A Decision Support System for Grain Harvesting, Storage, and Distribution Logistics

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Abstract

This paper presents a decision support system to help farmers compare different grain harvesting and distribution strategies—for example, whether to store grain on farm or use bulk storage facilities located away from the farm. The system is underpinned by a discrete-time mathematical model that incorporates features such as multiple crops, moisture management, yield loss, quality downgrades due to adverse weather events, and quality optimization through blending. The output variables from the mathematical model include the total yield of each crop, the duration required to complete the harvest, and the transport and storage costs. The model is validated via test simulations using data that reflects typical farming scenarios in Western Australia.

Keywords: on-farm storage, grain handling and distribution, discrete-time mathematical model
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1. Introduction

Grain growing is a complex enterprise that involves decision-making problems in four main areas: production, harvesting, storage, and distribution. For production, the decisions are about cropping strategy, while during harvest, the decisions are about how to collect the crops efficiently from the field. For storage, the decisions are around inventory control and managing grain quality, and for distribution, the decisions relate to crop movement down the supply chain for delivery to consumers.

Although there has been extensive research on decision-making in agricultural supply chains (see the reviews by **?**, **?**, and **?**), most work focuses on short-term perishable products such as fruits and vegetables, and not on grains (**???**). Some exceptions include a decision model developed by **?** to determine the optimal amount of wheat to transport from production sites to consumption sites over the course of a year; a bi-level game theory model developed by **?** for a three-echelon grain supply chain in which independent farmers can sell their product to export ports, local grain handlers, and a food company; and a facility location model by **?** for optimizing the locations of new pre-processing facilities and road and railway capacity expansions. **?** and **?** introduce mixed-integer mathematical programming models for optimizing transportation along grain supply chains in India, and **?** also use mathematical programming for a case study focusing on when and where to transport and store

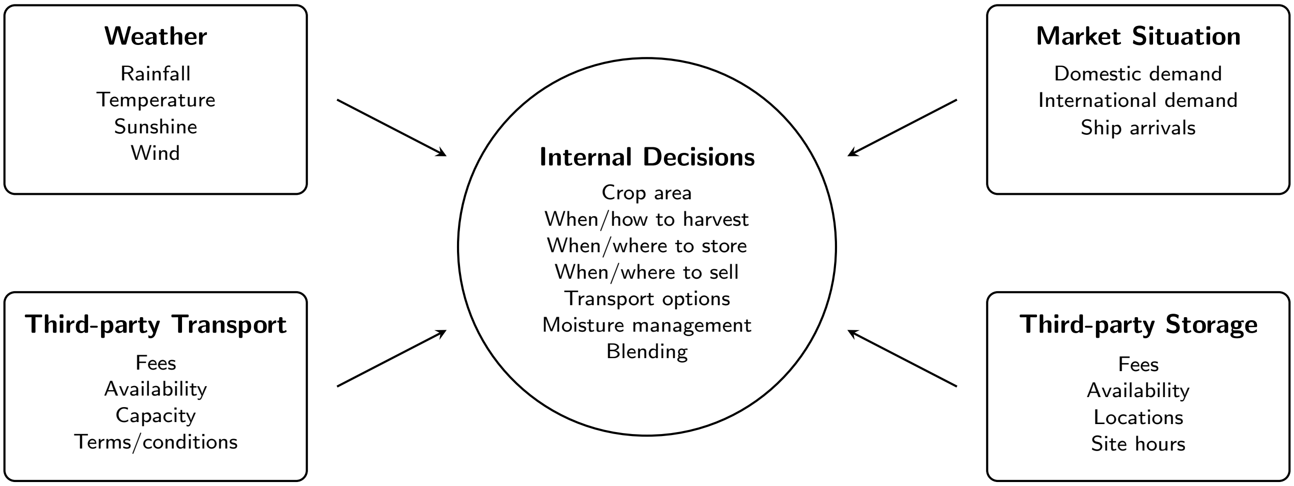


Figure 1: External factors affecting internal decisions at the farm level.

imported and domestically-produced wheat in Iran. The supply chain in this case study involves ports, silos, milling factories and flour factories.

The models described above all focus on strategic decision-making over the entire supply chain network. This is of interest to supply chain advisers and agricultural cooperative planners. However, individual grain growers face a different set of decisions and there is a lack of decision support models at the farm level that can help growers make optimal decisions. This is different to the case for perishable fruits and vegetables, where various decision support systems and advanced simulation applications are available (**?????????**). For grains, we are only aware of a previous study from about forty years ago that describes a computer simulation model for helping grain growers determine grain flow restrictions in grain harvesting-delivery-drying systems (**?**).

Figure 1 illustrates the complexity of the decisions faced by a grain grower in relation to harvesting, storage and distribution. There are some external factors that the grower cannot influence such as weather, market demand (both domestic and international), and the service offerings available for third-party transportation and grain handling. On the other hand, there are many other variables that can be controlled by the grower to increase profits. These variables arise in different stages of the production process, from pre-harvest to harvest to post-harvest activities. Since grain can be stored for much longer periods than fresh produce, one of the main decisions for a grain grower is around on-farm storage—specifically, whether to invest in on-farm storage facilities or use third-party bulk storage away from the farm. This decision then affects other decisions on storage and distribution during and after harvest. There are several potential benefits to on-farm storage which we explain below.

- *Increased harvesting hours.* The grain moisture limits at bulk storage sites are often restrictive, which constrains the times at which farmers can harvest. With on-farm storage, it may be possible to store grain at higher moisture levels, which enables harvesting to start earlier and finish later each day, when the temperature is colder and the moisture levels are higher (**?**). As such, harvest duration can be minimized by using on-farm storage (**???**).

- *Reduction in yield losses.* The yield from a standing crop starts to decrease once it reaches maturity. By using on-farm storage the duration of the harvest can be reduced, and hence yield losses are also reduced.

- *Reduction in quality losses.* Unfavourable weather during harvest can cause sprouting in grain (**???**). Harvesting faster by using on-farm storage reduces the amount of grain exposed to unfavorable weather conditions, thereby reducing the chance of quality downgrades. In addition, with on-farm storage, grain can be stored immediately once it is harvested, which reduces the chance of spoilage (**?**).

- *Reduction in transport cost.* Farmers rely on efficient transport to and from the farm during the harvesting period, and the less on-farm storage capacity, the more dependence on transportation (**?**). Trucking costs are typically highest during the harvest season because this is when demand peaks (**?**). Farmers with on-farm storage are able to make deliveries outside of the peak periods, and hence save on transportation costs.

- *Moisture management.* Grain consists of both dry matter and moisture, but the grain's grade depends only on the composition of the dry matter (**?**). The grain's weight, however, includes both the dry matter and the moisture. Grain growers with on-farm storage can raise moisture levels in their grain—for example, by periodically switching off moisture control systems or opening the tops of their silos at night to allow moist air to enter (**?**). This has the effect of increasing the weight of the grain so that the farmer gets paid for more grain at the same grade.

- *Quality optimization.* On-farm storage enables grain growers to segregate different grades of grain. This potentially opens up blending opportunities whereby some grain can be "uplifted" into a higher grade (**?**).

- *New market opportunities.* Storing grain in small lots on-farm enables farmers to: (1) cater for niche markets with unique requirements; and (2) sell crops post-harvest when there may be price premiums due to a lack of supply (**?**).

The aim of this paper is to describe a decision support tool for grain growers to help them choose between different options for the internal decisions shown in Figure 1. This tool is based on a discrete-time mathematical model that incorporates features not previously considered in the literature. These include moisture management, quality optimization through blending, and multiple crops with different on-farm storage allocations. The decision support tool is implemented as an Excel spreadsheet, which is an application widely used by farmers, and the tool allows farmers to easily enter inputs specific to their situation and run what-if scenario analysis. This tool follows on from an economic model developed by **??**, and it was recently used in a study by **?** to explore how changes in Australia's grain supply chains are likely to impact the nature and profitability of farming operations in the future. In this paper we focus on the technical derivations behind the mathematical model that underpins the decision support tool.

2. Overview of the Problem Setting

2.1. Harvesting

We consider a farm with multiple grain crops during a single harvest. The crops are harvested sequentially in a specified order—that is, the entire first crop is harvested, then the entire second crop, and so on. Each crop may be allocated on-farm storage facilities. During harvesting, the on-farm storage is filled first, and any surplus grain that cannot fit into on-farm storage is sent to a receival (bulk storage) site. See Figure 2 for an illustration. The area harvested and the grain obtained depend on the harvesting hours and harvesting rate, which in turn depend on the number of harvesters available

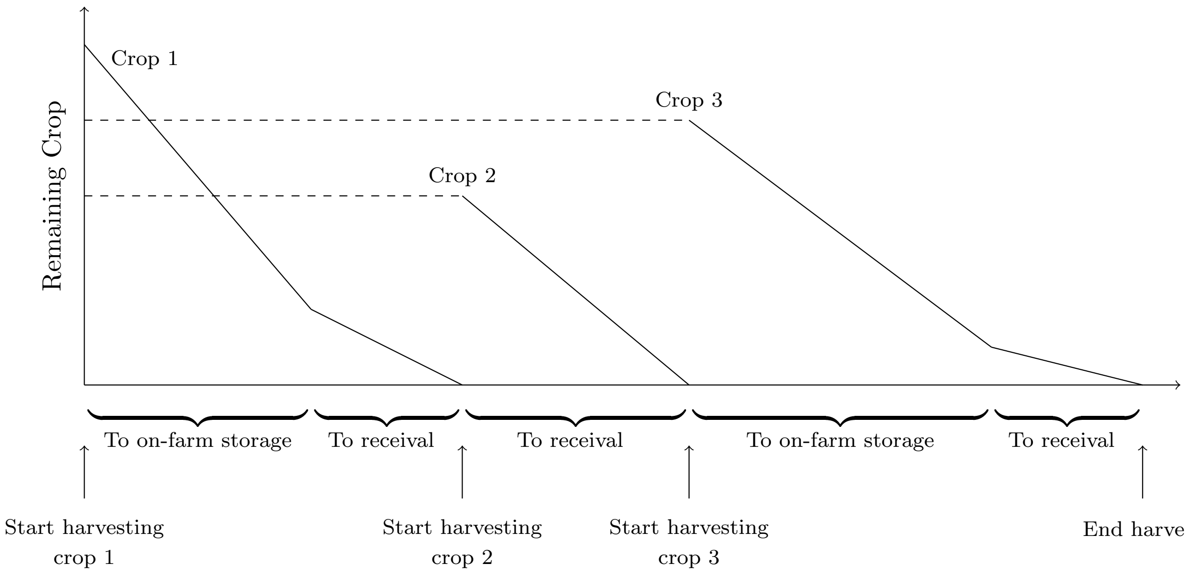


Figure 2: Harvesting three crops sequentially, where only crops 1 and 3 have on-farm storage. The harvesting rate typically slows once on-farm storage is full; see the slope changes for crops 1 and 3.

and their speeds. We assume that only one crop is harvested on each day. Hence, once a crop has been completely extracted, harvesting for the next crop does not commence until the next day, irrespective of how many hours are remaining in the current day.

2.2. Supply Chain Pathways

Harvested grain is exported or sold domestically either direct from farm or through a grain handler. The grain handler operates the distribution network and owns the receival sites, where grain growers deliver their grain. There are six different pathways for grain as shown in Figure 3:

- Field → On-farm storage → Port (export market);
- Field → On-farm storage → Domestic customer;
- Field → On-farm storage → Receival site → Port (export market);
- Field → On-farm storage → Receival site → Domestic customer;
- Field → Receival site → Port (export market); and
- Field → Receival site → Domestic customer.

The prices received through each pathway can differ because the sales may take place at different times—for example, a farmer may elect to sell grain in the receival system during harvest while keeping grain held in on-farm storage for a future sale during the year.

There are three types of costs: trucking costs, on-farm storage costs, and grain handling costs. The trucking costs are applicable to grain sent from farm to port, from farm to the domestic customer, and from farm to the receival site. The trucking costs depend linearly on the trucking rates. For grain sales using the receival system, trucking costs only include transport to the receival site; the next transport leg to port or to a domestic sale point is organized by the grain handler and hence the transport costs for this leg are included as part of the grain handler's fees. Trucking rates may differ depending on when

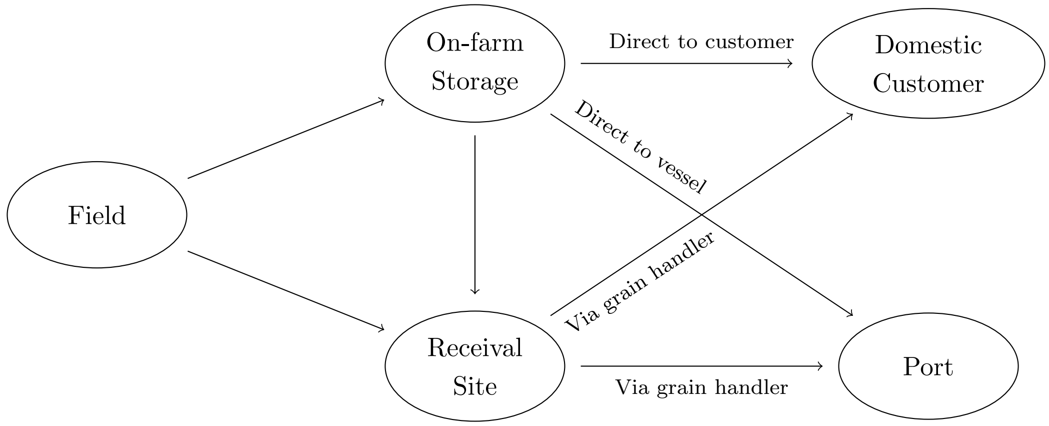


Figure 3: Possible pathways for harvested grain.

