INVESTING IN GRAIN STORAGE FACILITIES UNDER FLUCTUATING PRODUCTION*

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Fluctuating annual harvest volumes create a peak load problem in the provision of grain storage capacity. There are a number of technologies for handling and storing grain, ranging from capital intensive to labour intensive methods. Optimal provision of grain storage capacity can therefore be analysed in the framework of the conventional peak load pricing model. An investment model of grain storage is outlined and the optimal technology choices are determined according to simple investment rules. Capacity of the more capital intensive storage types should be only provided if the extra capital cost is justified by the saving in operating costs, which depends on the expected utilisation of storage. Some level of supply failure is justifiable. An examination of grain storage costs in Western Australia revealed that horizontal storage was the best technology for dealing with most grain storage demand at sites where turnover is limited in the receival period. This concurs with the general investment choices in Western Australia. However, there appears to be a high level of overcapacity at many sites, implying that the cost of supply failure is perceived to be greater than the marketable value of the grain.

Introduction

Post harvest handling, transport and marketing of grain represents a large proportion of the cost of grain production. For example, in 1986–87 grain handling, storage and transport charges were equal to 20% of the average free-on-board price for wheat (Royal Commission into Grain Storage, Handling and Transport (RCGH) 1988). The significance of grain handling and transport costs in the total costs of grain production implies that the achievement of efficiency gains in the grain distribution industry may provide an important way of improving future farm incomes. For example, for the average farm in Western Australia in 1986/87 producing about 1400t of grain, a $10/t (30%) reduction in grain handling and transport costs would have increased farm income by $14,000 (Australian Bureau of Agricultural and Resource Economics 1989).

One aspect of the grain handling system is storage of grain at country receival sites until rail or road transport is available to move it. Historically statutory grain handling authorities, such as CBH in

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Western Australia, have decided how to store grain and where and how much storage to provide. The short harvest period imposes a peak demand on the grain storage and distribution system and means the total annual harvest must be accommodated almost at once somewhere in the system. The location of grain storage facilities determines whether the burden of the annual peak demand is borne in the transport or the storage sector (Reid 1978). Moreover, year to year fluctuations in crop size affect the optimal type(s) and level of investment in grain storage facilities as the cost of under-utilised capacity must be traded off against the cost of not having enough storage in years of high production.

Grain handling authorities can utilise many different types of grain storage facilities, ranging from capital intensive structures such as concrete vertical silos with automated control of grain storage conditions to very basic forms involving little more than piling grain in heaps on the ground. Ideally, the problem of optimising investment in storage capacity at each potential site should be treated as part of a global optimising problem which also determines optimal level and location of investment in on-farm storage, rail and road transport facilities, port grain handling facilities, shipping, and so on. In the interests of analytical tractability, these related problems are treated as exogenously determined, in order to focus on the storage problem at country receival sites, which has not previously been analysed as an optimal inventory problem for Australian conditions.

Investment choices for this site problem can be analysed quite simply if it is recognised that each type of storage facility differs with respect to capital (construction) and operating costs. The essence of the choice between different types of grain storage can be represented as a trade-off between high capital costs and low operating costs at one extreme, and low capital but high operating costs at the other extreme.

Investment Criteria for Facilities under Demand Variability

The provision of plant capacity to meet uncertain demand has been considered previously in the literature. For example, Brown and Johnston (1969) showed that the appropriate investment rule for welfare maximising public utilities facing uncertain demand was to provide capacity up to the point where the expected welfare gains from satisfying a marginal unit of demand were just equal to the cost of providing the extra unit of capacity. Crew and Kleindorfer (1976) extended this model to show that investment in a combination of technologies with different capital intensities (with less capital intensive technologies being used to satisfy more uncertain demand) can reduce costs.

The nature of investment choices can be demonstrated graphically by comparing the marginal expected costs of alternative investment options. An efficiency frontier which depicts the cost minimising

combination of investment as a function of expected utilisation of
capacity is illustrated in Figure 1. The vertical axis represents the
expected cost of the marginal unit of capacity and is a function of
expected utilisation. Given a particular distribution of variable
demand, moving from left to right on the horizontal axis shows declin-
ing expected marginal utilisation as total investment in storage
capacity increases. Capital intensive technology costs less where
demand is certain but, for less frequent demand, capital costs represent
a larger proportion of expected investment costs so the less capital
intensive forms of storage become cheaper investment alternatives.

