RELIABILITY OF AGRICULTURAL SYSTEMS

The goal of every agricultural systems manager (ASM) is to develop a total system that functions without fail. We know that this is an unobtainable goal, yet we strive to approach this by setting a goal of some successful percentage, such as 97% of the time the system operates as we need it. In order to obtain a high reliability for a system we must set a reasonable goal and plan for how to get there. The planning involves analysis of each component and function of the system. Then we consider what devices are replaced, which require backup, and how much we can afford to spend on our way to attaining the system reliability goal.

Measuring performance of a system can be done in several ways, all depending on which of the criteria we wish to evaluate. The technical manager spends a high proportion of time evaluating the performance of the system. Every agricultural system can be viewed as a group of processes and components (including humans) that must perform satisfactorily and in a timely fashion to achieve the output we have specified. Within our context we shall consider reliability to generally mean the probability that our system performs successfully. And we as managers will predetermine what "success" is.

We will now explore some of the management implications of our working definition of reliability within the context of agricultural systems. In production management reliability is most often viewed as the probability that the system will perform satisfactorily when called upon under specified conditions. Thus, reliability of a system, a subsystem, a function, or a component is measured in terms of probabilities. Quantitatively, a component or system is expressed as 0.9999 or 0.94 or some positive value less than 1.00. It should be noted that not all the system components necessarily have to perform at the same time, but each component must operate at the proper time for a sufficient period of time to ensure that the system accomplishes its purpose. Operation of the jet propulsion engine on a space shuttle launch is a good example. The engine must perform for only a few critical minutes in the proper way to be deemed successful. ecified conditions" under which a unit or component is to function. Systems that would perform under all extremes of heat, dust, humidity, poor field or manufacturing conditions, vibration, and mismanagement and all possible conditions would be ideal—ideal but not very realistic. Systems must be evaluated within the limits of their intended use. These conditions should be explicitly stated or recognized before evaluating the performance reliability of a system. For example, it would not be a fair evaluation to state that the reliability was poor if a citrus harvest system failed because the hydraulic lift truck for moving pallets was stolen, or if a computer designed to operate in an air-conditioned working environment failed because it was exposed to 125°F temperatures in an incubation chamber. It is the job of the technical or agricultural systems manager to assist in planning and in setting needed, reasonable expectations.

Some critical processes may require component performances of extremely high reliability (launching astronauts, embryo incubation, refrigeration, evaporators, etc.). The words perform satisfactorily also carry great significance in the definition and in understanding the performance reliability concept. Tolerances must be specified so as to establish what acceptable reliability means. From the very beginning of the existence of a system degradation begins. As each component within the system ages, wears, or depletes with use, the output or system performance begins to vary. For a substantial period, the variance may be so minimal that it is not worthy of notice. Eventually the system may continue to function, but not at an acceptable level. A corn harvesting system consisting of a combine, tractor, wagons, augers, bucket elevators, grain drier, and storage bins is a good example. As the combine ages, field losses of grain increase. As the augers and bucket elevators wear, grain kernel damage increases and system flow rates decline. Drying rates may increase and fuel costs rise. There eventually comes a time when the unacceptable level is reached, and the system is deemed no longer reliable. One day the value may be 0.91 and the next day it can be deemed inoperable (zero). The manager can elect to replace components, change the system, get backup units, or even hire another system to perform the task.

Setting the acceptable levels of performance of various components is not always easy. First, one must recognize what criteria are typical. The following criteria often need acceptability levels established in field production agriculture:

- Speed of operation
- Crop loss acceptability
- Quality and condition of crop
- Timeliness of completion date or times
- Cost–profitability trade-offs
- Field efficiency
- Capacity of each system needed

To dwell on this topic of acceptability for just a moment, we might consider a farmer evaluating the levels of acceptability regarding capacity of his soybean harvest system. Due to the limited days of good weather in his Midwest fall season, he may know that his harvest system must maintain the overall daily capacity of 55 acres per day. If harvest capacity is less, he does not get all of the crops in before the snow arrives and ends the season. Low reliability or high downtime, as he may phrase it, would not be acceptable. Likewise, a corn producer must view the quality of the harvested crop. It would do no good to continue running a combine if the threshing unit had become so worn that the machine produced a crop with 20% of kernels cracked. The crop would be evaluated poorly when graded at the grain terminal and deemed a very low market grade (sample grade would yield a very low price)!