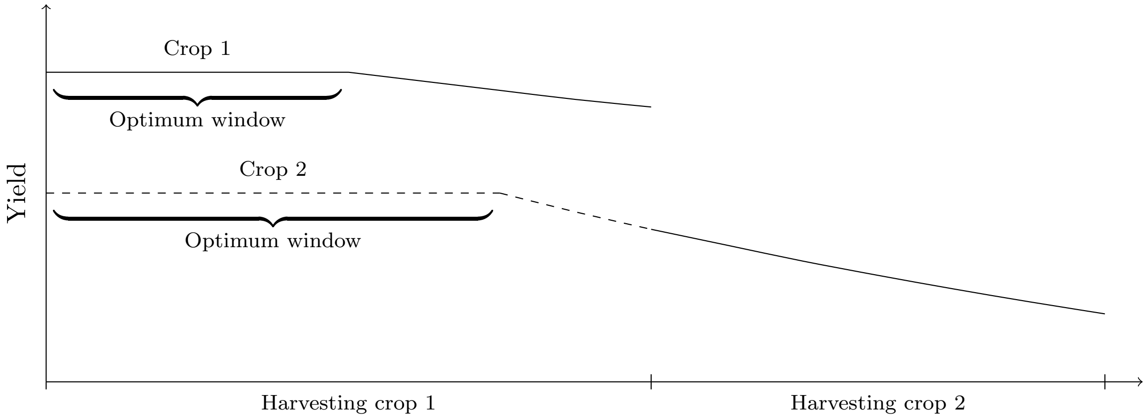


Figure 4: The optimum harvesting window for both crops 1 and 2 is measured from the harvest start date. In this example, yield loss for crop 2 starts before it is harvested.

the grain is transported. For example, transport from the farm to the receival occurs during peak time at harvest and thus is likely to be more expensive than trucking outside of the harvest season.

We assume that on-farm storage is provided as a service during harvest, at a fixed fee per tonne (that is, there is no capital cost to the farmer). The grain handling fees may include transport fees, moisture management fees, testing fees, and port loading fees. Grain handling fees are not required for domestic sales direct from the farm, since the grain handler's infrastructure is not required to facilitate this sale. However, grain handling fees are required for direct-to-vessel export sales since the grain handler's port infrastructure is required to load the grain onto a ship. For export and domestic sales through the receival system, grain handler fees can be a combination of fixed fees and time-based fees.

2.3. Yield Loss

The yield specifies the amount of grain produced from each hectare of crop. The maximum yield is obtained during the optimum harvesting window, after which the yield drops by a certain percentage each day. The optimum harvesting window for each crop is measured as the number of days from the harvest start date (when harvesting for the first crop commences), as shown in Figure 4. If the optimum harvesting window is set to zero, then yield loss begins immediately.

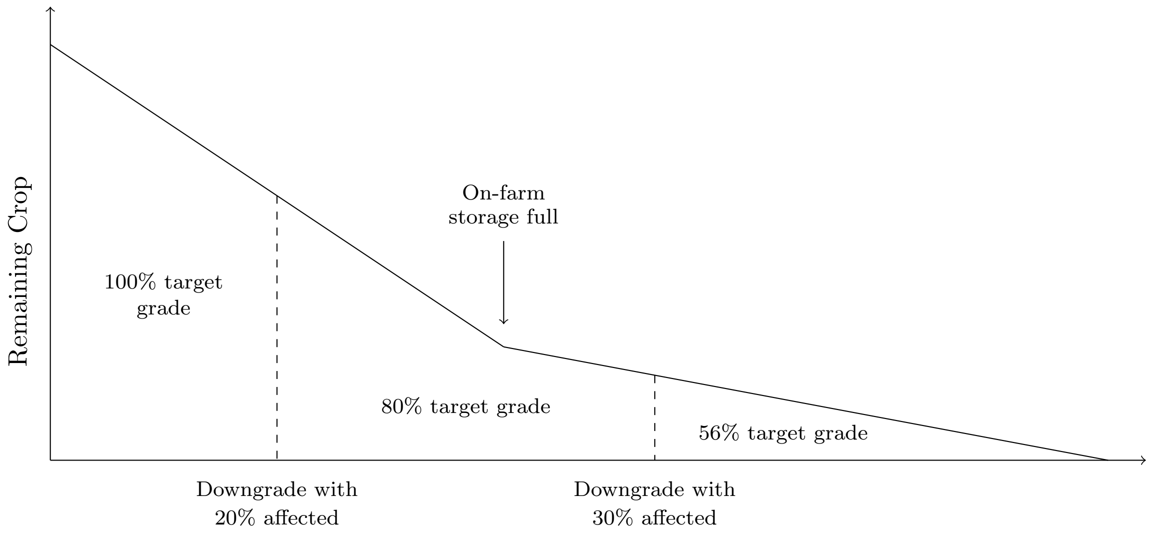


Figure 5: A crop with two quality downgrades affecting 20% and 30% of the target grade, respectively.

2.4. Moisture Management

At night when temperatures drop, moisture in the air condenses and gets absorbed by grain kernels, causing the grain's moisture content to rise. Then, during the day when the temperature is warmer, the moisture content decreases due to evaporation. Grain can only be harvested when its moisture content is below a certain threshold, which is different depending on whether the destination is on-farm storage or a receival site. Moreover, when grain is sent to a receival site, moisture and labour availability are not the only factors constraining the harvesting time each day: the receival site's opening hours, receiving/unloading capacity, hauling distance and the available trucking capacity are also factors. Indeed, harvesting can only take place when the receival site is open, and harvesting may need to be suspended if trucks cannot keep up with the harvesters. Because of these factors, the harvesting hours per day normally drops once on-farm storage is full, as shown by the slope changes in Figure 2.

On-farm storage facilities may contain moisture management systems for controlling the moisture level. Since increasing moisture causes the grain's weight to increase without affecting its dry matter, the concentrations of key nutrients—such as protein in wheat—will drop. However, in practice the nutrient concentrations (which define the grade achieved) are measured with respect to the dry matter only, while the weight is measured as a raw value including both dry matter and moisture. Hence, it is advantageous for farmers to increase moisture up to the maximum limit, since this increases the weight of their grain without affecting its grade. This is a key advantage of on-farm storage.

2.5. Weather Downgrades and Blending

Each crop has a target grade that is expected to be achieved. However, weather events may cause a certain percentage of the remaining target grade grain to be downgraded to secondary grade. Multiple downgrade events can occur for each crop; see Figure 5 for an example.

Target grade grain can be blended with secondary grade grain to achieve an overall grade uplift. The grades are defined by ranges within which key quality metrics should lie—for example, in wheat, protein content and falling number values are important indicators of grain quality. Since grain prices follow a staircase pattern with a constant price for each grade (see Figure 6), there is a significant penalty for missing the quality thresholds. Nevertheless, grain that just misses the quality thresholds can potentially be uplifted if it is blended with a sufficient amount of higher-quality grain. Two blending

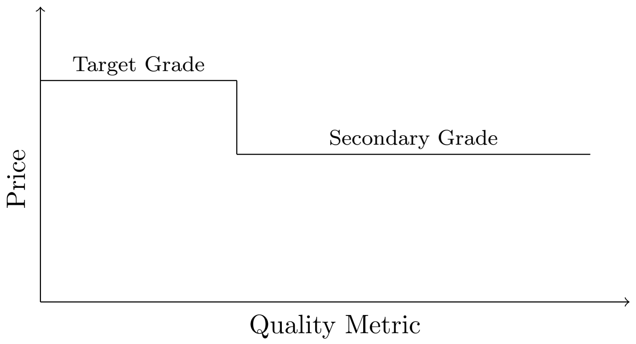


Figure 6: Grain pricing follows a staircase pattern.

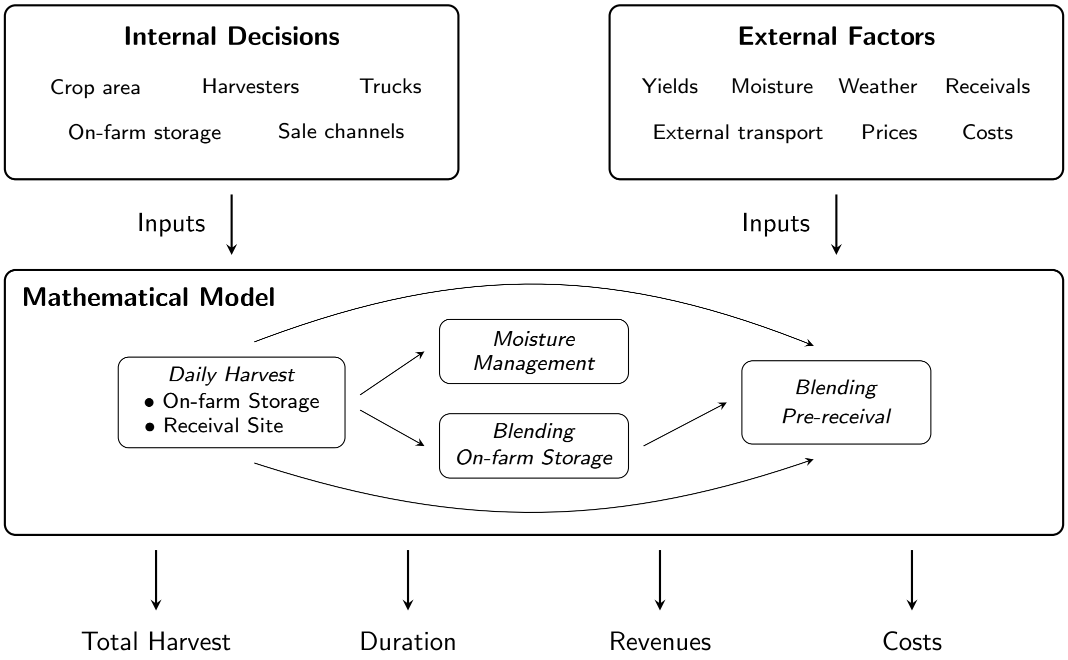


Figure 7: Structure of the mathematical model and simulation algorithm.

scenarios are possible: secondary grade held in on-farm storage can be uplifted by blending with target grade also held in on-farm storage, and secondary grade sent directly to the receival site can be uplifted by blending (prior to delivery) with target grade held in on-farm storage.

3. Mathematical Model for Daily Harvest

The structure of the mathematical model is illustrated in Figure 7. The inputs to the model consist of parameters that define the grain grower's internal decisions (such as harvesting capacity and on-farm storage) and parameters that define the external scenario (such as weather events and market prices). The mathematical model has four components:

- A simulation algorithm that computes, for each day, the area harvested and the total grain sent to on-farm storage and the receival site;
- A sub-model that calculates the weight increases obtained using moisture management;

Parameter	Unit	Description
A_c	Hectares	Crop area
Y_c	Tonnes per hectare	Maximum yield from the crop
T_c	Days	Number of days in optimum harvest window
r_c	Percentage	Daily yield reduction percentage after optimum harvest window
R_c	Tonnes	Capacity of on-farm storage
M_c^{field}	Percentage	Average grain moisture content in field
M_c^{target}	Percentage	Target moisture content after moisture management in on-farm storage
B_c	–	Blending ratio for mixing target grade grain with secondary grade
$[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$	Hours in $[0, 24]$	Valid moisture interval on day d for on-farm storage
$[a_{cd}^{\text{rcl}}, b_{cd}^{\text{rcl}}]$	Hours in $[0, 24]$	Valid moisture interval on day d for receival sites

Table 1: Input parameters defining crop c.

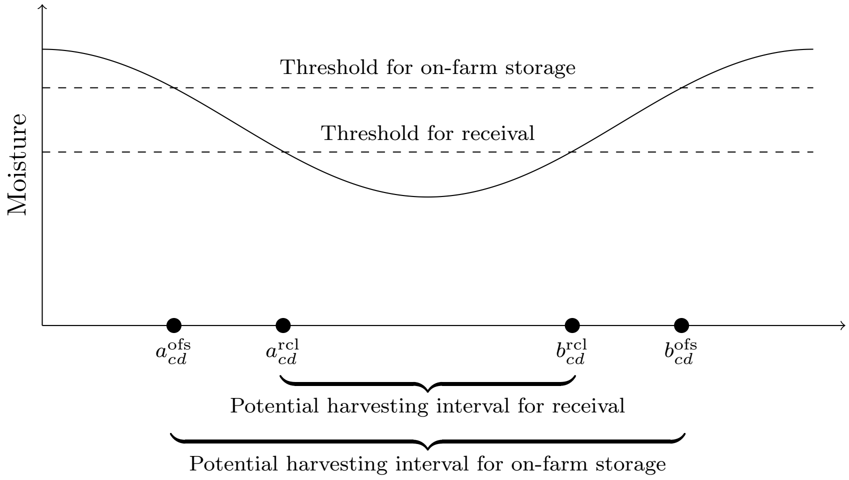


Figure 8: The potential harvesting window for crop c on day d depends on the moisture level.

- A sub-model that calculates the expected blending "uplift" obtained by mixing target and secondary grade grain within on-farm storage; and
- A sub-model that calculates the expected blending "uplift" obtained by mixing target and secondary grain prior to delivery to the receival site.

This section discusses the simulation algorithm for the daily harvest component. In the equations that follow, all "percentage" parameters are assumed to lie in $[0, 1]$. For example, 0.5% is expressed as 0.005.