FIGURE 1
The Marginal Cost of Investment in Storage Capacity

Decreasing Utilisation, Increasing Total Investment
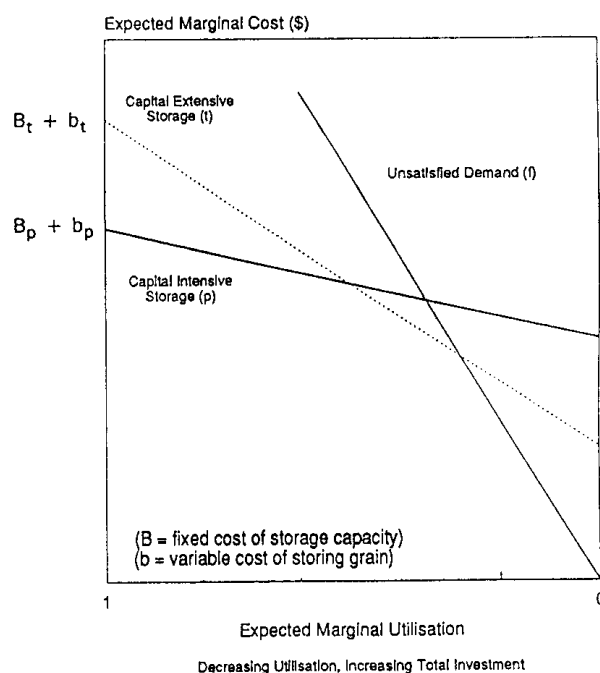
Also shown in the diagram is the cost of unsatisfied demand. The
expected cost of not investing in a marginal unit of capacity is equal
to the expected marginal value of unsatisfied demand. This declines as
total investment increases and marginal expected utilisation decreases.
At very low levels of expected utilisation, further investment in storage
capacity is not justified because the expected marginal investment cost
is more than the expected cost of unsatisfied demand.

An Investment Model for Grain Storage

The annual volume of grain delivered to a particular site can be
denoted by q_i, and its density function by $\phi(q_i)$. Hence expected annual
grain receivals at a site can be written:

(1) $$E(q) = \int_0^\infty q_i \phi(q_i) dq$$

and variance of annual receivals is

(2) $$V(q) = \int_0^\infty [q_i - E(q_i)]^2 . \phi(q_i) dq.$$

The cumulative density function which describes the probability that grain receivals will be greater than some amount $q*$ will be denoted by $\Phi(q*)$ *where* :

(3) $$\Phi(q*) = \int_{q*}^\infty \phi(q_i) dq$$

(4) $$\text{so } 0 \leq \Phi(q*) \leq 1$$

Using the simplifying assumption that all of the grain that is delivered to the site is stored there, the total demand for grain storage capacity is equal to the volume of grain delivered to the site. Consequently, as in Equation 3, the probability is given that grain receivals will be greater than or equal to $q*$, and also the probability is given that the marginal unit of storage capacity (at $q*$) will be used. The expected total volume of grain that will be stored in a storage capacity of size $q*$ is given by:

(5) $$\mu(q*) = \int_0^{q*} q_i \phi(q_i) dq + q* \int_{q*}^\infty \phi(q_i) dq$$

Grain Storage Costs

For simplicity, two types of storage technology can be defined: permanent (capital intensive) and temporary (labour intensive) storage. Annual capital costs per tonne are represented by B_p and B_t, where $B_p > B_t$. Operating costs per tonne for permanent and temporary storage can be denoted respectively by b_p, and b_t. Likewise capacity is denoted by K_p and K_t respectively. Operating costs are inversely related to capital costs, so that $b_p < b_t$. In addition it is assumed that $B_p + b_p < B_t + b_t$.

It can be seen that if demand for storage were known with certainty, then the investment decision with respect to the mix of storage type would be trivial. Simply, sufficient permanent storage should be built to fully cater for the known level of demand, and no other type of storage would be needed. On the other hand, when demand for storage

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[1] This is an oversimplification as a number of sites handle a volume of grain that is larger than the physical storage capacity, with a substantial railing out program during the harvest period. Nevertheless, it is a reasonable assumption for many sites, because the rail system could not shift all the grain to the port during the harvest period without requiring grossly uneconomic extra capacity.

is stochastic, and therefore unknown in any particular year, the optimal mix of permanent and temporary storage will depend *inter alia* on expected throughput of grain.

Expected Costs

Because horizontal facilities have lower operating costs these facilities will always be utilised first. Hence the actual cost of grain storage for horizontal storage can be approximated[2] as:

(6a) $C_p = K_p.B_p + b_p.q_i$ if $q_i < K_p$

(6b) $= K_p.B_p + b_p.K_p$ if $q_i \geq K_p$

Likewise, for temporary storage costs, C_t:

(7a) $C_t = K_t.B_t$ if $q_i < K_p$

(7b) $= K_tB_t + b_t(q_i - K_p)$ if $K_p \leq q_i < K_p + K_t$.

(7c) $= K_tB_t + b_tK_t$ if $q_i \geq K_p + K_t$.

Supply Failure Costs

Supply failure refers to the excess demand that arises when there is insufficient grain storage capacity to store the entire harvest. Supply failure costs are analogous to the value of unsatisfied demand and are the costs of alternative (emergency) methods of handling the grain. It is assumed for simplicity that the unit cost of supply failure is constant. By definition, such failure costs do not include any fixed cost component, so the costs of supply failure can be denoted by C, where:

(8a) $C_f = 0$ if $q_i < K_p + K_t$

(8b) $C_f = b_f(q_i - K_p - K_t)$ if $q_i \geq K_p + K_t$

where b_f = average and marginal failure cost measured in dollars per tonne.

The Cost Minimization Problem

The investment problem is formulated as a cost minimisation problem, which minimises the system costs including the cost of investing in centralised grain storage facilities, as well as the cost associated with not having enough storage in years of peak production.