In biological processing, packaging, or food processing, added factors such as the following could be determinants:

- Percent loss
- Yield
- Critical time durations met
- Cost per unit
- Food quality
- Food safety
- Contamination
- Cost of rework

Let's suppose a pecan processor is making bagged, crushed nuts for a candy manufacturer. The pecan processor delivers several truckloads of nuts. It is found that the nuts contain many pieces of shell. The candy manufacturer rejects the product (they do not want lawsuits from customers who break their teeth). If it is found that the screening devices are no longer capable of use because they are too worn, then the reliability of the processing line becomes zero.

HUMAN INTERACTIONS

Most agricultural systems consist of mechanical equipment and humans. In some cases biological, chemical, or physical processes are components as well. Humans are often required for planning, initiation, maintenance, operation, vigilance, ending operations, or any variety of tasks. They may provide the "backup" to any number of potentially failed components.

If one considers only equipment or process factors in systems planning, then one is assuming operator performance to have the probability of r = 1.00. Obviously, the reliability of humans is not perfect, or 1.00. Leaving out the valuation of human elements would give grossly inflated systems reliabilities, as often happens. However, the proper management of human interaction can lead toward exceptionally high systems reliability, as we will see later in this chapter.

Humans are much more complex than any machine or process used in agricultural systems today. The challenge of duplicating higher human functions such as perception, recognition, and decision making has just begun, through artificial intelligence algorithms and electronic circuitry. The field of robotics is still expensive and in its infancy.

Human limitations are numerous. They are less stable than machines and are influenced by and more responsive to the work environment. Human performance is affected by physiological conditions, fatigue, noise, incentives, rewards, previous learning, and conditioning (good and bad). However, thanks to the study of human factors, or ergonomics, it is possible to treat human operators mathematically, as one does for other components and processes as we estimate reliability of systems. In terms of inputs and outputs, a common descriptive language exists from empirically derived research. This permits a mathematical treatment that can be applied to man, machine, or processes. We will return to this topic.

ESTIMATING THE SYSTEMS RELIABILITY VALUES

There are many questions for which estimation of reliability can assist in providing technical management answers. Always remember: The system must work when you need it. If it doesn't, all other aspects of a system are irrelevant. Here are just a few of the decisions that quantification can help answer:

- What percent of the time does this system really work?
- Which machine should be replaced to gain reliability?
- Should a new machine (or person) be purchased, or can a used machine be utilized?
- If other machines are available for "backup," how will this affect performance?
- How many "backup" units are needed?
- Which is more profitable renting, buying, or leasing?
- Will the system work if a particular unit fails?
- How does the human operator or manager in the system affect the probability of success? Do we need more management or less?
- How much will I gain in efficiency and capacity by increasing reliability or decreasing it and saving costs?
- What level of reliability is economically acceptable?

Production managers, salespersons, service personnel, and design engineers need to fully understand that system reliability is inherently the absolute bottom line in selecting equipment, people, and resources. Granted, selections are often made for other reasons (economic, safety, etc.), but reliability must always be at an acceptable level.

Estimating System Reliabilities

Components in Series

Many agricultural systems are arranged in series. The successful operation of a series system depends upon the successful performance of each component in the system: man; machine; or process. Two conditions often exist:

(1) Failure of any given unit results in a complete system failure, and

(2) the component failures are independent of each other.

Gordon showed that in series systems the probability that a system operates acceptably is the product of the reliabilities of the individual units or components.

If, for example, there are three components in a system, each with a reliability of 0.90, the reliability of the system would be a product of the three, or 0.729. Lusser presented the original formula for sequential events as:

$$R_{\text{system}} = R_1 {}^* R_2 {}^* R_3 {}^* \cdots {}^* R_n \tag{2-1}$$

The inherent weakness of most agricultural systems is the sequential nature, leading to overall low system performance reliability [4]. Think of a simple wheat harvesting system consisting of a tractor (0.90) to pull a wagon (0.90) that the combine (0.85) unloads into a storage tank (Fig. 2-1). The system reliability is only 0.6885. One unit fails and the whole system stops.

As more units are added to an agricultural system, each unit must be very close to unity (1.00) if the system is to remain acceptable. There

With parallel units, there are two or more that are performing the same function or are available to perform the same function at any particular time. This is referred to as either "backup" or redundancy. NASA missile research showed that parallel system reliability of like units can be estimated by combining the probabilities of unit success (reliabilities) of the individual units using the following formula [2]:

$$R_{\text{system}} = [1 - (1 - r)^m]^n \tag{2-2}$$

where:

- Rsystem is the reliability of the system.
- r is the reliability of a single unit.