The key variables in the simulation algorithm for the daily harvest are the area harvested and the grain obtained. These variables depend on the harvesting hours on each day, which in turn depends on whether grain is sent to on-farm storage (in which case moisture is the key factor), or whether grain is sent to the receival site (in which case site opening hours and trucking availability also play a role).

Let d be an index variable representing the harvest day, where $d = 1$ is the day on which the harvest commences. Furthermore, let c be another index variable representing the crop currently being harvested. Each crop c is defined by the input parameters summarized in Table 1. Let $[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$ denote a valid harvesting interval on day d during which the grain moisture content for crop c is below the maximum moisture threshold for on-farm storage, and let $[a_{cd}^{\text{rcl}}, b_{cd}^{\text{rcl}}]$ denote the analogue of $[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$ for grain sent to a receival site. See Figure 8 for an illustration. Intervals $[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$ and $[a_{cd}^{\text{rcl}}, b_{cd}^{\text{rcl}}]$ may also

Parameter	Unit	Description
H_l	Tonnes per hour	Harvesting rate of harvester l
Q_m	Tonnes	Capacity of truck m
S_m	Kilometers per hour	Speed of truck m
L	Tonnes per hour	Grain loading rate at farm
U	Tonnes per hour	Grain unloading rate at receival site
δ_{load}	Hours	Set-up/waiting time for grain loading at farm
δ_{unload}	Hours	Set-up/waiting time for grain unloading at receival site

Table 2: Input parameters defining the equipment.

Parameter	Unit	Description
$[\alpha_d^{\text{rcl}}, \beta_d^{\text{rcl}}]$	Hours in $[0, 24]$	Receival site opening interval on day d
$D^{\text{farm:rcl}}$	Kilometers	Distance between farm and receival site
$D^{\text{farm:exp}}$	Kilometers	Distance between farm and port
$D^{\text{farm:dom}}$	Kilometers	Distance between farm and domestic sale point

Table 3: Input parameters defining the distances and receival site opening times.

incorporate desired working hours in addition to moisture considerations. For example, in hot and dry conditions, moisture content may be below the threshold even at night, but harvesting continuously may still not be feasible due to a lack of labour, and hence in this case $[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$ and $[a_{cd}^{\text{rcl}}, b_{cd}^{\text{rcl}}]$ would need to be restricted accordingly.

The moisture threshold for receival sites is typically less than the moisture threshold for on-farm storage, which means $[a_{cd}^{\text{rcl}}, b_{cd}^{\text{rcl}}]$ is normally shorter than $[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$. The simulation algorithm automatically calculates the harvesting hours based on how many cycles each truck can complete between the farm and receival site. This depends on the valid moisture intervals (defined previously in Table 1) and the additional inputs defining the equipment, distances, receival site unloading rate and operating hours (see Tables 2 and 3, respectively).

The simulation algorithm maintains the following continuous-valued variables:

- $\tilde{A}_c$ = total area harvested of crop c (in hectares);
- $\tilde{G}_{cd}^{\text{ofs}}$ = amount of crop c sent to on-farm storage on day d (in tonnes); and
- $\tilde{G}_{cd}^{\text{rcl}}$ = amount of crop c sent to the receival site on day d (in tonnes).

These variables are initialized to zero. The simulation algorithm iterates over each harvest day d, changing crop when $\tilde{A}_c = A_c$, where A_c is the total area for crop c (see Table 1). Since the yield of crop c drops by a factor of r_c each day after the optimum harvesting window, the yield on day d is

$$Y_c(1-r_c)^{\max(d-T_c,0)} = \begin{cases} Y_c, & \text{if day } d = 1, \ldots, T_c, \\ Y_c(1-r_c)^{d-T_c}, & \text{if day } d > T_c, \end{cases}$$

where T_c is the length of the optimum harvesting window for crop c (see Table 1) and Y_c is the yield of crop c during the optimum harvesting window (see Table 1). Thus, at the start of day d, the amount of grain in the remaining unharvested area for crop c is

$$\underbrace{(A_c - \tilde{A}_c)}_{\text{area remaining}} \cdot \underbrace{Y_c(1-r_c)^{\max(d-T_c,0)}}_{\text{yield}}.$$

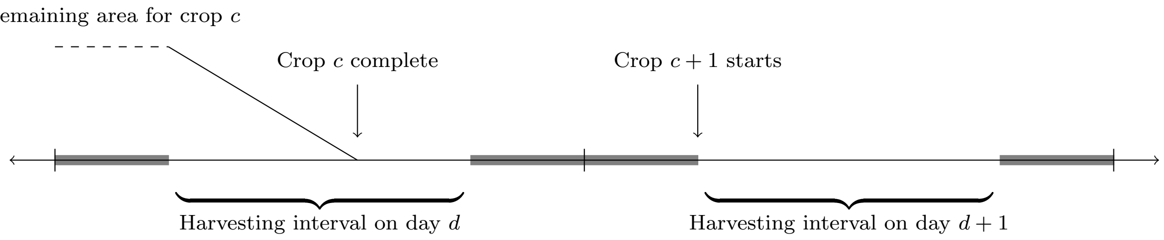


Figure 9: Harvesting for crop $c+1$ starts on the next day after crop c is complete.

This implies that the total grain and crop area harvested in τ hours on day d are, respectively,

$$\min\left\{\sum_l \tau H_l, (A_c - \tilde{A}_c) Y_c (1 - r_c)^{\max(d-T_c,0)}\right\} \tag{1}$$

and

$$\min\left\{A_c - \tilde{A}_c, \sum_l \frac{\tau H_l}{Y_c (1 - r_c)^{\max(d-T_c,0)}}\right\}, \tag{2}$$

where H_l is the harvesting rate of harvester l (see Table 2) and the subscript l denotes summation over all harvesters.

The simulation algorithm starts with $d = 1$ and $c = 1$. For each day d, the algorithm checks whether the current crop has been harvested completely. This is done using the logical test $\tilde{A}_c = A_c$. If this holds and c is the final crop, then there is no more grain to harvest, and the algorithm stops. On the other hand, if $\tilde{A}_c = A_c$ and c is not the final crop, then the algorithm moves to the next crop by incrementing c. For each day d, the simulation algorithm considers three cases for the daily harvest:

1. On-farm storage for crop c is full – in this case, all grain harvested on day d is sent to the receival site;

2. On-farm storage for crop c is not full and the remaining storage capacity can hold the harvest on day d – in this case, all grain harvested on day d is sent to on-farm storage; and

3. On-farm storage for crop c is not full but the remaining storage capacity cannot hold the harvest on day d – in this case, some grain harvested on day d is sent to on-farm storage, and the remainder is sent to the receival site.

Note that only one crop is harvested on each day, and hence the algorithm moves immediately to the next day once a crop has been completely extracted; see Figure 9.

Cases 1-3 are described in detail in the following subsections. A summary of the algorithm logic is given in Algorithm 1.

3.1. Daily Harvest: Case 1

The logical test for Case 1 is

$$\sum_{d'<d} \tilde{G}^{\text{ofs}}_{cd'} = R_c, \tag{3}$$

where R_c is the on-farm storage capacity for crop c (see Table 1). In this case, on-farm storage for crop c is full, and thus all grain harvested on day d must be sent to the receival site. The grain is transported

Algorithm 1 Logic for the daily harvest simulation.

```
Initialize the variables:
    $1 \to d, \quad 1 \to c, \quad 0 \to \tilde{A}_c, \quad 0 \to \tilde{G}^{\text{ofs}}_{cd}, \quad 0 \to \tilde{G}^{\text{rcl}}_{cd}$
while $c$ does not exceed the number of crops do
    if On-farm storage for crop $c$ is full (i.e., (3) holds) then
        All harvested grain is sent to the receival site: define $\tilde{G}^{\text{rcl}}_{cd}$ using (9), with $\tau_d$ given by (8)
        Update $\tilde{A}_c$ using (10), with $\tau_d$ given by (8)
    else if On-farm storage for crop $c$ can hold the harvest from day $d$ (i.e., (11) holds) then
        All harvested grain is sent to on-farm storage: define $\tilde{G}^{\text{ofs}}_{cd}$ using (12), with $\tau_d$ given by $\tau_d = b^{\text{ofs}}_{cd} - a^{\text{ofs}}_{cd}$
        Update $\tilde{A}_c$ using (13), with $\tau_d$ given by $\tau_d = b^{\text{ofs}}_{cd} - a^{\text{ofs}}_{cd}$
    else
        On-farm storage is filled first with remaining grain sent to the receival site
        Define $\tilde{G}^{\text{ofs}}_{cd}$ using (15) and update $\tilde{A}_c$ using (16), with $\tau^{\text{ofs}}_d$ given by (14)
        Define $\tilde{G}^{\text{rcl}}_{cd}$ using (18) and update $\tilde{A}_c$ again using (19), with $\tau^{\text{rcl}}_d$ given by (17)
    end if
    Update the harvest day: $d + 1 \to d$
    if $\tilde{A}_c = A_c$ then
        Go to the next crop: $c + 1 \to c$
    end if
end while
```

using trucks that perform round trips (cycles) between the farm and receival site. A cycle consists of the following activities: waiting and set-up at the farm, loading grain at the farm, travelling to the receival site, waiting and set-up at the receival site, unloading at the receival site, and travelling back to the farm. Thus, the cycle time (in hours) for truck m can be expressed mathematically as

$$\Delta_m = \underbrace{\delta_{\text{load}}}_{\substack{\text{waiting}\\\text{(farm)}}} + \underbrace{\frac{Q_m}{L}}_{\text{loading}} + \underbrace{\frac{D^{\text{farm:rcl}}}{S_m}}_{\text{travel}} + \underbrace{\delta_{\text{unload}}}_{\substack{\text{waiting}\\\text{(receival)}}} + \underbrace{\frac{Q_m}{U}}_{\text{unloading}} + \underbrace{\frac{D^{\text{farm:rcl}}}{S_m}}_{\text{travel}}, \tag{4}$$

where Q_m is the capacity of truck m, S_m is the speed of truck m, L is the loading rate, U is the unloading rate, δ_{load} is the expected set-up and wait time before loading grain at the farm, δ_{unload} is the expected set-up and wait time before unloading grain at the receival site, and $D^{\text{farm:rcl}}$ is the distance between the farm and receival site (see Tables 2 and 3).

Figure 10 shows the different activities comprising a truck cycle. The activities at the farm (set-up, waiting, grain loading) must occur during the interval $[a^{\text{rcl}}_{cd}, b^{\text{rcl}}_{cd}]$ (see Table 1), and the activities at the receival site (set-up, waiting, unloading) must occur during the interval $[\alpha^{\text{rcl}}_d, \beta^{\text{rcl}}_d]$ (see Table 3). The intersection of $[a^{\text{rcl}}_{cd}, b^{\text{rcl}}_{cd}]$ and $[\alpha^{\text{rcl}}_d, \beta^{\text{rcl}}_d]$ is

$$\left[a^{\text{rcl}}_{cd}, b^{\text{rcl}}_{cd}\right] \cap \left[\alpha^{\text{rcl}}_d, \beta^{\text{rcl}}_d\right] = \left[\max\{a^{\text{rcl}}_{cd}, \alpha^{\text{rcl}}_d\}, \min\{b^{\text{rcl}}_{cd}, \beta^{\text{rcl}}_d\}\right]. \tag{5}$$

Consider a given truck m. On the first cycle for truck m, grain loading and travel to the receival site can occur before the receival site opens. Thus, ignoring the time needed to harvest the first truckload of grain, the earliest time at which the first cycle for truck m can begin is

$$\begin{aligned}\max\left\{a^{\text{rcl}}_{cd}, \alpha^{\text{rcl}}_d - \delta_{\text{load}} - \frac{Q_m}{L} - \frac{D^{\text{farm:rcl}}}{S_m}\right\} &= \max\left\{a^{\text{rcl}}_{cd}, \alpha^{\text{rcl}}_d - \Delta_m + \delta_{\text{unload}} + \frac{Q_m}{U} + \frac{D^{\text{farm:rcl}}}{S_m}\right\}\\ &\geq \max\{a^{\text{rcl}}_{cd} - \Delta_m, \alpha^{\text{rcl}}_d - \Delta_m\} = \max\{a^{\text{rcl}}_{cd}, \alpha^{\text{rcl}}_d\} - \Delta_m. \end{aligned} \tag{6}$$

On the last cycle for truck m, the first travel leg and grain unloading can occur after harvesting stops, and the final travel leg can occur after the receival site closes. Thus, the latest time at which the final

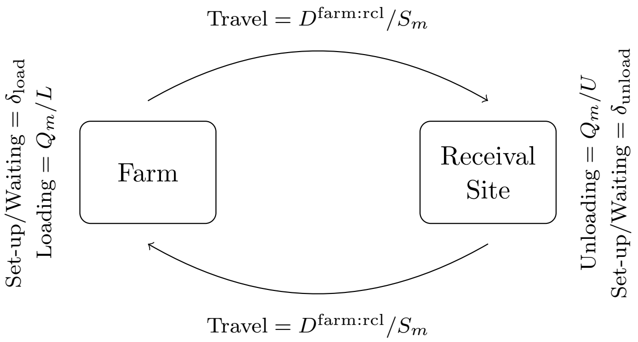


Figure 10: Truck cycles between the farm and receival site.