The total cost function can be written:

(9) $TEC = K_p B_p + b_p \mu(K_p) + K_tB_t + b_t\mu(K_t)$
                   $+ b_f[E(q) - \mu(K_p) - \mu(K_t)]$

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[2] It is possible that these cost functions could be non-linear. However, in the absence of strong empirical evidence or other grounds for assuming non-linear functions, the analytically simpler form has been assumed.

where: $\mu(K_p) = \int_0^{K_p} q_i \phi(q_i)\ dq + K_p \int_{K_p}^{\infty} \phi(q_i) dq$

= expected grain put through permanent storage

and: $\mu(K_t) = \int_{K_p}^{K_p+K_t} (q_i - K_p)\ \phi(q_i) dq + K_t \int_{K_p+K_t}^{\infty} \phi(q_i) dq$

= expected grain put through temporary storage.

Also note that $[E(q) - \mu(K_p) - \mu(K_t)]$ is total expected supply failure (i.e. the amount of grain that is produced in excess of storage capacity).

Investment Rules

First order conditions for cost minimisation are obtained by differentiating the total cost function with respect to the level of capacity of each type of storage, and setting each partial derivative equal to zero. Setting $\dfrac{\partial TEC}{\partial K_p} = 0$, the following first order condition[3] is obtained

(10) $B_p = (b_t - b_p)[\Phi(K_p) - \phi(K_p + K_t)] + (b_f - b_p)\Phi(K_p + K_t)$

Likewise, setting $\dfrac{\partial TEC}{\partial K_t} = 0$, we obtain:

(11) $B_t = (b_f - b_t)\Phi(K_p + K_t)$.

Simultaneous solution of these two conditions, gives the standard criterion that investment in permanent storage capacity, K_p :

(12) $\Phi(K_p) > (B_p - B_t)/(b_t - b_p)$

This criterion is:

> Invest in permanent (capital intensive) storage up to the point where the marginal utilisation of permanent capacity is just equal to the ratio of the savings in capital costs and the extra operating costs associated with using temporary storage.

The total investment rule is derived from Equation 11 after solution of Equation 12. The investment rule is:

> Desist from further investment in storage at very low expected utilisation levels as it is cheaper to bear the high cost of infrequent failure.

These investment rules correspond to the kinks in the efficiency frontier shown in Figure 1.

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[3] See Appendix A for derivation.

An Empirical Analysis of Optimal Storage Technology

These investment rules were applied in an examination of the optimal levels of storage technology in Western Australia, and to assess, to some extent, the efficiency of past investment decisions. There are four major types of storage technology used in Western Australia. They are (in order of decreasing capital intensity) — Vertical, Horizontal, Conveyor Loading System (CLS) bunker and non-CLS bunker storage. Vertical and horizontal storage types both have high capital costs and are characterised by being totally closed structures with fixed machinery for loading the grain into storage and then re-loading it onto rail. Vertical storage has much lower operating costs, as the grain outloads via gravity. However, the capital cost of this storage type is higher. At the other extreme, there is bunker storage, which is simply a bitumen pad with corrugated iron walls, with the grain covered with PVC sheeting. Filling and emptying this type of storage is labour intensive. A more capital intensive version of this storage has some fixed machinery (a Conveyor Loading System) which reduces some of the filling costs.

Supply failure may be accommodated by a number of means. The lead time between planting and harvesting a crop means that the bulk handling authority can prepare to some extent for looming supply failure in advance. Inadequate supply of storage can be handled by railing some of the grain to the port during the receival period, or by diverting deliveries to another site where there is space available. However, the transport option is limited by the capacity of the transport system in the peak period. Alternative methods of handling expected excess production include on-farm storage and construction of additional bunker storage prior to harvest.

Capital Costs

Capital costs are annually recurring costs not specifically related to use, and include amortised construction costs and some maintenance costs. Estimates of marginal construction costs for permanent facilities were obtained from Quiggin and Fisher (1988). Costs of bunker storage and the conveyor loading system were obtained from Co-operative Bulk Handling Ltd. (CBH). Capital costs were amortised at a rate of 5% and, to take account of the effects of segregation, capital costs were increased to reflect the cost of an effective unit of storage capacity. The increases were 5% for vertical storage (Kerin 1985) and 15% for all other storage types (Co-operative Bulk Handling Ltd. (CBH) 1988). Capital costs are shown in Table 1.

TABLE 1
Grain Storage Marginal Costs

Cost Component	Vertical Storage $/t	Horizontal Storage $/t	CLS Bunker Storage $/t	Emergency Bunker Storage $/t
Operating	1.01	1.65	5.252	21
Capital	5.196	2.714	2.656	0

Operating Costs

Operating costs are those costs that are only incurred if a unit of storage is used. Operating costs have a fixed component (e.g. Kerin 1985, Piggot, Coelli and Fleming 1988) which is largely due to the need for a basic minimum labour force to receive the grain in the harvest period (Kerin 1985). It is assumed that this receival cost is independent of the mix of technology at the site. Marginal operating costs include other labour costs as well as pest control, maintenance, electricity and other expenses. These costs were obtained from CBH (1986) and CBH (1987) and are shown in Table 1.