- m is the number of components in parallel for each function.
- n is the number of functions the unit must perform.

Suppose one were baling hay and a tractor is needed to pull and power the baler. The farmer needs only a single functioning tractor at one time to pull the hay baler. However, if he had two identical tractors, both available 100% of the time if needed and, say, with unit reliabilities of 0.90, the joint probability of having a tractor available to pull the baler would be (Fig. 2-2):

$$R_{\text{tractor fuction}} = [1-(1-0.9)^2]^1$$
$$= 0.99$$

Thus, even with relatively low component reliabilities such as 0.70, a system with four units in parallel could achieve a system reliability of 0.992. In some systems the components could be very different types, such as a human backing up a machine unit, or vice versa.

Achieving redundancy, or "backup," in a system can be accomplished in several ways. Some common management alternatives are:

- Purchasing another machine
- Borrowing a "backup" machine when needed
- Using a unit from another operation
- Leasing another unit
- Renting another unit
- Assured availability warranty from manufacturer

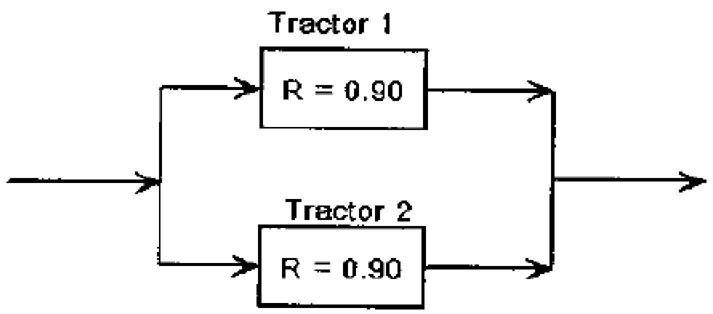

Figure 2-2 Parallel identical units: $R_{\text{sys}} = [1-(0.1)^2]^1 = 0.99$.

Equation (2-2) is very useful because it expresses the real world of agricultural systems fairly well. The equation, however, applies only where the components in parallel for each of the n functions is exactly the same and unit reliability of each component is the same. Where these conditions do not apply, the derivation becomes more complex. And in reality it is rare to find two components or processes that are identical. For example, a new tractor may be in use with a reliability value of 0.95; but if the new tractor were to fail, the manager might bring in the old tractor from the shed (0.78) to back the newer unit up. This situation is very typical in field production agriculture and processing. Complexity occurs in deriving a set of equations, since the selection of the first unit is a parameter open to management. An iterative technique is essential.

Heterogeneous Units

Redundant units in parallel possessing different reliability values can be termed heterogeneous backup units. An iterative technique would work as follows: For the components in parallel, select the first. If the system only had that one, that subsystem reliability, Rs, would be equal to that of the component, R1. The reliability of the subsystem that included both components 1 and 2 (call it Rs(1,2)) would be the probability that the first unit functions (R1) plus the probability that the first unit fails (1 - R1) and the backup unit functions (R2). These last two reliabilities are multiplied to get the reliability of the backup system's functioning. Therefore, the reliability of the subsystem with a heterogeneous backup unit is

$$R_{s(1,2)} = R_1 + (1 - R_1)^* R_2 \qquad (2\text{-}3)$$

and for three parallel components is

$$R_{s(1,2,3)} = R_{s(1,2)} + (1 - R_{s(1,2)})^* R_3 \qquad (2\text{-}4)$$

Thus a general form would be

$$R_{s(1,2,3,\ldots,\mathrm{n})} = R_{s(1,2,\ldots,n-1)} + (1 - R_{s(1,2,\ldots,n-1)}) R_n \qquad (2\text{-}5)$$

Suppose two tractors are in parallel to form some subsystem. Let’s say that tractor 1 has a unit reliability of 0.90 and unit 2 is 0.78 (Fig. 2-3). Using Eq. (3), the reliability calculation would be:

$$R_{s(1,2)} = R_1 + (1 - R_1) R_2$$

Assuming Tractor 1 is selected first,

$$R_{s(1,2)} = 0.9 + (1 - 0.9)^* 0.78 = 0.978$$

The dynamics of production agriculture systems can become quite complex. Tractors may back up several subsystems, performing several functions, or be unable to serve as backups because of incompatibility of components or unmatched horsepower requirements. Reliabilities seldom are identical. The best approach is to calculate reliabilities for each subsystem separately and then to combine the subsystem values to attain the complete system reliability.