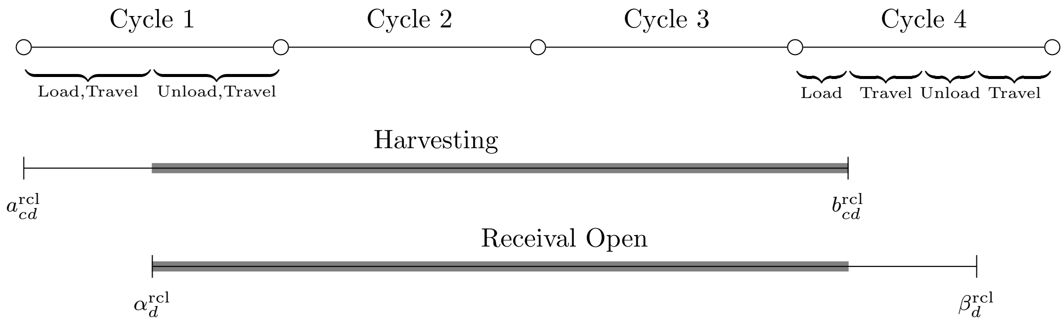


Figure 11: The first cycle can start before the receival site opens, and the last cycle can finish after harvesting stops. The two intermediate cycles are within the intersection (5), which is shaded in grey.

cycle for truck m can finish is

$$\begin{aligned}
&\min\left\{24, b_{cd}^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m} + \delta_{\text{unload}} + \frac{Q_m}{U} + \frac{D^{\text{farm:rcl}}}{S_m}, \beta_d^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m}\right\} \\
&\quad = \min\left\{24, b_{cd}^{\text{rcl}} + \Delta_m - \delta_{\text{load}} - \frac{Q_m}{L}, \beta_d^{\text{rcl}} + \Delta_m - \delta_{\text{load}} - \frac{Q_m}{L} - \delta_{\text{unload}} - \frac{Q_m}{U} - \frac{D^{\text{farm:rcl}}}{S_m}\right\} \\
&\quad \leq \min\{24 + \Delta_m, b_{cd}^{\text{rcl}} + \Delta_m, \beta_d^{\text{rcl}} + \Delta_m\} = \min\{b_{cd}^{\text{rcl}}, \beta_d^{\text{rcl}}\} + \Delta_m. \qquad (7)
\end{aligned}$$

Inequality (6) implies that the first cycle cannot finish before $\max\{a_{cd}^{\text{rcl}}, \alpha_d^{\text{rcl}}\}$, and inequality (7) implies that the last cycle cannot start after $\min\{b_{cd}^{\text{rcl}}, \beta_d^{\text{rcl}}\}$. Thus, it follows from (5) that all intermediate cycles—that is, not the first and last cycles—must occur during the intersection of the harvesting interval and the receival opening period; see Figure 11.

Based on the arguments above, the duration of time on day d during which truck m can operate is

$$\begin{aligned}
\eta_{dm} = &\underbrace{\min\left\{24, b_{cd}^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m} + \delta_{\text{unload}} + \frac{Q_m}{U} + \frac{D^{\text{farm:rcl}}}{S_m}, \beta_d^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m}\right\}}_{\text{latest end time for the final cycle}} \\
&- \underbrace{\max\left\{a_{cd}^{\text{rcl}}, \alpha_d^{\text{rcl}} - \delta_{\text{load}} - \frac{Q_m}{L} - \frac{D^{\text{farm:rcl}}}{S_m}\right\}}_{\text{earliest start time for the first cycle}}.
\end{aligned}$$

Note that $\eta_{dm} \geq 0$ whenever the intersection (5) is non-empty. This follows immediately from

$$\max\left\{a_{cd}^{\text{rcl}}, \alpha_d^{\text{rcl}} - \delta_{\text{load}} - \frac{Q_m}{L} - \frac{D^{\text{farm:rcl}}}{S_m}\right\} \leq \max\{a_{cd}^{\text{rcl}}, \alpha_d^{\text{rcl}}\}$$

and

$$\min\left\{24, b_{cd}^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m} + \delta_{\text{unload}} + \frac{Q_m}{U} + \frac{D^{\text{farm:rcl}}}{S_m}, \beta_d^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m}\right\} \geq \min\{b_{cd}^{\text{rcl}}, \beta_d^{\text{rcl}}\}.$$

The maximum number of cycles that can be completed by truck m on day d is the floor of $\max\{\eta_{dm}, 0\}$ divided by the cycle time:

$$N_{dm} = \left\lfloor \frac{\max\{\eta_{dm}, 0\}}{\Delta_m} \right\rfloor.$$

Therefore, the total transport capacity on day d is

$$\sum_m Q_m N_{dm},$$

where the subscript m denotes summation over all trucks. This assumes there is no interaction between trucks, and also that the time taken to harvest grain for the first cycle of each truck is negligible (this time could, in fact, be folded into the set-up time). Since harvesting on day d is restricted to the period $[a_{cd}^{\text{rcl}}, b_{cd}^{\text{rcl}}]$, the maximum harvesting time on day d is

$$\tau_d = \min\left\{b_{cd}^{\text{rcl}} - a_{cd}^{\text{rcl}}, \left(\sum_m Q_m N_{dm}\right) \div \left(\sum_l H_l\right)\right\}. \tag{8}$$

The total grain and area harvested on day d are then obtained by substituting $\tau = \tau_d$ into (1) and (2), respectively. Thus, variable $\tilde{G}_{cd}^{\text{rcl}}$ is defined as follows:

$$\min\left\{\sum_l \tau_d H_l, (A_c - \tilde{A}_c) Y_c (1 - r_c)^{\max(d - T_c, 0)}\right\} \to \tilde{G}_{cd}^{\text{rcl}}. \tag{9}$$

Furthermore, variable $\tilde{A}_c$ is updated as follows:

$$\tilde{A}_c + \min\left\{A_c - \tilde{A}_c, \sum_l \frac{\tau_d H_l}{Y_c (1 - r_c)^{\max(d - T_c, 0)}}\right\} \to \tilde{A}_c. \tag{10}$$

3.2. Daily Harvest: Case 2

In Case 2, all grain harvested on day d can fit into on-farm storage. In this case, the harvesting period is $[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$ and the harvesting time is $\tau_d = b_{cd}^{\text{ofs}} - a_{cd}^{\text{ofs}}$. Hence, using (1) with $\tau = \tau_d$, the logical test for Case 2 is

$$\underbrace{R_c - \sum_{d' < d} \tilde{G}_{cd'}^{\text{ofs}}}_{\substack{\text{remaining on-farm} \\ \text{storage capacity}}} \geq \underbrace{\min\left\{\sum_l (b_{cd}^{\text{ofs}} - a_{cd}^{\text{ofs}}) H_l, (A_c - \tilde{A}_c) Y_c (1 - r_c)^{\max(d - T_c, 0)}\right\}}_{\text{grain harvested on day } d}. \tag{11}$$

Variable $\tilde{G}_{cd}^{\text{ofs}}$ is defined as follows with $\tau_d = b_{cd}^{\text{ofs}} - a_{cd}^{\text{ofs}}$:

$$\min\left\{\sum_l \tau_d H_l, (A_c - \tilde{A}_c) Y_c (1 - r_c)^{\max(d - T_c, 0)}\right\} \to \tilde{G}_{cd}^{\text{ofs}}. \tag{12}$$

Furthermore, variable $\tilde{A}_c$ is updated as follows with $\tau_d = b_{cd}^{\text{ofs}} - a_{cd}^{\text{ofs}}$:

$$\tilde{A}_c + \min\left\{A_c - \tilde{A}_c, \sum_l \frac{\tau_d H_l}{Y_c (1 - r_c)^{\max(d - T_c, 0)}}\right\} \to \tilde{A}_c. \tag{13}$$

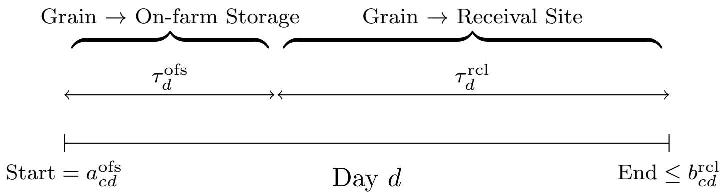


Figure 12: In Case 3, the remaining on-farm storage capacity is insufficient to hold the total harvest on day d.

3.3. Daily Harvest: Case 3

In Case 3, the remaining on-farm storage capacity is insufficient to hold the harvest on day d. Thus, using $\tau = b_{cd}^{\text{ofs}} - a_{cd}^{\text{ofs}}$ in (1) to define the potential harvest on day d, the logical test for Case 3 is

$$0 < \underbrace{R_c - \sum_{d'<d} \tilde{G}_{cd'}^{\text{ofs}}}_{\substack{\text{remaining}\\ \text{capacity}}} < \underbrace{\min\left\{ \sum_l (b_{cd}^{\text{ofs}} - a_{cd}^{\text{ofs}}) H_l, (A_c - \tilde{A}_c) Y_c (1 - r_c)^{\max(d - T_c, 0)} \right\}}_{\text{potential harvest on day } d}.$$

Initially, grain harvested on day d is sent to on-farm storage, and then once on-farm storage is full, the remaining grain is sent to the receival site. Let τ_d^{ofs} denote the time spent harvesting for on-farm storage, and let τ_d^{rcl} denote the time spent harvesting for the receival site. Then day d is divided into two intervals: the first τ_d^{ofs} hours is for grain destined for on-farm storage and the next τ_d^{rcl} hours is for grain destined for the receival site. See Figure 12 for an illustration. Note that τ_d^{rcl} may in fact be zero if $[a_{cd}^{\text{ofs}}, b_{cd}^{\text{ofs}}]$ is significantly wider than $[a_{cd}^{\text{rcl}}, b_{cd}^{\text{rcl}}]$.

It follows from (1) that $\tau_d^{\text{ofs}} < b_{cd}^{\text{ofs}} - a_{cd}^{\text{ofs}}$ satisfies

$$\underbrace{\sum_l \tau_d^{\text{ofs}} H_l}_{\text{harvest in } \tau_d^{\text{ofs}} \text{ hours}} = \underbrace{R_c - \sum_{d'<d} \tilde{G}_{cd'}^{\text{ofs}}}_{\substack{\text{maximum grain that can}\\ \text{be sent to on-farm storage}}},$$

which gives

$$\tau_d^{\text{ofs}} = \left(R_c - \sum_{d'<d} \tilde{G}_{cd'}^{\text{ofs}} \right) \div \left(\sum_l H_l \right). \tag{14}$$

Hence, for the first interval $[a_{cd}^{\text{ofs}}, a_{cd}^{\text{ofs}} + \tau_d^{\text{ofs}}]$, variables $\tilde{G}_{cd}^{\text{ofs}}$ and $\tilde{A}_c$ are updated using (1) and (2) as follows:

$$R_c - \sum_{d'<d} \tilde{G}_{cd'}^{\text{ofs}} \to \tilde{G}_{cd}^{\text{ofs}}, \tag{15}$$

$$\tilde{A}_c + \min\left\{ A_c - \tilde{A}_c, \sum_l \frac{\tau_d^{\text{ofs}} H_l}{Y_c (1 - r_c)^{\max(d - T_c, 0)}} \right\} \to \tilde{A}_c. \tag{16}$$

Now, after time $a_{cd}^{\text{ofs}} + \tau_d^{\text{ofs}}$, when on-farm storage is full, the delivery trucks will perform continuous cycles between the farm and receival site. Using similar arguments to Section 3.1, the duration of time on day d during which truck m can deliver to the receival site is

$$\eta_{dm} = \min\left\{ 24, b_{cd}^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m} + \delta_{\text{unload}} + \frac{Q_m}{U} + \frac{D^{\text{farm:rcl}}}{S_m}, \beta_d^{\text{rcl}} + \frac{D^{\text{farm:rcl}}}{S_m} \right\}$$
$$- \max\left\{ a_{cd}^{\text{ofs}} + \tau_d^{\text{ofs}}, \alpha_d^{\text{rcl}} - \delta_{\text{load}} - \frac{Q_m}{L} - \frac{D^{\text{farm:rcl}}}{S_m} \right\}$$

and the maximum number of cycles that can be completed by truck m on day d is

$$N_{dm} = \left\lfloor \frac{\max\{\eta_{dm}, 0\}}{\Delta_m} \right\rfloor,$$

where Δ_m is the cycle time for truck m defined by (4). Therefore, the total transport capacity on day d is

$$\sum_m Q_m N_{dm}.$$

Hence, τ_d^{rcl} is defined by

$$\tau_d^{\text{rcl}} = \min\left\{ \max\{b_{cd}^{\text{rcl}} - a_{cd}^{\text{ofs}} - \tau_d^{\text{ofs}}, 0\}, \left(\sum_m Q_m N_{dm}\right) \div \left(\sum_l H_l\right)\right\}. \tag{17}$$

Finally, for the second harvesting interval on day d, variables $\tilde{G}_{cd}^{\text{rcl}}$ and $\tilde{A}_c$ are updated using (1) and (2) as follows:

$$\min\left\{\sum_l \tau_d^{\text{rcl}} H_l, (A_c - \tilde{A}_c) Y_c (1 - r_c)^{\max(d - T_c, 0)}\right\} \rightarrow \tilde{G}_{cd}^{\text{rcl}}, \tag{18}$$

$$\tilde{A}_c + \min\left\{A_c - \tilde{A}_c, \sum_l \frac{\tau_d^{\text{rcl}} H_l}{Y_c (1 - r_c)^{\max(d - T_c, 0)}}\right\} \rightarrow \tilde{A}_c. \tag{19}$$

Note that $\tilde{A}_c$ must be updated in (16) before applying (18) to ensure that the crop sent to on-farm storage is added to the area harvested. Moreover, the harvesting hours on day d are $\tau_d = \tau_d^{\text{ofs}} + \tau_d^{\text{rcl}}$.

4. Moisture Management and Blending

This section describes the moisture management and blending components of the mathematical model. These components rely on the outputs from the simulation algorithm discussed in Section 3.