Also shown in Table 1 is the marginal cost of supply failure. For simplicity this is represented as the cost of building extra storage in a peak year, where all the capital costs of the emergency storage are imposed in the peak year. This is likely to overestimate the cost of responses to supply failure options because some cheaper transport alternatives may be available. Also, emergency storage can be dismantled and used at another site in another year, reducing effective capital costs. The conservatively high supply failure cost used here meant that results will err on the side of overestimating total optimal investment.

Marginal Efficiency Conditions Showing Optimal Technology

The marginal costs of the alternative storage technologies shown in Table 1 are plotted on an efficiency frontier in Figure 2. As shown on the efficiency frontier, horizontal storage should be used to meet all grain storage demand in 85% of years. The supply failure option, which involves constructing emergency bunker storage, should be used to satisfy the extra production occurring in peak production years.

These results are based on the assumption that the turnover of storage capacity at the site, which is defined as grain receivals divided by storage capacity, cannot exceed unity. Higher turnover levels increase the expected utilisation of storage capacity, and reduce the

relative costs of capital intensive storage. This means that the efficiency frontier shown in Figure 2 can be extrapolated to the left, beyond ϕ (K) = 1, for vertical storage where availability of rail allows turnover to exceed unity. Thus investment in vertical storage is justified under certain demand conditions provided that the turnover of capacity is greater than the ratio of capital and operating costs. From the costs shown in Table 1, this is justified where turnover levels of 4 are achieved. This is only likely to occur at the ports and sub-terminals.

The sensitivity of optimal levels of horizontal storage to variability of grain receivals is shown in Table 2, by comparing results for three sample distributions which have similar means but different variance. It can be seen that the site with the most variable production has a higher optimal level of storage. This is because for more variable production a higher level of investment, relative to the mean, is needed to achieve the same optimal marginal utilisation. Average costs are higher at sites with greater variability because total capital costs are higher. In addition, the expected value of supply failure is greater where production is more variable.

FIGURE 2
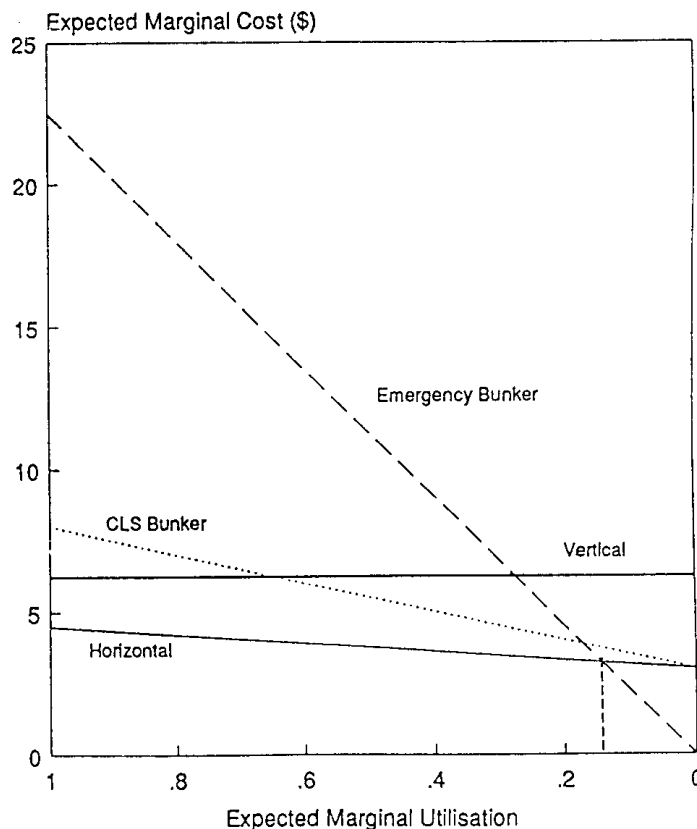### The Efficiency Frontier for Storage Types in W.A.

TABLE 2
Effect of Variance on Optimal Investment

Coefficient of Variation	Optimal Investment (tonnes)	Expected Marginal Utilisation	Average Expected Cost $ / t
0.3	33250	0.75	8.16
0.4	36250	0.69	8.43
0.5	39000	0.64	8.89

Mean production is 25000 tonnes.

TABLE 3
Sensitivity of Optimal Investment and Expected Cost of Horizontal Storage to Changes in all Operating and Capital Costs, and Supply Failure Costs Alone

	Optimal Investment (tonnes)	Percentage Difference	Average Expected Cost $ / t	Difference $ / t
Base Assumptions	36250		8.43	
All Operating Costs reduced by 30%	33750	−7	7.51	−0.92
All Operating Costs increased by 30%	37750	4	9.35	0.91
All Capital Costs reduced by 30%	38250	6	6.80	−1.63
All Capital Costs increased by 30%	34500	−5	10.02	1.59
Supply Failure Costs alone increased by 30%	33500	−8	8.22	−0.21
Supply Failure Costs alone increased by 30%	37750	4	8.69	0.25

Mean Receivals are 25000t, c.v. is .4.

