows the opportunity cost of an hour of scarce transport capacity. The first order conditions imply that grain should be transported from a site j only if the marginal cost of storage is equal to the opportunity cost of transporting grain from this site. For sites that have high opportunity costs associated with transporting grain (due to higher transport intensity), it is cheaper to store the grain at the site in the peak period. Grain is transported from a site in the peak period if its transport intensity α_j is low.

This result, that transport be allocated to (throughput increased at) sites which make the most efficient use of transport capacity when it is scarce, has intuitive appeal. The total amount of grain that is transported out of the system in the peak period is increased when transport capacity is allocated to the least intensive users, and this is consistent with the concept of achieving economies of throughput examined in earlier approaches. However, the difference between this approach and previous representations of the problem is that there is more to be gained from increasing throughput at one site, compared to another, because of differences in the intensity of transport use.

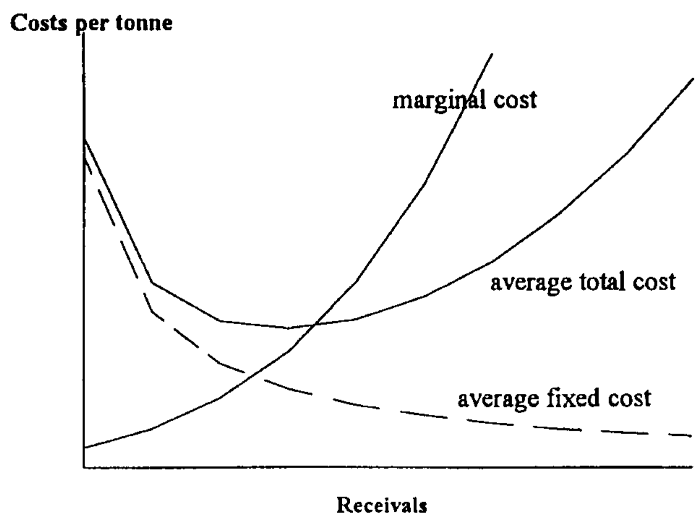
A second implication of the first-order conditions is that in cases where low-cost storage capacity is scarce at a site (so that marginal storage costs are high) it pays to allocate some scarce transport to these sites. This is because sites with relatively high marginal storage costs can also satisfy the requirements specified in equation 4a and compete with less intensive users for scarce transport capacity in the peak period. This was also expected. A short term response to shortages in storage capacity is to clear grain from the site using transport. However, in the longer term, it may be worthwhile investing in more storage capacity at the transport intensive sites.

It is clear from this discussion that the shape of operating costs at country receival points depend on the amount of transport capacity allocated to each site, and there is no such thing as a unique optimal turnover level. Moreover, with some sites (those satisfying the requirements of equation 4b) it pays not to allocate any of the peak transport capacity, so receivals will only exceed the capacity of permanent storage if high cost bunker storage is used at the margin. At these sites, the downward sloping section of the average cost curve will be limited because of increasing marginal costs. At the sites that satisfy the requirements of equation 4a), it pays to allocate transport capacity during the peak period, because they are economical users of transport capacity. Thus the total deliveries to these site should exceed permanent storage capacity, and the average cost curve observed at the site will exhibit more significant economies of turnover. This is because the marginal cost curve is a different shape at these sites. The low cost option of railing grain directly to the port means that the onset of high marginal costs occurs at a much higher level of receivals at these sites. The effect of rail out on the shape of average cost curves are illustrated in Figure 1.

FIGURE 1
Average Grain Handling Costs



(a) With Rail Out



(b) Without Rail Out

Differences in Transport Factor Intensity

The extent to which average cost curves differ between sites will be affected by differences in the amount of transport capacity allocated to each site in the peak period. In a system which is operated optimally, differences in the allocation of transport capacity will be determined by the transport intensity for each site. If these are very different, then the marginal cost of relocating transport capacity to a site that is a costly user of transport capacity in the peak period will be high. In Table 1, some results derived from a study of a Western Australian grain distribution system are shown. The opportunity costs of peak transport are shown for a range of sites, for two different rail systems. These were calculated by using the values for intensity of transport use (α_j) which were calculated using a model of train turnaround time for different site characteristics, cited in Brennan (1992). The shadow cost of a scarce train hour λ was estimated using a 2 period transhipment model of a grain distribution system in Western Australia. In this model, the costs of the grain distribution system were minimised taking into account the costs of farm-to-depot transport, depot-to-port transport, the costs and capacities of the various storage facilities at each site, and the availability of scarce transport capacity in the peak period. The shadow costs of scarce train hours for each type of rail system were derived from the cost minimisation model.