4.1. Quality Downgrades

Downgrade events are model inputs that reflect the grain grower's expectations around weather conditions. Each downgrade event is defined as a tuple (d_i, c_i, ω_i), where d_i is the day on which the downgrade occurs, c_i is the crop affected, and ω_i is the fraction of target grade affected (see Table 4). For example, a downgrade event with $d_i = 20$ and $\omega_i = 0.8$ means that on day 20 of the harvest, 80% of the remaining target grade in the field is downgraded to secondary grade.

A downgrade event affects grain harvested on the day of the downgrade plus all future days, and multiple downgrade events can be specified for each crop. For example, consider two downgrade events (d_1, c, ω_1) and (d_2, c, ω_2) for crop c. All grain harvested before the first downgrade on day d_1 meets the target grade. On day d_1, a fraction ω_1 of the remaining crop is downgraded, leaving $1 - \omega_1$ of grain meeting the target. On day d_2, another downgrade occurs; ω_2 of the remaining target grade is downgraded, leaving a fraction $(1 - \omega_1)(1 - \omega_2)$ of grain meeting the target.

If multiple downgrades for the same crop share the same day, then the model uses the one affecting the largest portion of the crop. Let $\tilde{\theta}_{cd}^{\text{field}}$ denote the fraction of remaining crop c that meets the target grade on day d. The target and secondary grades are assumed to be uniformly distributed throughout

Parameter	Unit	Description
d_i	–	Day on which the downgrade occurs
c_i	–	Crop affected by the downgrade
ω_i	Percentage	Proportion of target grade grain affected

Table 4: Input parameters for downgrade event i.

Parameter	Unit	Description
$\xi_c^{\text{ofs:exp}}$	Percentage	Proportion of grain in on-farm storage sent direct to port
$\xi_c^{\text{ofs:dom}}$	Percentage	Proportion of grain in on-farm storage sent direct to domestic customer
$\xi_c^{\text{ofs:rcl}}$	Percentage	Proportion of grain in on-farm storage sent to the receival site
$\xi_c^{\text{rcl:exp}}$	Percentage	Proportion of grain in receival site allocated to export market
$\xi_c^{\text{rcl:dom}}$	Percentage	Proportion of grain in receival site allocated to domestic customer

Table 5: Input parameters defining the destinations for crop c.

the crop. Thus, if $\tilde{\theta}_{cd}^{\text{field}} = 0.7$ for example, then 70% of the grain harvested on day d is target grade and 30% is secondary grade. Clearly,

$$\tilde{\theta}_{cd}^{\text{field}} = \tilde{\theta}_{c,d-1}^{\text{field}} \left(1 - \max \left\{ 0, \sup_{i:\, c_i = c,\, d_i = d} \omega_i \right\} \right), \tag{20}$$

where $\tilde{\theta}_{c0}^{\text{field}} = 1$ and

$$\sup_{i:\, c_i = c,\, d_i = d} \omega_i = \begin{cases} -\infty, & \text{if } \{\, i : c_i = c,\, d_i = d \,\} = \emptyset, \\ \max\limits_{i:\, c_i = c,\, d_i = d} \omega_i, & \text{otherwise.} \end{cases}$$

Hence, by mathematical induction,

$$\tilde{\theta}_{cd}^{\text{field}} = \prod_{d'=1}^{d} \left(1 - \max \left\{ 0, \sup_{i:\, c_i = c,\, d_i = d'} \omega_i \right\} \right). \tag{21}$$

In theory, it is more efficient to compute $\tilde{\theta}_{cd}^{\text{field}}$ recursively using equation (20) instead of the explicit formula (21). In practice, however, the harvest only spans one or two months and there are typically only several downgrade events per crop (if any), and thus (20) and (21) should be roughly the same in terms of computational speed.

4.2. Moisture Management

The model assumes that the receival site, domestic customer, and port terminal are the same for each crop. The inputs in Table 5 define the proportions of grain sent along each pathway in Figure 3.

Note that the grain held at the receival site is the sum of the grain sent directly from the field and the grain sent via on-farm storage. Hence, the sum of $\xi_c^{\text{ofs:exp}}$, $\xi_c^{\text{ofs:dom}}$, and $\xi_c^{\text{ofs:rcl}}$ in Table 5 should be 100%, and the sum of $\xi_c^{\text{rcl:exp}}$ and $\xi_c^{\text{rcl:dom}}$ should also be 100%.

The average field moisture level and the target moisture level for each crop are input parameters defined previously in Table 1. The average field moisture level is the average moisture content when the grain is harvested, and the target moisture level is the moisture content after moisture management in on-farm storage. If moisture management is not available for crop c, then the field moisture and target moisture levels for crop c are the same (that is, $M_c^{\text{field}} = M_c^{\text{target}}$). Moisture management only affects grain transported from on-farm storage (the links emanating from the on-farm storage node in Figure 3), since the moisture level of grain transported directly from the field cannot be modified. The mathematical model automatically calculates the weight increases obtained if moisture management is available. The time-delay for raising moisture content is ignored.

Increasing the moisture content of grain held in on-farm storage increases its weight and thus moisture is a key variable to consider. The derivations in the previous sections are based on the average field moisture level, denoted by M_c^{field} for crop c, which is the average moisture content for crop c during harvest (see Table 1). Thus, variables $\tilde{G}_{cd}^{\text{ofs}}$ and $\tilde{G}_{cd}^{\text{rcl}}$ are measured with respect to moisture level M_c^{field}, which is expressed as a fraction between zero and one.

A mass of G tonnes of crop c at the average moisture content M_c^{field} contains $(1 - M_c^{\text{field}})G$ tonnes of dry matter. Hence, changing the moisture content from M_c^{field} to M_c^{target} results in the weight G being multiplied by factor $(1 - M_c^{\text{field}})/(1 - M_c^{\text{target}})$. If $M_c^{\text{target}} > M_c^{\text{field}}$, then the weight increases, and conversely if $M_c^{\text{target}} < M_c^{\text{field}}$, then the weight decreases. There is no change when $M_c^{\text{field}} = M_c^{\text{target}}$, which is the case when moisture management for crop c is unavailable. Note that the on-farm storage limit R_c corresponds to moisture level M_c^{field}. The model assumes that the on-farm storage facilities can always accommodate weight increases via moisture management, even when at capacity.

Based on the arguments above, the weight of crop c received at port from on-farm storage is

$$W_c^{\text{ofs:exp}} = \xi_c^{\text{ofs:exp}} \frac{1 - M_c^{\text{field}}}{1 - M_c^{\text{target}}} \sum_d \tilde{G}_{cd}^{\text{ofs}}, \tag{22}$$

where $\xi_c^{\text{ofs:exp}}$ is the fraction of grain in on-farm storage allocated to the export market (see Table 5). Similarly, the weight of crop c received at the domestic sale point from on-farm storage is

$$W_c^{\text{ofs:dom}} = \xi_c^{\text{ofs:dom}} \frac{1 - M_c^{\text{field}}}{1 - M_c^{\text{target}}} \sum_d \tilde{G}_{cd}^{\text{ofs}}, \tag{23}$$

where $\xi_c^{\text{ofs:dom}}$ is the fraction of grain in on-farm storage allocated to the domestic market (see Table 5).

Equations (22) and (23) refer to grain sent directly from on-farm storage to the final destination. Alternatively, farmers can elect to use the grain handler's distribution network via delivery to a receival site during harvest. The weight of crop c delivered to the receival site from on-farm storage is

$$W_c^{\text{ofs:rcl}} = \xi_c^{\text{ofs:rcl}} \frac{1 - M_c^{\text{field}}}{1 - M_c^{\text{target}}} \sum_d \tilde{G}_{cd}^{\text{ofs}}, \tag{24}$$

where $\xi_c^{\text{ofs:rcl}}$ is the fraction of grain in on-farm storage allocated to the receival site (see Table 5). The total weight delivered to the receival site consists of the amount sent directly from the field and the amount sent via on-farm storage:

$$W_c^{\text{rcl}} = \underbrace{\sum_d \tilde{G}_{cd}^{\text{rcl}}}_{\text{direct from field}} + \underbrace{\xi_c^{\text{ofs:rcl}} \frac{1 - M_c^{\text{field}}}{1 - M_c^{\text{target}}} \sum_d \tilde{G}_{cd}^{\text{ofs}}}_{\text{via on-farm storage}}. \tag{25}$$

Hence, the weight of crop c received at port from the receival is

$$W_c^{\text{rcl:exp}} = \xi_c^{\text{rcl:exp}} \sum_d \tilde{G}_{cd}^{\text{rcl}} + \xi_c^{\text{rcl:exp}} \xi_c^{\text{ofs:rcl}} \frac{1 - M_c^{\text{field}}}{1 - M_c^{\text{target}}} \sum_d \tilde{G}_{cd}^{\text{ofs}}, \tag{26}$$

where $\xi_c^{\text{rcl:exp}}$ is the fraction of grain in the receival allocated to the export market (see Table 5). Similarly, the weight of crop c received at the domestic sale point from the receival is

$$W_c^{\text{rcl:dom}} = \xi_c^{\text{rcl:dom}} \sum_d \tilde{G}_{cd}^{\text{rcl}} + \xi_c^{\text{rcl:dom}} \xi_c^{\text{ofs:rcl}} \frac{1 - M_c^{\text{field}}}{1 - M_c^{\text{target}}} \sum_d \tilde{G}_{cd}^{\text{ofs}}, \tag{27}$$

where $\xi_c^{\text{rcl:dom}}$ is the fraction of grain in the receival allocated to the domestic market (see Table 5). The weights in (22)–(27) are needed to calculate the revenue along each supply chain pathway in Figure 3.

4.3. Blending: Grade Uplift in On-farm Storage

The mathematical model takes blending into account through a blending ratio B_c for each crop c (defined previously in Table 1), which is the number of tonnes of target grade required to uplift one tonne of secondary grade at the same moisture level. For example, a blending ratio of $B_c = 3$ means that when three tonnes of target grade are mixed with one tonne of secondary grade, the entire four tonne mixture meets the requirements for target grade. If blending is not possible for crop c, then $B_c = \infty$. Note that B_c is independent of the moisture—one tonne of secondary grade at moisture level M_c^{field} requires B_c tonnes of target grade at moisture level M_c^{field}, and one tonne of secondary grade at moisture level M_c^{target} also requires B_c tonnes of target grade at moisture level M_c^{target}. The mathematical model automatically calculates the optimum grade uplifts achieved based on the blending ratio for two blending scenarios: secondary grade held in on-farm storage is uplifted by blending with target grade also held in on-farm storage, and secondary grade sent directly to the receival site is uplifted by blending with target grade held in on-farm storage.

Using variables $\tilde{\theta}_{cd}^{\text{field}}$, the total amount of crop c sent to on-farm storage (measured with respect to the average field moisture level) is comprised of target grade and secondary grade as follows:

$$\sum_d \tilde{G}_{cd}^{\text{ofs}} = \underbrace{\sum_d \tilde{\theta}_{cd}^{\text{field}} \tilde{G}_{cd}^{\text{ofs}}}_{\text{target grade}} + \underbrace{\sum_d (1 - \tilde{\theta}_{cd}^{\text{field}}) \tilde{G}_{cd}^{\text{ofs}}}_{\text{secondary grade}}.$$

The two terms on the right-hand side are the unmanaged amounts (pre-blending) of target and secondary grade. If $B_c = \infty$, then blending is not possible, and the fraction of target grade crop c in on-farm storage is

$$\tilde{\theta}_c^{\text{ofs}} = \left(\sum_d \tilde{\theta}_{cd}^{\text{field}} \tilde{G}_{cd}^{\text{ofs}} \right) \div \left(\sum_d \tilde{G}_{cd}^{\text{ofs}} \right). \tag{28}$$

This formula is only relevant if crop c is allocated on-farm storage (that is, $R_c > 0$). In this case, the amount of grain sent to on-farm storage (the denominator in (28)) is non-zero, because on-farm storage is always used first before grain is sent to the receival site, and thus the ratio in (28) is well-defined.

When blending for crop c is possible (that is, $B_c < \infty$), the amount of secondary grade uplifted to target grade in on-farm storage (assuming both are at the same moisture level) is

$$\min \left\{ \underbrace{\sum_d \frac{\tilde{\theta}_{cd}^{\text{field}} \tilde{G}_{cd}^{\text{ofs}}}{B_c}}_{\substack{\text{maximum possible} \\ \text{uplift}}}, \underbrace{\sum_d (1 - \tilde{\theta}_{cd}^{\text{field}}) \tilde{G}_{cd}^{\text{ofs}}}_{\substack{\text{secondary grade} \\ \text{pre-blending}}} \right\}.$$

Therefore, after blending, the fraction of target grade crop c in on-farm storage is

$$\tilde{\theta}_c^{\text{ofs}} = \Bigg(\underbrace{\sum_d \tilde{\theta}_{cd}^{\text{field}} \tilde{G}_{cd}^{\text{ofs}}}_{\text{original target grade}} + \underbrace{\min \left\{ \sum_d \frac{\tilde{\theta}_{cd}^{\text{field}} \tilde{G}_{cd}^{\text{ofs}}}{B_c}, \sum_d (1 - \tilde{\theta}_{cd}^{\text{field}}) \tilde{G}_{cd}^{\text{ofs}} \right\}}_{\text{uplifted secondary grade}} \Bigg) \div \left(\sum_d \tilde{G}_{cd}^{\text{ofs}} \right). \tag{29}$$

Again, this formula is only relevant and well-defined if $R_c > 0$.