Effect of Different Cost Assumptions

The effects on the optimal investment in storage when alternative assumptions are used about the general level of all operating costs, and of all capital costs, are shown in Table 3. Also shown are the effects alternative assumptions have on the costs of supply failure, *ceteris paribus*. In each case, the choice of technology is not affected by these alternative cost assumptions. Although horizontal storage remains the

optimal storage type, there is some change in the optimal level of investment in horizontal storage. For example, if there is an increase in all operating costs, including supply failure, or a decrease in all capital costs, then the optimal level of investment in horizontal storage will decrease. This is because a decrease in all operating costs favours the storage type with higher operating costs (in this case the use of emergency bunker storage) over the more capital intensive horizontal storage. This can be seen by looking at Equation 12. Because operating costs are the denominator, a percentage decrease in the size of the denominator increases optimal marginal utilisation of horizontal storage. This implies that less horizontal (and total permanent) storage is optimal. In other words, if labour costs suddenly became relatively cheap, it would be harder to justify investing in the capital intensive horizontal storage at low levels of expected utilisation. By the same logic, a decrease in all capital costs, or a decrease in the operating cost of horizontal storage with no change in supply failure costs, decreases optimal marginal utilisation of horizontal storage.
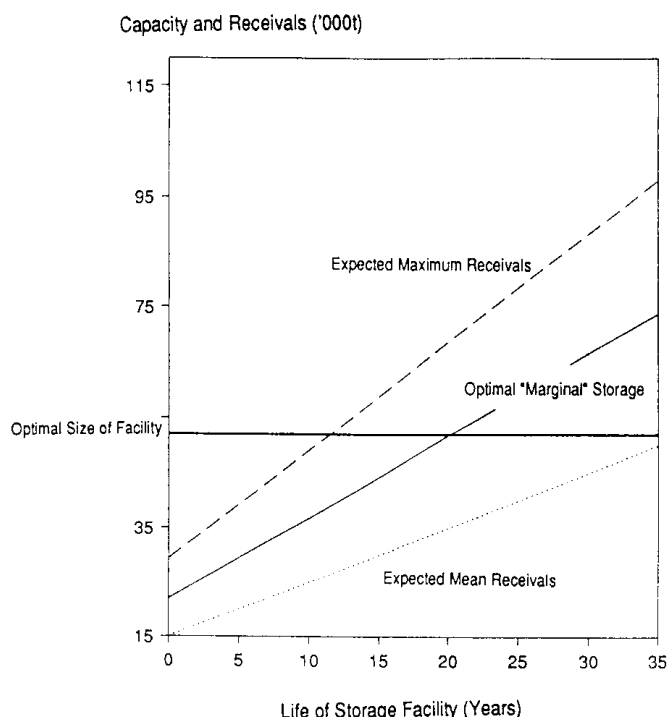
Limitations of Marginal Analysis

A limitation of the marginal analysis is that it does not take account of the effect of fixed costs. The presence of fixed costs for permanent storage structures means that average costs are much higher than marginal costs where average receivals are low, so marginal conditions for cost minimisation may not be sufficient. It implies that the cost of adjusting capacity to respond to changes in expected demand is high. The effect of growing demand and fixed costs is demonstrated in Figure 3. In this figure is shown the optimal level of investment as demand grows over time, under the assumption that adjustment of capacity is costless and variance grows proportionately with demand. Also shown is the dynamically optimal scenario where an investment decision is made at the beginning of the period of demand growth, and the investment decision is based on the expected utilisation of the facility over the entire demand growth period. The dynamically optimal level of storage is greater than the mid point or average level of storage indicated by the continuous adjustment scenario. This is because, under demand growth, there is greater variability attached to future stages of production, which results in a skewed production density function, and a much higher coefficient of variation.

As shown in Figure 3, static observations about optimal capacity may be erroneous. Failure to take account of the expected level of demand over the life of the plant, and the time of construction of the storage, may not indicate the level of investment that is optimal where there are fixed costs associated with expansion of capacity and there is growth in demand. Static analysis of optimal investment based on current demand levels would indicate that dynamically optimal investment was too high, if observations were made during the earlier stages of the life of the plant. At later stages in the life of the facility, the

statically determined optimal investment levels will be higher than the dynamically optimal level of storage.

FIGURE 3

Investment under Demand Growth with Fixed Construction Costs

Capacity and Receivals ('000t)

Life of Storage Facility (Years)

Another limitation of the marginal analysis is that it does not account for the possible external benefits of vertical storage. The presence of vertical storage at a site reduces the costs of transporting grain from the site by rail, because faster loading rates reduce the turnaround time of trains. This effect cannot be examined using marginal analysis, because all that is required to achieve this benefit from rapid loading is sufficient buffer storage to load a train quickly. An analysis of the rail transport benefit provided by vertical storage revealed that investment in some limited vertical storage as a handling technology could reduce average costs at sites that were large enough to cover the extra investment cost.

A Comparison of Actual Storage Levels

Investment levels at 80 country receival terminals (a sample of 50% of Western Australian sites) were assessed. The sites chosen had not historically used 'rail out' in the harvest period, so the assumption that emergency storage was used as a supply failure option was valid. Optimal investment levels were determined by considering the expected volume of grain receivals at each receival point and the

variability of grain receivals. The variability of receivals was derived by multiplying historical yield distributions with expected variability of area cropped. Expected variability of crop area was derived from current average crop area, a price elasticity of crop area response of 0.6 (Hall and Menz 1985, Myers 1982) and a coefficient of price variation of 17% (Sarris and Freebairn 1983). The resulting expectations functions for demand at each receival point reflect current expectations about demand.

