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ECONOMICS OF THROUGHPUT AND TRANSPORT BOTTLENECKS IN GRAIN DISTRIBUTION SYSTEMS

D.C. Brennan

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Nedlands, Western Australia 6009

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Introduction

Most studies of Australian grain distribution systems have analysed grain storage and transport costs from a system wide perspective (eg. McAulay, 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 farm to silo delivery. These results are driven by the shape of curves used to depict the costs of receiving grain at country receival points.

For example, in their model of the northern New South Wales region, MacAulay, Batterham and Fisher (1988) 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 undertaken by Piggot, Coelli and Fleming (1988) 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 unreliable 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 acheived by doubling the amount of grain that was railed from the site during the peak period.

In this note, the issue of "economies of throughput" is examined from the perspective of the transport bottlenecks that exist in the harvest period. For example, turnover at a site (receivals vs. storage capacity) can only be increased above one 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, and failure to account for this 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 loading the grain into storage, and outloading it. 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 relatively inexpensive. 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 outloaded. 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).

The "double handling" process associated with long term storage at country sites implies that the cheapest option for handling grain is to transport it directly to the port. For grain that is stored at country sites, the technology with the lowest operating cost will be used first. This implies that the marginal cost of operating country receival points will be an upward sloping function of grain receivals. There are also significant fixed costs associated with operating country receival points (Kerin 1988).

It follows that average operating costs will be U-shaped, as the effect of declining average fixed costs are eventually outweighed by the increasing marginal costs of storage. This idea is consistent with pervious work which has estimated U-shaped storage functions (eg. Piggot et al), which use receivals and turnover of storage capacity as explanatory variables. However, these previous studies have treated receival points as "independent" and have failed to recognise the importance of "rail out" as an option.

"Rail out" is the cheapest method of handling grain, and the shape of average operating costs will depend on whether this option is used at a site. If it is not available, marginal costs will increase more rapidly as receivals increase. But since this "rail out" option is limited by scarce transport capacity which all sites must compete for in the peak period, grain handling costs at different sites are interdependent. These interdependencies are demonstrated in the following model, which describes the relationship between grain handling costs and peak transport constraints. It is shown that the quest for an optimal level of turnover for country sites is not relevant. Rather, the important issue is how transport capacity should be allocated between sites in the peak period, that is, how turnover should vary between sites.

A Model of Peak Transport-Storage Trade-offs

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

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

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

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) $$C(T_j) = \sum_j^n S_j(D_j - T_j)$$

Which must be minimised subject to the constraint in Equation 1.

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) $S_j^{'} = \lambda \alpha_j$; $T_j > 0$

(4b) $S_j^{'} < \lambda \alpha_j$; $T_j = 0$

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 transport factor intensity.

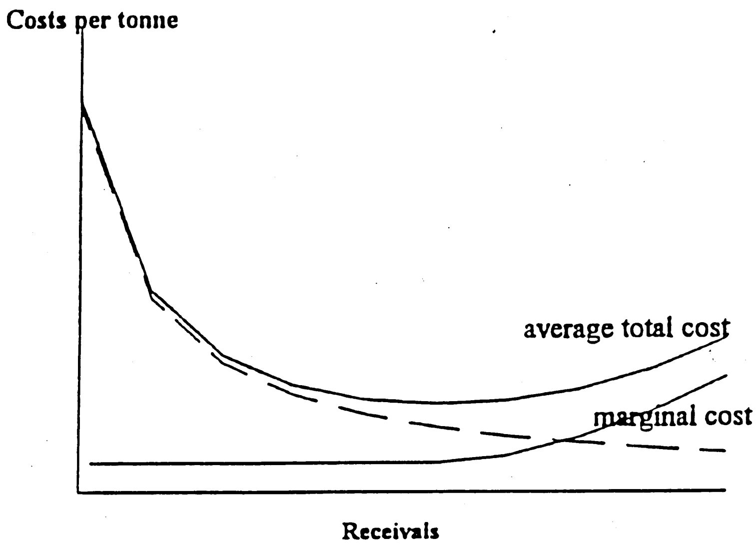
A second implication of the first-order conditions is that in cases where low-cost storage capacity is scarce at a site (so that marginal storage costs are high) it pays to allocate some scarce transport to these sites. This is because sites with relatively high marginal storage costs can also satisfy 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, the some sites (those satisfying 4b) it pays not to allocate any of the scarce transport capacity, so an upper limit on turnover at these sites will be 1. At these sites, the downward sloping section of the average cost curve will be limited, as the only influence will be declining average fixed costs. At other sites (satisfying 4a), it pays to allocate transport capacity during the peak period, because of the low transport factor intensity at these sites. Thus the total deliveries to the site should exceed physical storage capacity, and the average cost curve observed at the site will exhibit more significant economies of turnover. The effect of "rail out" on the shape of average cost curves are illustrated in Figure 1.

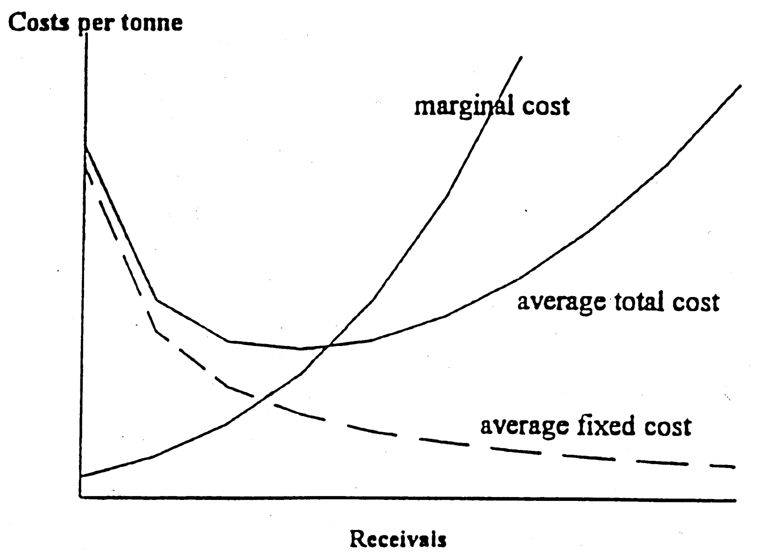
Differences in Transport Factor Intensity

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 an optimally run system, differences in the allocation of transport capacity will be determined by the transport factor 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 of transport factor intensity α_j which were calculated using a physical model of train turnaround time for different site characteristics, cited in Brennan

FIGURE 1
Average Grain Handling Costs



(a) With Rail Out



(b) Without Rail Out

(1990). 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 and storage costs 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)

Site	*Opportunity Cost ($ per tonne)*
Standard Gauge System	
Avon	1.16
Merredin	1.62
Tammin	2.32
Bodallin	3.02
Moorine Rock	4.41
Narrow Gauge System	
Wickepin	3.88
Tincurrin	5.98
Narrogin	6.92
Coomberdale	7.42
Watheroo	8.79
Yoting	9.9
Bullaring	12.33
Wubin	13.40

Clearly, there are large difference 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 "turnover" varies significantly between sites.

Implications

Model Specification

This exposition 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 also clear that researchers need to 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 the achievement of economies of throughput. Failure to take this into account will 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 will 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 encouraged farmers to deliver grain over an extended period to reduce the peak load problem. This point 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 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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