TABLE 1
Opportunity Costs of Peak Rail Transport ($\alpha_j\lambda$)
(For Country Receival Points in Western Australia)

Standard Gauge System	Opportunity Cost ($ per tonne)	Narrow Gauge System	Opportunity Cost ($ per tonne)
Avon	1.16	Wickepin	3.88
Merredin	1.62	Tincurrin	5.98
Tammin	2.32	Narrogin	6.92
Bodallin	3.02	Coomberdale	7.42
Moorine Rock	4.41	Watheroo	8.79
		Yoting	9.90
		Bullaring	12.33
		Wubin	13.40

There are large differences between sites. In both examples shown here, there are sites that are four times as intensive in their use of rail capacity than others. The extra cost that would be imposed by reallocating scarce rail capacity from (say) Avon to Moorine Rock will be over $3/t. This arises because it takes a much longer time to complete a round trip from Moorine Rock to the port (compared to the Avon round trip), so more grain has to be put into long term storage in the peak period, raising operating costs. The differences are even higher for the other rail system reported here. The marginal cost associated with transporting a tonne of grain from (say) Wubin instead of from Wickepin will be almost \$10/t. These results indicate the importance of the transport factor intensity in determining the costs of the system. The opportunity cost of increasing grain turnover varies significantly between sites.

Implications

Model Specification

This analysis has important implications for the specification of grain handling cost functions. Most importantly, the transport option must be specified as a determinant of grain handling costs. It is also clear that grain handling costs between sites are interdependent and there is no unique optimal turnover level.

It is important that researchers take account of transport bottlenecks when building transhipment models which consider economies of throughput in agricultural distribution systems. The availability of transport capacity in the peak period imposes a major constraint on achieving economies of throughput. Failure to take this into account may overestimate the benefits of increasing centralisation. Even when the peak transport constraint is recognised, failure to take account of the differences in the productivity of transport at different locations may lead to incorrect results.

Avenues for Cost Reduction

Recognition of the importance of transport bottlenecks on the cost of operating intermediate nodes in a grain distribution system reveals avenues for cost reduction. Policies designed to alleviate transport bottlenecks will reduce the cost of operating receival points. An example might be a peak load pricing scheme which encourages farmers to deliver grain over an extended period to reduce the peak load problem. Without price signals to reflect the benefits of an extended receival period, farmers have no incentive to slow down their delivery rate as it would impose extra temporary on farm storage costs. A peak load pricing scheme aimed at changing delivery patterns has been suggested previously by Quiggin (1988).

Transport Pricing Policies

It was shown that the existence of transport bottlenecks results in interdependence between sites because operating costs are affected by the amount of transport capacity allocated to a site. This has important implications for the administration of transport services. When receival points are individually owned, there will be conflicts involved with allocating transport services between sites in the peak period. That is, the availability of transport services to a site creates a positive externality in that it lowers average handling costs. Transport services would be allocated efficiently if the transport companies used a peak load pricing scheme to signal to managers at individual sites the opportunity cost of transport services in the peak period. In this way, optimal levels of investment in storage, and of turnover at each site, would be ensured.

Design of Commodity Distribution Systems

For simplicity, only the short term aspects of the peak load problem were considered in this exposition. However, longer term implications for the design of commodity distribution systems are evident from the above discussion. Transport bottlenecks mean that storage and transport are substitutes to some extent. The design of agricultural distribution systems should take into account the differences in transport factor intensity between sites. In the short term model presented here, it was shown that sites with high marginal storage costs can compete with the less transport-intensive sites for scarce transport capacity. Sites with high marginal storage costs are those that have limited capacity of low-cost storage facilities and have to use labour intensive methods of storage at the margin. In the longer term, it may be worthwhile investing in more capital intensive (lower operating cost) storage capacity at sites that are unproductive users of rail as this would allow more of the transport service to be allocated to the more productive users of transport in the peak period. Using the Western Australian examples presented in Table 1, suppose that, due to storage bottlenecks (high marginal storage costs), 'Moorine Rock' satisfied the requirements of equation 4a and received an allocation of peak transport capacity in the short term. Since Moorine Rock is 4 times more intensive than Avon in its use of transport capacity, the construction of an extra unit of storage at Moorine Rock would free up transport services so that an extra 4 units of grain could be transported out from Avon in the peak period. In the long term, this would mean that a unit of storage constructed at Moorine Rock could replace 4 units of storage constructed at Avon. In general, the model presented in this paper indicates that relatively more storage should be located at sites that are more intensive users of transport. In contrast, higher turnover are justified at sites that are less intensive users of rail in the peak period.

Summary

The model outlined here shows how transport is used to reduce the costs of operating hinterland grain storage facilities. The use of transport in the peak period to shift grain to the port reduces system costs because less grain has to be put into costly hinterland storage facilities. It is demonstrated that grain handling costs between sites are interdependent because they compete for transport capacity which is in limited supply. It is important that transport be allocated efficiently because different grain handling facilities are more or less intensive users of the scarce transport capacity. There are a number of important research and policy implications.

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