Horizontal Storage

Determination of the optimal investment rules based on expected future production at each site revealed that optimal levels of horizontal storage at the sites examined in W.A varied between about 1.1 and 1.5 of the mean, depending on the variance of production. The average level of optimal turnover of horizontal storage capacity, measured as capacity divided by mean receivals, was 0.76. Observed investment levels did not coincide with optimal levels.

Ten sites had other types of technology, including six which had vertical storage instead of horizontal storage, and three which had CLS bunker storage with no permanent facilities at the site. In addition, at one site receivals were so low that the associated fixed costs incurred through investing in horizontal storage were not justified. A comparison between 'optimal' and actual levels of investment in horizontal storage, for those 70 sites that had horizontal storage, is shown in Table 4. Under-investment in horizontal storage was much more common than over-investment. At least 56 sites had insufficient horizontal storage. At these sites, horizontal storage capacity fell short of optimal levels by up to 44%. Relatively few sites had over invested in horizontal storage.

As discussed, the observed differences in 'optimal' and actual investment may be due to the differences between current expectations and the ex-ante expectations existing at the time the investment decision was made. As shown in Figure 3 the effect of demand growth and high fixed costs of adjustment may imply that observed under/over-investment should be correlated with the age of equipment. In Figure 4 is shown the the level of under- and over-investment in horizontal storage, plotted against the year of construction of the storage facility. Apart from two outliers which are indicated in the figure, under-investment in horizontal storage is more evident at sites where storage was built earlier, indicating that under-investment may be explained by the effect of demand growth and the cost of adjusting capacity. Further analysis of the efficiency of past investment decision in horizontal storage was not undertaken because of the subjectivity associated with determining the ex-ante expectations of historical decision makers.

FIGURE 4
Investment in Horizontal Storage and the Timing of Construction

% Deviation of Actual Total Storage Capacity from Optimal Capacity

Year of Construction
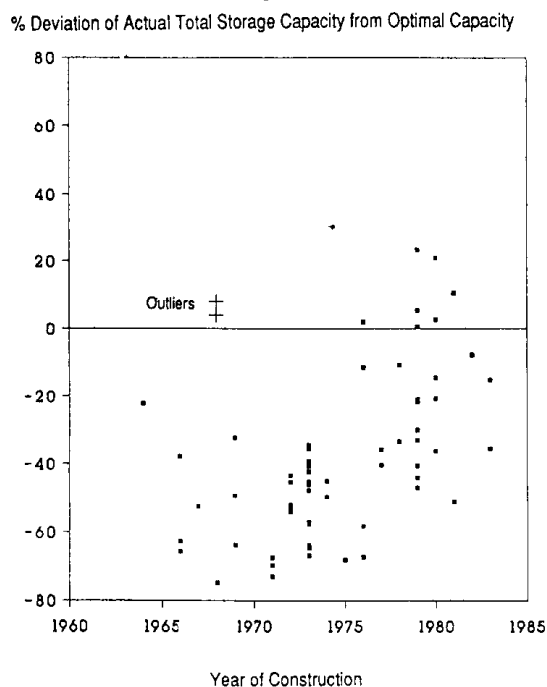
Total Storage

Because the fixed costs of bunker storage types are minimal, decision makers can adapt total storage levels to changing expectations as demand changes over time. Consequently, an objective comparison of actual and 'currently optimal' total investment levels can be made. A comparison of optimal and actual total levels of investment is summarised in Table 4. More than half the sites had investment levels that exceeded the optimal level of investment. However, there were other sites that had under-invested in total storage.

TABLE 4
Comparison of Actual with Optimal Investment

	Horizontal Storage	Total Storage
Number of sites having —		
Not enough storage	56	19
Too much storage	10	39
No significant difference	4	12
Average percentage difference		
Not enough storage	–44	–21
Too much storage	31	34

Differences greater than 5% designated as significant.

Implied Failure Costs

There was a large degree of variation in the observed levels of under-investment and over-investment. From Equation 11 the total level of investment in grain storage is determined according to the cost of supply failure. By re-arrangement of Equation 11, the implied cost of supply failure can be written:

(13) $b_f = B_t / \Phi(K_p + K_t) - b_t.$

This means where under-investment is observed, supply failure costs at these sites were lower than the \$21/t assumed in this analysis. This is plausible because the supply failure cost used in this analysis was based on a conservative estimate of the re-use of bunker storage between sites. Also, lower cost options such as railing grain out during the receival period, or encouraging growers to deliver to other locations, may also be used to reduce the capacity shortages at a site. These lower cost options would reduce the optimal investment levels below those calculated in this analysis and there would be less evidence of under-investment.