4.4. Blending: Grade Uplift pre-Receival

After blending grain held in on-farm storage (assuming $B_c < \infty$), any unblended target grade can potentially be blended with grain sent directly to the receival site. This is only possible if $\tilde{\theta}_c^{\mathrm{ofs}} = 1$, since $\tilde{\theta}_c^{\mathrm{ofs}} < 1$ implies that the original target grade in on-farm storage is insufficient to uplift all of the secondary grade, and thus there is no target grade left for additional blending with grain sent directly to the receival site. Thus, when $B_c = \infty$ or $\tilde{\theta}_c^{\mathrm{ofs}} < 1$, grain sent directly from the field to the receival site cannot be blended, and in this case the fraction of target grade crop c stored at the receival site is

$$\tilde{\theta}_c^{\mathrm{rcl}} = \Bigg(\underbrace{\sum_d \tilde{\theta}_{cd}^{\mathrm{field}} \tilde{G}_{cd}^{\mathrm{rcl}}}_{\text{target grade from field}} + \underbrace{\tilde{\theta}_c^{\mathrm{ofs}} \xi_c^{\mathrm{ofs:rcl}} \frac{1 - M_c^{\mathrm{field}}}{1 - M_c^{\mathrm{target}}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}}}_{\text{target grade from on-farm storage}} \Bigg) \div \Bigg(\underbrace{\sum_d \tilde{G}_{cd}^{\mathrm{rcl}}}_{\text{total from field}} + \underbrace{\xi_c^{\mathrm{ofs:rcl}} \frac{1 - M_c^{\mathrm{field}}}{1 - M_c^{\mathrm{target}}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}}}_{\text{total from on-farm storage}} \Bigg), \tag{30}$$

assuming that some crop c was indeed sent to the receival (that is, the denominator is non-zero).

Now, in the other case when $B_c < \infty$ and $\tilde{\theta}_c^{\mathrm{ofs}} = 1$ (blending is possible), it follows from the formula for $\tilde{\theta}_c^{\mathrm{ofs}}$ that

$$\min \left\{ \sum_d \frac{\tilde{\theta}_{cd}^{\mathrm{field}} \tilde{G}_{cd}^{\mathrm{ofs}}}{B_c}, \sum_d (1 - \tilde{\theta}_{cd}^{\mathrm{field}}) \tilde{G}_{cd}^{\mathrm{ofs}} \right\} = \sum_d (1 - \tilde{\theta}_{cd}^{\mathrm{field}}) \tilde{G}_{cd}^{\mathrm{ofs}}.$$

Hence, the amount of unblended target grade in on-farm storage is

$$\underbrace{\sum_d \tilde{\theta}_{cd}^{\mathrm{field}} \tilde{G}_{cd}^{\mathrm{ofs}}}_{\text{original target grade}} \underbrace{- B_c \min \left\{ \sum_d \frac{\tilde{\theta}_{cd}^{\mathrm{field}} \tilde{G}_{cd}^{\mathrm{ofs}}}{B_c}, \sum_d (1 - \tilde{\theta}_{cd}^{\mathrm{field}}) \tilde{G}_{cd}^{\mathrm{ofs}} \right\}}_{\text{blended target grade}} = \sum_d (B_c \tilde{\theta}_{cd}^{\mathrm{field}} + \tilde{\theta}_{cd}^{\mathrm{field}} - B_c) \tilde{G}_{cd}^{\mathrm{ofs}}.$$

This implies that the maximum amount of secondary grade that can be uplifted is

$$B_c^{-1} \min \left\{ \sum_d (B_c \tilde{\theta}_{cd}^{\mathrm{field}} + \tilde{\theta}_{cd}^{\mathrm{field}} - B_c) \tilde{G}_{cd}^{\mathrm{ofs}}, \xi_c^{\mathrm{ofs:rcl}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}} \right\}.$$

where $\xi_c^{\mathrm{ofs:rcl}}$ is the fraction of crop c in on-farm storage allocated to the receival site (see Table 5). Note that this value corresponds to the weight at moisture level M_c^{field}. Finally, the actual amount of secondary grade uplifted to target grade is

$$\begin{aligned} &\min \Bigg\{ \underbrace{B_c^{-1} \min \left\{ \sum_d (B_c \tilde{\theta}_{cd}^{\mathrm{field}} + \tilde{\theta}_{cd}^{\mathrm{field}} - B_c) \tilde{G}_{cd}^{\mathrm{ofs}}, \xi_c^{\mathrm{ofs:rcl}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}} \right\}}_{\text{maximum possible uplift}}, \underbrace{\sum_d (1 - \tilde{\theta}_{cd}^{\mathrm{field}}) \tilde{G}_{cd}^{\mathrm{rcl}}}_{\text{secondary grade pre-blending}} \Bigg\} \\ &\quad = B_c^{-1} \min \left\{ \sum_d (B_c \tilde{\theta}_{cd}^{\mathrm{field}} + \tilde{\theta}_{cd}^{\mathrm{field}} - B_c) \tilde{G}_{cd}^{\mathrm{ofs}}, \xi_c^{\mathrm{ofs:rcl}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}}, \sum_d B_c (1 - \tilde{\theta}_{cd}^{\mathrm{field}}) \tilde{G}_{cd}^{\mathrm{rcl}} \right\}. \end{aligned}$$

Thus, the fraction of target grade crop c stored at the receival site when $B_c < \infty$ and $\tilde{\theta}_c^{\mathrm{ofs}} = 1$ is

$$\begin{aligned} \tilde{\theta}_c^{\mathrm{rcl}} = \Bigg(&\underbrace{B_c^{-1} \min \left\{ \sum_d (B_c \tilde{\theta}_{cd}^{\mathrm{field}} + \tilde{\theta}_{cd}^{\mathrm{field}} - B_c) \tilde{G}_{cd}^{\mathrm{ofs}}, \xi_c^{\mathrm{ofs:rcl}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}}, \sum_d B_c (1 - \tilde{\theta}_{cd}^{\mathrm{field}}) \tilde{G}_{cd}^{\mathrm{rcl}} \right\}}_{\text{uplifted secondary grade from field}} \\ &+ \underbrace{\sum_d \tilde{\theta}_{cd}^{\mathrm{field}} \tilde{G}_{cd}^{\mathrm{rcl}}}_{\substack{\text{original target grade} \\ \text{from field}}} + \underbrace{\xi_c^{\mathrm{ofs:rcl}} \frac{1 - M_c^{\mathrm{field}}}{1 - M_c^{\mathrm{target}}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}}}_{\substack{\text{target grade from} \\ \text{on-farm storage}}} \Bigg) \div \Bigg(\underbrace{\sum_d \tilde{G}_{cd}^{\mathrm{rcl}}}_{\text{total from field}} + \underbrace{\xi_c^{\mathrm{ofs:rcl}} \frac{1 - M_c^{\mathrm{field}}}{1 - M_c^{\mathrm{target}}} \sum_d \tilde{G}_{cd}^{\mathrm{ofs}}}_{\text{total from on-farm storage}} \Bigg), \end{aligned} \tag{31}$$

Algorithm 2 Logic for calculating the fractions of target grade grain.

```
Compute variables $\tilde{\theta}^{\text{field}}_{cd}$ using the recurrence relationship (20)
for all crops $c$ do
    Initialize $0 \to \tilde{\theta}^{\text{ofs}}_{c}$ and $0 \to \tilde{\theta}^{\text{rcl}}_{c}$
    if on-farm storage is available for crop $c$ (i.e., $R_c > 0$) then
        if blending for crop $c$ is not possible (i.e., $B_c = \infty$) then compute $\tilde{\theta}^{\text{ofs}}_{c}$ using (28)
        else compute $\tilde{\theta}^{\text{ofs}}_{c}$ using (29)
        end if
    end if
    if crop $c$ is sent to the receival (i.e., $\xi^{\text{ofs:rcl}}_{c} > 0$ or $\sum_d \tilde{G}^{\text{rcl}}_{cd} > 0$) then
        if $B_c = \infty$ or $\tilde{\theta}^{\text{ofs}}_{c} < 1$ then compute $\tilde{\theta}^{\text{rcl}}_{c}$ using (30)
        else compute $\tilde{\theta}^{\text{rcl}}_{c}$ using (31)
        end if
    end if
end for
```

Parameter	Unit	Description
$P^{\text{ofs:exp}}_{c}$	Dollars per tonne	Target grade price for export sale direct from farm
$P^{\text{ofs:dom}}_{c}$	Dollars per tonne	Target grade price for domestic sale direct from farm
$P^{\text{rcl:exp}}_{c}$	Dollars per tonne	Target grade price for export sale via receival system
$P^{\text{rcl:dom}}_{c}$	Dollars per tonne	Target grade price for domestic sale via receival system
$\rho^{\text{ofs:exp}}_{c}$	Dollars per tonne	Secondary grade discount for export sale direct from farm
$\rho^{\text{ofs:dom}}_{c}$	Dollars per tonne	Secondary grade discount for domestic sale direct from farm
$\rho^{\text{rcl:exp}}_{c}$	Dollars per tonne	Secondary grade discount for export sale via receival system
$\rho^{\text{rcl:dom}}_{c}$	Dollars per tonne	Secondary grade discount for domestic sale via receival system

Table 6: Prices for crop c.

assuming the denominator is non-zero. The derivations above for the case $\tilde{\theta}^{\text{ofs}}_{c} = 1$ imply that grain in on-farm storage is sent to the receival site via two pathways: some of the grain is combined with grain sent directly from the field (to uplift secondary grade grain), and the remaining grain is sent separately to the receival without blending. The model maximizes the amount of secondary grade uplift in the first pathway. Note that moisture management in on-farm storage does not affect the amounts required for blending (since the grade is determined by the dry matter only), but it does affect the weight of grain sent to the receival from on-farm storage, and hence the ratio of target grade grain held at the receival. The process for calculating the fractions of target grade grain in on-farm storage and the receival site is summarized in Algorithm 2.

5. Revenues and Costs

As shown in Figure 7, the outputs from the mathematical model include the harvest duration, the total harvest from each crop, the revenue from each crop, and the logistics costs. The first two outputs are obtained directly from Algorithm 1. This section discusses the calculations for revenues and costs.

5.1. Revenues

Figure 13 shows the various pathways in the grain distribution network and equations (22), (23), (26), and (27) define the total grain delivered through each pathway. Table 6 defines the price input parameters; each sale pathway has a price for target grade grain and a price discount for secondary

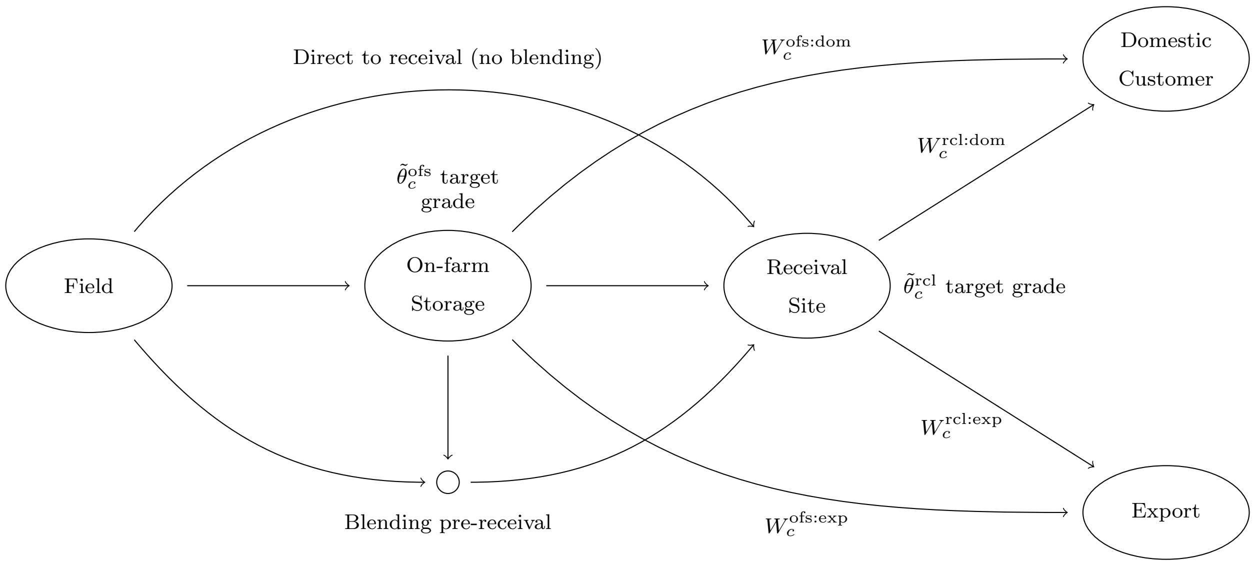


Figure 13: Possible pathways for harvested grain from crop c.

grade grain. For a given pathway with target grade price P and secondary grade discount ρ, the revenue received from W tonnes of grain with target grade fraction θ is

$$\underbrace{P\theta W}_{\text{target grade}} + \underbrace{(P-\rho)(1-\theta)W}_{\text{secondary grade}} = \underbrace{(P+(\theta-1)\rho)}_{\text{average price}} W.$$

This formula can be evaluated along each sale pathway as follows.