However, there is more evidence of over-investment in total storage shown in Table 4, implying that at these sites, the cost of supply failure was higher than the cost assumed in this analysis. High implied supply failure costs could be explained by the high perceived cost associated with emergency options. Historically, when bulk handling authorities had monopoly protection and the industry was 'service based', it may have been seen as being undesirable to incur any supply failure. This is because emergency options may impose extra costs on the farmer which could not be hidden in the pooled price for storage services. For example, the use of a 'fill and close' method, forcing growers to deliver to alternative sites when their local receival point became full, may have been considered undesirable because it was inconvenient for farmers. Similarly, delays in scheduling rail-out operations, or delays in constructing extra bunker storage may have delayed delivery and/or harvest operations, and so may also have been considered undesirable.

From Equation 13, an examination of the observed levels of over-investment can reveal information about the range of implied supply failure costs. Results are shown in Table 5. A large number of sites had implied risk premiums that were in excess of \$200/t, which exceeds the marketable value of the grain. At these sites, it is likely that some storage will never be used, based on current expectations about future production. It is unlikely that such high implied risk premiums would have been observed if the historical environment had been a more competitive one. Moreover, the range of implied supply failure costs, both higher and lower than the cost assumed in this analysis, indicate that in the past decision making may not have followed consistent investment criteria.
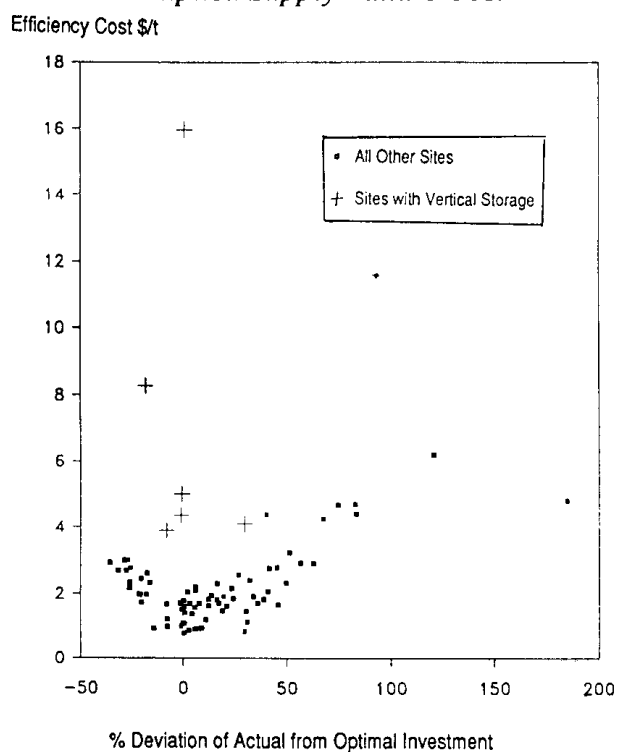
TABLE 5
Implied Supply Failure Cost

Implied Failure Cost $ / t	Number of Sites	Average Implied Failure Cost $ / t
< 30	2	28
< 50	3	35
< 100	9	68
< 200	3	175
> 200	27	

For sites with Total Overinvestment, at 5% Significance.

FIGURE 5
Implied Supply Failure Cost

Efficiency Cost $/t

% Deviation of Actual from Optimal Investment

Efficiency Costs

In Figure 5 is shown the efficiency costs of investment decisions, which are measured as the difference in actual and optimal average expected costs, plotted against the deviation in actual and optimal investment. There are two main factors explaining efficiency costs.

First, the deviation of actual and optimal investment is a main indicator of efficiency costs. A strong linear trend can be seen between the level of over- or under-investment and efficiency costs. However, the relationship is not symmetrical, as under-investment is more costly than over-investment. This might partly explain why over-investment was more evident than under-investment.

The other main factor causing large efficiency costs was the presence of vertical storage at the site, which can be seen by examining the outliers in Figure 5. Apart from these sites having vertical storage, deviation about the linear trend was relatively small and implied that some differences in the mix of technology between horizontal and bunker storage has little effect on costs.

These results can be explained by examining the efficiency frontier in Figure 2. The difference between vertical storage and other storage types is very large. The efficiency frontier also shows that the difference between options at around the utilisation levels where the marginal cost curves of horizontal and bunker storage cross is quite small. This implies that for a range of expected utilisation levels, the efficiency costs from having the wrong mix between horizontal and bunker storage technology are quite low.

At an aggregate level, the total cost difference between optimal investment levels and actual investment levels was $3.7m. This is shown in Table 6. There was over-expenditure on capital costs, because the high level of excess expenditure on bunker storage at some sites more than outweighed the savings associated with the general level of under-investment in horizontal storage. The aggregate costs of operating the system were higher than optimal, because the savings in supply failure costs associated with having a high level of excess storage capacity in the system did not outweigh the high operating costs that resulted from under-investment in horizontal storage. While the cost differences measured here may not be totally attributable to inefficiency, because of the problem of indivisibility and the interpretation of historical ex-ante expectations, the results provide some evidence of inefficiency in historical investment decisions.

TABLE 6
Total Expenditure Optimal and Actual

	Optimal	Actual	Difference
Capital Expenditure $m	9.3	10	0.7
Operating Expenditure $m	3.8	6.7	2.9
Total Expenditure $m	13.1	16.7	3.6

For sites analysed, which comprised about 50% total sites.