- From on-farm storage to port: $P = P_c^{\text{ofs:exp}}$, $\rho = \rho_c^{\text{ofs:exp}}$, $W = W_c^{\text{ofs:exp}}$, $\theta = \tilde{\theta}_c^{\text{ofs}}$.
- From on-farm storage to domestic customer: $P = P_c^{\text{ofs:dom}}$, $\rho = \rho_c^{\text{ofs:dom}}$, $W = W_c^{\text{ofs:dom}}$, $\theta = \tilde{\theta}_c^{\text{ofs}}$.
- From receival site to port: $P = P_c^{\text{rcl:exp}}$, $\rho = \rho_c^{\text{rcl:exp}}$, $W = W_c^{\text{rcl:exp}}$, $\theta = \tilde{\theta}_c^{\text{rcl}}$.
- From receival site to domestic customer: $P = P_c^{\text{rcl:dom}}$, $\rho = \rho_c^{\text{rcl:dom}}$, $W = W_c^{\text{rcl:dom}}$, $\theta = \tilde{\theta}_c^{\text{rcl}}$.

The total revenue is easily obtained by summing the revenues for the four sale pathways.

5.2. Costs

The costs can be divided into three categories:

- Trucking costs from farm to the receival site, from farm direct to port, and from farm direct to the domestic sale point;
- On-farm storage costs; and
- Grain handling costs for using the grain handler's distribution network (inclusive of transport costs from the receival site to port).

The trucking costs depend linearly on the trucking rates, which are input parameters defined in Table 7. The input parameters defining on-farm storage and grain handler fees are summarized in Table 8.

Parameter	Unit	Description
$\pi^{\text{farm:exp}}$	Dollars per tonne per kilometer	Trucking rate from farm to port
$\pi^{\text{farm:dom}}$	Dollars per tonne per kilometer	Trucking rate from farm to domestic customer
$\pi^{\text{farm:rcl}}$	Dollars per tonne per kilometer	Trucking rate from farm to receival site

Table 7: Input parameters defining the trucking rates.

Parameter	Unit	Description
σ_c	Dollars per tonne	Fixed fee for on-farm storage
$\lambda_c^{\text{ofs:exp}}$	Dollars per tonne	Fixed fee for export sale direct from farm
$\lambda_c^{\text{rcl:exp}}$	Dollars per tonne	Fixed fee for export sale via receival system
$\Lambda_c^{\text{rcl:exp}}$	Dollars per tonne per month	Time-based fee for export sale via receival system
$\lambda_c^{\text{rcl:dom}}$	Dollars per tonne	Fixed fee for domestic sale via receival system
$\Lambda_c^{\text{rcl:dom}}$	Dollars per tonne per month	Time-based fee for domestic sale via receival system
$t_c^{\text{rcl:exp}}$	Months	Time spent in receival system before export sale
$t_c^{\text{rcl:dom}}$	Months	Time spent in receival system before domestic sale

Table 8: Input parameters defining the on-farm storage and grain handler fees for crop c.

The total trucking cost is

$$\sum_c \Bigg(\underbrace{\pi^{\text{farm:exp}} D^{\text{farm:exp}} W_c^{\text{ofs:exp}}}_{\text{direct to port}} + \underbrace{\pi^{\text{farm:dom}} D^{\text{farm:dom}} W_c^{\text{ofs:dom}}}_{\text{direct to domestic customer}} + \underbrace{\pi^{\text{farm:rcl}} D^{\text{farm:rcl}} W_c^{\text{rcl}}}_{\text{to receival site}} \Bigg), \tag{32}$$

where $D^{\text{farm:exp}}$, $D^{\text{farm:dom}}$, and $D^{\text{farm:rcl}}$ are the transportation distances (see Table 3) and $\pi^{\text{farm:exp}}$, $\pi^{\text{farm:dom}}$, and $\pi^{\text{farm:rcl}}$ are the trucking rates (see Table 7).

The model assumes that farmers are charged an annual service fee for on-farm storage and this fee is proportional to the total storage capacity. Specifically, the total on-farm storage cost is

$$\sum_c \sigma_c R_c, \tag{33}$$

where σ_c is the cost rate of on-farm storage for crop c (see Table 8).

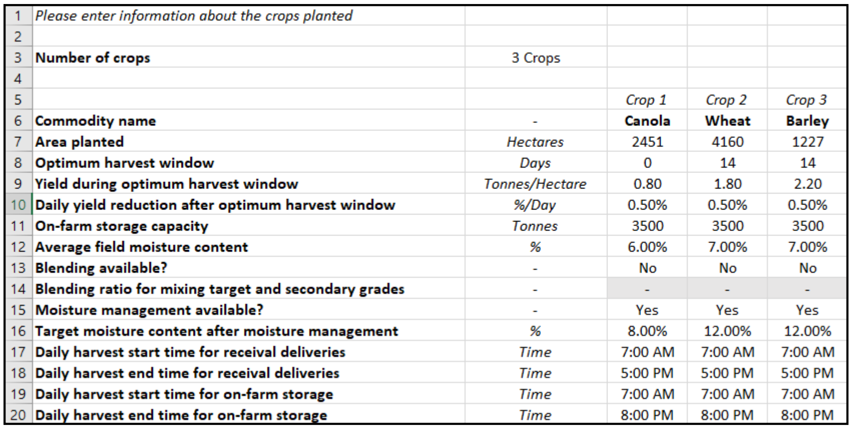
Finally, the total grain handling cost is

$$\sum_c \Bigg(\underbrace{\lambda_c^{\text{ofs:exp}} W_c^{\text{ofs:exp}}}_{\text{direct to port}} + \underbrace{(\lambda_c^{\text{rcl:exp}} + \Lambda_c^{\text{rcl:exp}} t_c^{\text{rcl:exp}}) W_c^{\text{rcl:exp}}}_{\text{receival site to port}} + \underbrace{(\lambda_c^{\text{rcl:dom}} + \Lambda_c^{\text{rcl:dom}} t_c^{\text{rcl:dom}}) W_c^{\text{rcl:dom}}}_{\text{receival site to domestic customer}} \Bigg), \tag{34}$$

where $t_c^{\text{rcl:exp}}$ and $t_c^{\text{rcl:dom}}$ are the receival storage times, $\lambda_c^{\text{ofs:exp}}$, $\lambda_c^{\text{rcl:exp}}$, and $\lambda_c^{\text{rcl:dom}}$ are the fixed handling fees, and $\Lambda_c^{\text{rcl:exp}}$ and $\Lambda_c^{\text{rcl:dom}}$ are the time-based handling fees (see Table 8).

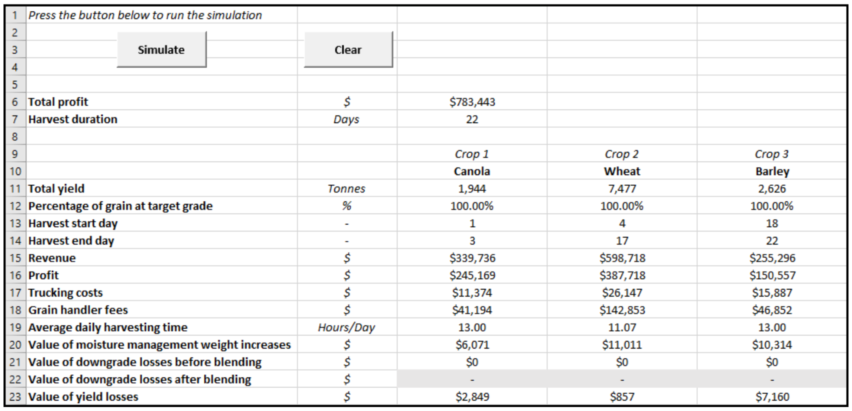
6. Decision Support System: Implementation and Testing

Our decision support system for farmers is a Microsoft Excel spreadsheet that implements the mathematical model described in the previous sections. Excel was chosen as the user platform because it is a familiar tool for farmers. The Excel spreadsheet includes five tabs for specifying the input variables:



1	*Please enter information about the crops planted*				
2					
3	**Number of crops**	3 Crops			
4					
5			*Crop 1*	*Crop 2*	*Crop 3*
6	**Commodity name**	-	**Canola**	**Wheat**	**Barley**
7	**Area planted**	*Hectares*	2451	4160	1227
8	**Optimum harvest window**	*Days*	0	14	14
9	**Yield during optimum harvest window**	*Tonnes/Hectare*	0.80	1.80	2.20
10	**Daily yield reduction after optimum harvest window**	*%/Day*	0.50%	0.50%	0.50%
11	**On-farm storage capacity**	*Tonnes*	3500	3500	3500
12	**Average field moisture content**	*%*	6.00%	7.00%	7.00%
13	**Blending available?**	-	No	No	No
14	**Blending ratio for mixing target and secondary grades**	-	-	-	-
15	**Moisture management available?**	-	Yes	Yes	Yes
16	**Target moisture content after moisture management**	*%*	8.00%	12.00%	12.00%
17	**Daily harvest start time for receival deliveries**	*Time*	7:00 AM	7:00 AM	7:00 AM
18	**Daily harvest end time for receival deliveries**	*Time*	5:00 PM	5:00 PM	5:00 PM
19	**Daily harvest start time for on-farm storage**	*Time*	7:00 AM	7:00 AM	7:00 AM
20	**Daily harvest end time for on-farm storage**	*Time*	8:00 PM	8:00 PM	8:00 PM

(a) Crops tab



1	*Press the button below to run the simulation*				
2					
3	Simulate	Clear			
4					
5					
6	**Total profit**	*$*	$783,443		
7	**Harvest duration**	*Days*	22		
8					
9			*Crop 1*	*Crop 2*	*Crop 3*
10			**Canola**	**Wheat**	**Barley**
11	**Total yield**	*Tonnes*	1,944	7,477	2,626
12	**Percentage of grain at target grade**	*%*	100.00%	100.00%	100.00%
13	**Harvest start day**	-	1	4	18
14	**Harvest end day**	-	3	17	22
15	**Revenue**	*$*	$339,736	$598,718	$255,296
16	**Profit**	*$*	$245,169	$387,718	$150,557
17	**Trucking costs**	*$*	$11,374	$26,147	$15,887
18	**Grain handler fees**	*$*	$41,194	$142,853	$46,852
19	**Average daily harvesting time**	*Hours/Day*	13.00	11.07	13.00
20	**Value of moisture management weight increases**	*$*	$6,071	$11,011	$10,314
21	**Value of downgrade losses before blending**	*$*	$0	$0	$0
22	**Value of downgrade losses after blending**	*$*	-	-	-
23	**Value of yield losses**	*$*	$2,849	$857	$7,160

(b) Results tab

Figure 14: Screenshots of the decision support tool.

- Crops tab (the input variables in Table 1)
- Equipment tab (the input variables in Table 2)
- Destinations tab (the input variables in Tables 3 and 5)
- Downgrades tab (the input variables in Table 4)
- Prices tab (the input variables in Table 6)
- Costs tab (the input variables in Tables 7 and 8)

Figure 14 contains screenshots of the crops tab and the results tab, which gives the harvest duration for each crop, the total harvest and revenue from each crop, and the cost breakdown.

For testing, we considered four hypothetical farms in the West Australian farming regions of Bonnie Rock, Morawa, Kukerin, and Munglinup. These regions belong to the Kwinana, Geraldton, Albany, and Esperance port zones, respectively; see the map in Figure 15. Table 9 gives the distance from each farm to the receival site, port, and domestic sale point.

Each hypothetical farm grows canola, wheat, and barley, harvested in this order. These are the three largest crops in Western Australia (**??**). Bonnie Rock in the Kwinana zone is an inland region with low rainfall, high temperatures, and low relative humidity during harvest; we assume that it experiences one

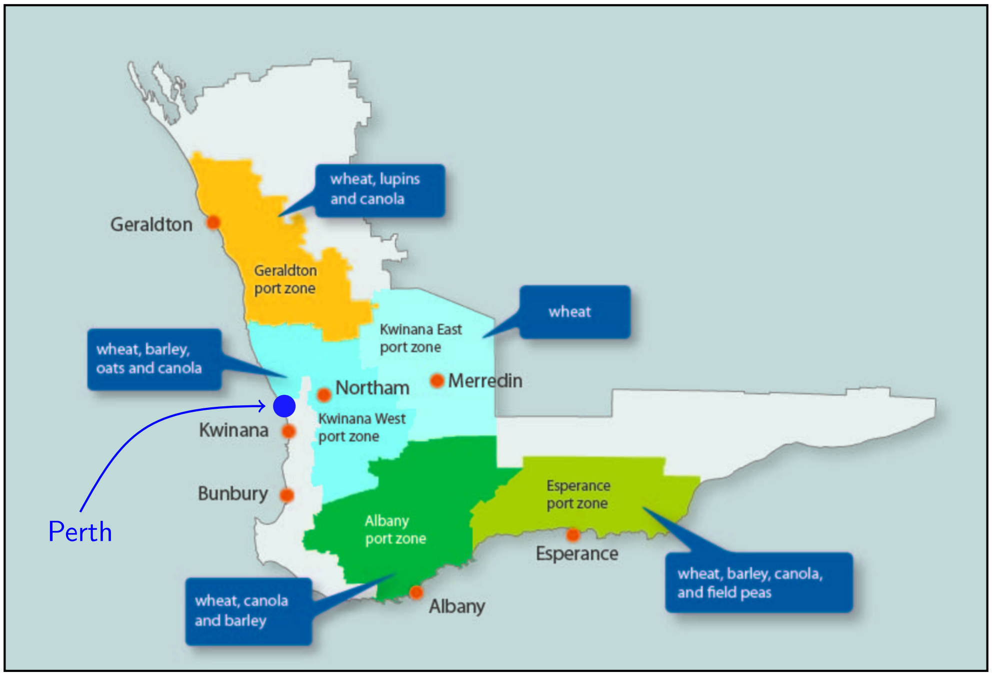


Figure 15: West Australian grain growing regions and export port zones (downloaded from the Department of Primary Industries and Regional Development website, https://www.agric.wa.gov.au/). The major city of Perth is shown in blue.

	Distance from Farm (km)		
Location	Receival Site	Port	Domestic Sale
Bonnie Rock	100	400	200
Morawa	20	170	400
Kukerin	40	290	450
Munglinup	50	50	700

Table 9: Distances for the testing scenarios.

downgrade event occurring on day 5 of the harvest, with 50% of the canola crop affected. Morawa and Kukerin, in the Geraldton and Albany zones respectively, experience medium rainfall, high temperatures and low relative humidity during harvest. These regions are prone to unfavourable weather, so we assume that there are two downgrade events during the harvest; the first downgrade on day 3 affects 50% of the canola crop, and the second downgrade on day 10 affects 50% of the wheat crop. Finally, Munglinup in the Esperance zone is a coastal location with wet and cool ambient conditions, leading to higher relative humidity and summer rainfall events. As such we assume that there are three downgrade events for this location, affecting 50% of the canola crop on day 2, 50% of the wheat crop on day 8, and 50% of the barley crop on day 14.

Canola and barley have shorter optimum harvest windows than wheat (?). We take the optimum harvest windows to be 3 days for canola, 14 days for wheat, and 10 days for barley. The crop areas and yields are given in Table 10. For all crops, we assume that moisture management is not available and the daily yield reduction after the optimum harvest window is 0.5% (?).

The daily harvest window for all farms is 7am to 8pm for on-farm storage and 7am to 5pm for receival deliveries. The number of harvesters and trucks depends on the scenario (specified later), but all harvesters have a harvesting rate of 25 tonnes per hour, and all trucks have a capacity of 55 tonnes

	Area Planted (ha)			Crop Yield (tonnes/ha)			Potential Harvest (tonnes)		
Location	Canola	Wheat	Barley	Canola	Wheat	Barley	Canola	Wheat	Barley
Bonnie Rock	300	1,100	600	1.85	1.66	3.95	555	1,826	2,370
Morawa	750	2,750	1,500	1.97	2.68	2.55	1,478	7,370	3,825
Kukerin	750	2,750	1,500	1.54	1.92	2.55	1,155	5,280	3,825
Munglinup	1,500	5,500	3,000	1.80	2.42	2.80	2,700	13,310	8,400

Table 10: Crop areas and yields; the yield data is obtained from **?**.

	Fixed Grain Handling Fee ($/tonne)											
	Bonnie Rock			Morawa			Kukerin			Munglinup		
	Canola	Wheat	Barley	Canola	Wheat	Barley	Canola	Wheat	Barley	Canola	Wheat	Barley
Export Sale	83	76	77	68	61	63	73	66	67	63	56	58
Domestic Sale	59	52	53	44	37	39	49	42	43	39	32	34

Table 11: Fixed storage and handling fees at receival site.

and an average speed of 80 kilometers per hour. The cost for trucking is assumed to be $0.04 per tonne per kilometer for travel to port or to a domestic customer, and $0.16 per tonne per kilometer for travel to receival sites. The latter occurs during the peak harvest period, which is why the cost is so much more expensive. The grain loading rate at the farm and the grain unloading rate at receival sites are both taken as 1000 tonnes per hour.

We consider a blending ratio of 1.0 for each crop. For the grain prices, using data from AWB (https://www.awb.com.au/), we took the price of canola as $520 per tonne for each farm, the price of barley as $285 per tonne for each farm, and the price of wheat as $285 per tonne for Bonnie Rock, $281 per tonne for Morawa, $277 per tonne for Kukerin, and $260 per tonne for Munglinup. The price discounts for secondary grade are $40 per tonne for canola at all farms, $5 per tonne for wheat at Bonnie Rock, and $7 per tonne for wheat at Morawa; in all other situations there is no discount.

We assume that on-farm storage costs $13 per tonne for canola, $7.80 per tonne for wheat and $9 per tonne for barley at all farms. The fixed fees for receival storage and handling are given in Table 11. In Western Australia, there are typically no time-based handling fees and hence these have been ignored. For direct-to-port deliveries from on-farm storage, the grain handling fee at port is $45 per tonne from Munglinup and $36 per tonne from the other locations.

The base case for each farm involves no on-farm storage—that is, all grain is sent to the receival site—with 90% of the grain allocated to the export market and 10% allocated to a domestic sale. The farms in Bonnie Rock, Morawa and Kukerin use one harvester and one truck in the base case, and the farm in Munglinup uses two harvesters and one truck in the base case.

To generate different scenarios, we introduced the following variations to the base case.

(1) On-farm storage with capacity to store the entire harvest.

(2) One additional harvester and one additional truck with the same specifications as before.

(3) Receival allocation: 70% export, 30% domestic sale.

(4) On-farm storage allocation: 30% export, 10% domestic sale, 60% receival site.

(5) On-farm storage allocation: 50% export, 10% domestic sale, 40% receival site.

		Scenarios: % change						
	Base Case	(1,4)	(2)	(3)	(1,2,4)	(1,3,5)	(2,3)	(1,2,3,5)
Canola target fraction	1.00	-	-	-	-	-	-	-
Wheat target fraction	1.00	-	-	-	-	-	-	-
Barley target fraction	1.00	-	-	-	-	-	-	-
Harvest duration	23 days	−30.4%	−43.5%	-	−65.2%	−30.4%	−43.5%	−65.2%
Total yield	4,661 tonnes	+1.4%	+1.7%	-	+1.9%	+1.4%	+1.7%	+1.9%
Total profit	$1,034,726	+6.1%	+1.5%	+2.2%	+10.3%	+10.4%	+3.7%	+11.1%
Grain handling cost	$349,532	−24.5%	+1.7%	−6.4%	−34.6%	−37.5%	−4.7%	−37.2%
Yield loss value	$74,577	−70.6%	−89.9%	-	−100%	−70.6%	−89.9%	−100%

Table 12: Results for Bonnie Rock.

		Scenarios: % change						
	Base Case	(1,4)	(2)	(3)	(1,2,4)	(1,3,5)	(2,3)	(1,2,3,5)
Canola target fraction	0.61	+64.3%	+17.7%	-	+64.3%	+64.3%	+17.7%	+64.3%
Wheat target fraction	0.57	+74.7%	+28.7%	-	+74.7%	+74.7%	+28.7%	-
Barley target fraction	1.00	-	-	-	-	-	-	-
Harvest duration	40 days	−20.0%	−45.0%	-	−57.5%	−20.0%	−45.0%	−57.5%
Total yield	9,739 tonnes	+1.8%	+3.8%	-	+4.5%	+1.8%	+3.8%	+4.5%
Total profit	$2,282,570	+4.3%	+3.8%	+2.0%	+6.9%	+7.3%	+6.0%	+9.9%
Grain handling cost	$630,865	−21.8%	+3.7%	−7.4%	−19.7%	−33.8%	−3.9%	−32.0%
Yield loss value	$148,108	−26.6%	−63.6%	-	−80.8%	−26.6%	−63.6%	−80.8%

Table 13: Results for Kukerin.

We considered seven scenarios formed by combining the base case with one or more of the variations defined above. The seven scenarios are: variations 1 and 4; variation 2 only; variation 3 only; variations 1, 2, and 4; variations 1, 3, and 5; variations 2 and 3; and variations 1, 2, 3, and 5. Tables 12–15 report the model outputs for the base case (no on-farm storage) and each scenario. Note that in these tables, the numbers in the base case column are raw values, and the numbers in the scenario columns are percentage changes with respect to the base case. The model reports an increase in profit for each scenario over the base case; this is because the variations to the base case are generally advantageous to the farmer (either through on-farm storage to enable blending, additional harvesting and trucking capacity, or diverting more grain to domestic sales with reduced grain handler fees). Figure 16 shows the increase in profit for each scenario compared with the base case.

		Scenarios: % change						
	Base Case	(1,4)	(2)	(3)	(1,2,4)	(1,3,5)	(2,3)	(1,2,3,5)
Canola target fraction	0.59	+70.9%	+14.4%	-	+70.9%	+70.9%	+14.4%	+70.9%
Wheat target fraction	0.54	+86.8%	+25.2%	-	+86.8%	+86.8%	+25.2%	+86.8%
Barley target fraction	1.00	-	-	-	-	-	-	-
Harvest duration	49 days	−20.4%	−46.9%	-	−57.1%	−20.4%	−46.9%	−57.1%
Total yield	11,816 tonnes	+2.3%	+5.2%	-	+5.9%	+2.3%	+5.2%	+5.9%
Total profit	$2,890,145	+4.4%	+5.1%	+2.0%	+7.9%	+8.2%	+7.1%	+10.4%
Grain handling cost	$709,196	−20.1%	+5.1%	−8.0%	−17.2%	−31.5%	−3.3%	−29.0%
Yield loss value	$243,665	−24.5%	−60.3%	-	−72.8%	−24.5%	−60.3%	−72.8%

Table 14: Results for Morawa.

		Scenarios: % change						
	Base Case	(1,4)	(2)	(3)	(1,2,4)	(1,3,5)	(2,3)	(1,2,3,5)
Canola target fraction	0.50	+100%	-	-	+100%	+100%	-	+100%
Wheat target fraction	0.50	+100%	+11.4%	-	+100%	+100%	+11.4%	+100%
Barley target fraction	0.50	+100%	-	-	+100%	+100%	-	+100%
Harvest duration	58 days	−34.5%	−43.1%	-	−55.2%	−34.5%	−43.1%	−55.2%
Total yield	22,186 tonnes	+5.0%	+6.2%	-	+7.8%	+5.0%	+6.2%	+7.8%
Total profit	$5,184,747	+5.2%	+5.7%	+2.1%	+7.9%	+8.2%	+7.9%	+10.3%
Grain handling cost	$1,221,695	−11.3%	+6.2%	−8.7%	−8.9%	−18.8%	−3.0%	−16.6%
Yield loss value	$620,671	−41.2%	−52.9%	-	−68.6%	−41.2%	−52.9%	−68.6%

Table 15: Results for Munglinup.

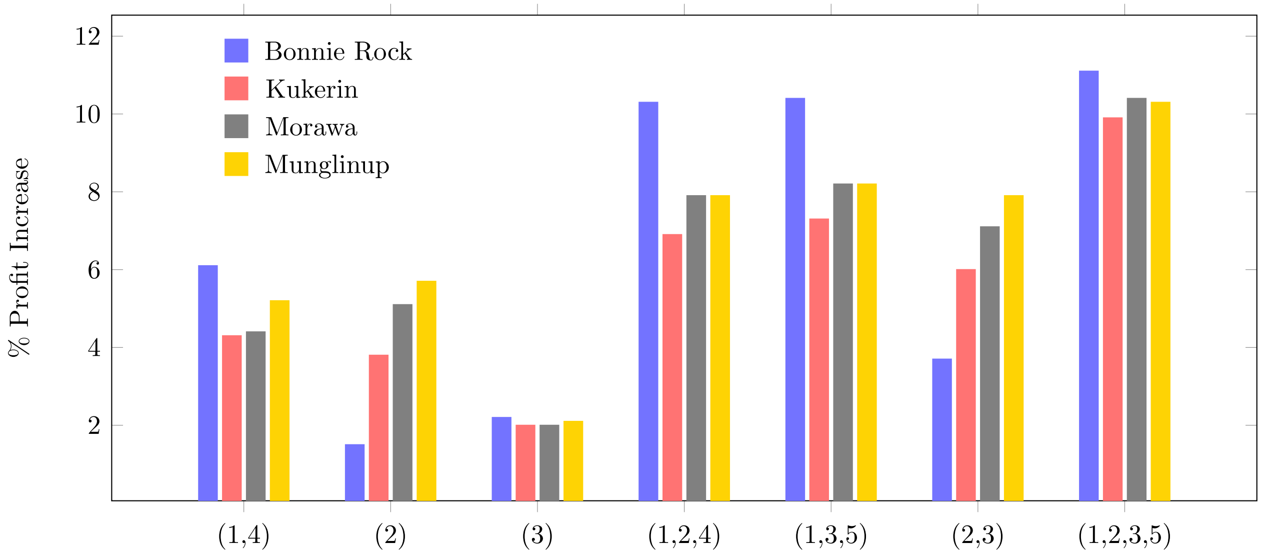


Figure 16: Profit increase for each scenario with respect to the base case.

7. Discussion and Conclusion

The decision support system described in this paper was developed during a collaborative research project with Global Grain Handling Solutions Pty Ltd. The system is underpinned by a discrete-time mathematical model, described in Sections 3–5, that builds on the existing cost-benefit models for on-farm storage proposed in **??**). Our model incorporates more advanced features such as moisture management and blending, in addition to catering for multiple crops with different on-farm storage allocations. In Section 6, we tested the model on various scenarios for four prototypical grain farms in Western Australia, each from a different region with different weather characteristics. The base case for each farm involved no on-farm storage and we then considered different scenarios with on-farm storage, more harvesters and trucks, or different supply chain pathways. The results show that on-farm storage is highly beneficial to grain growers, with a minimum profit increase of 4.3% over all scenarios involving on-farm storage compared with the base case. The increase in profit is over 10% in some scenarios, and the model correctly shows that with on-farm storage, harvest duration and yield losses decrease, and the total yield increases. Interestingly, the changes in profit from scenario to scenario do not always follow the same pattern across all farms—for example, for the farm in Bonnie Rock, investing in on-farm storage (scenario (1,4)) appears to be more profitable than investing in additional equipment (scenario (2)), but for the farm in Morawa the opposite is true. The decision support system enables farmers to compare these different investment options in a robust, objective manner. The reader can also consult the recent paper by **?**, where this decision support system was used to explore how changes in the Australian grains industry are affecting farm profitability.

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