Conclusion

Optimal investment rules for country grain storage require consideration of the variability of production and the cost of alternative technologies. Capital investment in appropriate grain storage technology ought only be provided where the expected marginal utilisation of storage is greater than the ratio of the difference in the capital and operating costs of the capital intensive and less capital intensive storage types.

An examination of grain storage costs reveals that the optimal combination of technology for country receival points, where turnover does not exceed one, is to invest in horizontal storage capacity to satisfy production in 17 years out of 20, and to rely on emergency bunker storage to deal with peak production in three years in 20. This conclusion is relatively robust when subject to various assumptions about operating costs and discount rates. However, variation in costs will affect the actual mix between horizontal and emergency storage.

The result that horizontal storage is superior to vertical storage at low rail out sites indicates the importance of examining both capital and operating costs when considering optimal technology. An interstate analysis of operating costs alone would indicate that the state with the largest vertical storage capacity had the least cost system. On the other hand, it is not correct to conclude that an efficient system should not have any vertical technology. Vertical storage is beneficial in allowing fast rail loading rates, so investment in small amounts of vertical storage as a handling technology could reduce costs. Further, at high rail out sites as well as at port loading facilities, vertical storage is an efficient technology for storing grain provided turnover is sufficiently high.

The analysis of actual and optimal investment at a range of sites in Western Australia was conducted based on current expectations about future production. Differences between actual and optimal levels of investment in horizontal storage may be partly attributable to the subjectivity of ex-ante expectations and the problem of growth in demand. The efficiency cost of small deviations in optimal horizontal storage were not that large. The main causes of observed inefficiencies were the presence of vertical storage, and total over-investment in storage estimated to be of the order of $3.6 million.[4] The level of over-investment is difficult to explain in terms of any efficiency criteria. It is considered unlikely that high levels of over-investment, which imply enormous failure costs at some sites, would have been observed in a more competitive environment.

[4]This is a per annum cost which includes the opportunity cost of over-investment.

APPENDIX A

The total cost function to be minimised is :

$$TEC = K_p.B_p + b_p\int_0^{K_p} q_i\phi(q_i)dq + b_p.K_p.\int_{K_p}^\infty \phi(q_i)dq$$

$$+ K_t.B_t + b_t.\int_{K_t}^{K_p+K_t} (q_i - K_p).\phi(q_i)dq + b_t.K_t\int_{K_p+K_t}^\infty \phi(q_i)dq$$

$$+ b_f.\int_{K_p+K_t}^\infty (q_i - K_p - K_t).\phi(q_i)dq$$

which can be rewritten as :

$$TEC = K_pB_p + b_p\mu(K_p) + K_tB_t + b_t\mu(K_t) + b_f [E(q) - - \mu(K_p) - (K_t)]$$

$$= K_pB_p + (b_p - b_f)\mu(K_p) + K_tB_t + (b_t - b_f)\mu(K_t) + b_f [E(q)]$$

$$\text{where: } \mu(K_p) = \int_0^{K_p} q_i \phi(q_i) dq + K_p\int_{K_p}^\infty \phi(q_i)dq$$

$$\text{and: } \mu(K_t) = \int_{K_p}^{K_p+K_t} (q_i - K_p)\phi(q_i)dq + K_t\int_{K_p+K_t}^\infty \phi(q_i)dq$$

Taking partial derivatives, we obtain:

$$\partial\mu(K_p)/\partial K_p = \int_{K_p}^\infty \phi(q_i)dq; \ \partial\mu(K_t)/\partial K_t = \int_{K_p+K_t}^\infty \phi(q_i)dq;$$

$$\partial\mu(K_t)/\partial K_p = -\int_{K_p}^{K_p+K_t} \phi(q_i)dq;$$

and differentiating TEC we get :

$$\partial TEC/\partial K_p = B_p + (b_p - b_f)\partial\mu(K_p)/\partial K_p + (b_t - b_f)\partial\mu(K_t)/\partial K_p$$

$$= B_p + (b_p - b_f)\int_{K_p}^\infty \phi(q_i)dq - (b_t - b_f)\int_{K_p}^{K_p+K_t} \phi(q_i)dq$$

$$= B_p + b_p\int_{K_p}^\infty \phi(q_i)dq - b_t\int_{K_p}^{K_p+K_t} \phi(q_i)dq - b_f\int_{K_p+K_t}^\infty \phi(q_i)dq$$

$$\partial TEC/\partial K_t = B_t + (b_t - b_f)\partial\mu(K_t)/\partial K_t$$

$$= B_t + (b_t - b_f)\int_{K_p+K_t}^\infty \phi(q_i)dq.$$

Solving simultaneously, the investment rules are derived: Invest in horizontal storage capacity as long as:

$$\Phi(K_p) > (B_p - B_t)/(b_t - b_p)$$

and thereafter invest in temporary storage capacity as long as:

$$\Phi(K_p + K_t) > (B_t)/(b_f - b_t).$$

The cost minimisation problem involves determining the right balance of infrastructure so that more permanent facilities are used to cope with more certain demand, while temporary facilities are used to store the extra grain that is produced less frequently thus resulting in lower utilisation (throughput relative to capacity) of any additional capacity. At some level of capacity it will not pay to construct additional centralised storage capital to cope with the very infrequent demand arising from bumper harvests.

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