Suppose farmer A had two enterprises: dairy and peanuts. To some extent, the two separate agricultural systems must share equipment, such as tractors. Farmer A must recognize the strengths and weaknesses of this arrangement. Let's analyze farmer A's peanut harvesting operation, as shown in the following table and Figure 2-4. Suppose it consists of a large tractor pulling a peanut combine. A wagon attached to the combine receives the peanuts. Another small tractor pulls the wagon away, empties the load and returns just in time to exchange wagons with the combine unit. The iterative process assumes that the unit of highest reliability is always used first. This is the usual management situation.

The calculations of each subsystem would be as follows:

Subsystem 1:

- Rss1 = 0.83 + 0.17 * (0.83)^3 = 0.9272

Subsystem 2:

- Rs(1,2) = 0.85 + (1 - 0.85) * 0.72 = 0.9580

Farmer A's System

Subsystem	Machinery available	Reliabilities
1	1 100-hp tractor dedicated to pulling combine	0.83 each
1	100-hp tractor backs up pulling unit, small tractor in subsystem 5, and tractor working at the dairy operation	
2	1 peanut combine	0.85
2	1 backup combine	0.72
3	1 wagon behind combine	0.90
4	1 wagon behind tractor	0.90
4	1 extra wagon to back up either subsystem 3 or 4	0.90
5	1 40-hp tractor to pull wagon	
6	1 40-hp tractor to pull wagon	

Note: The table provides information about the machinery available for each subsystem, along with their respective reliabilities.

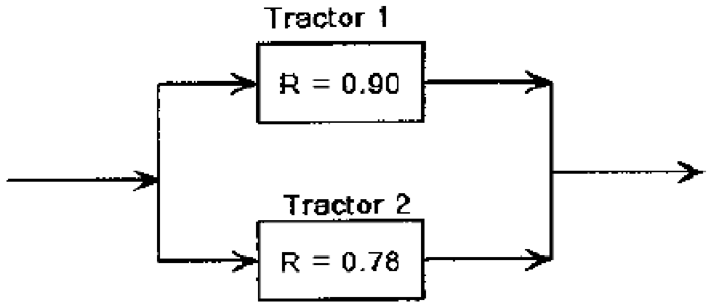

Figure 2-3 Heterogeneous parallel machines: R = 0.90 + 0.10 * 0.78 = 0.978.

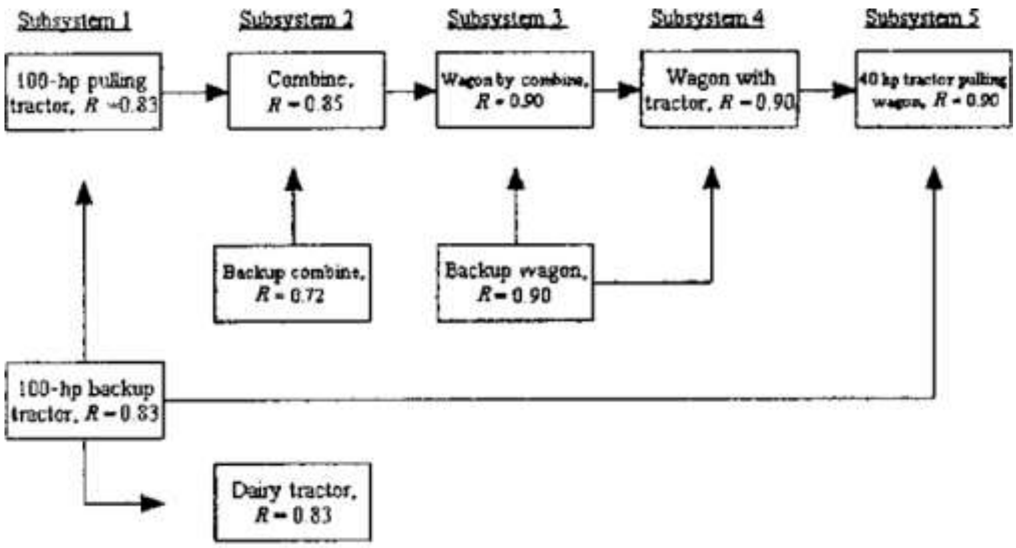

Figure 2-4 Peanut combine system with backups.

Subsystems 3 and 4. The added backup wagon is the same as having three wagons that must perform two functions. Thus, from Eq. (3):

$$R_{ss(3,4)} = 0.90 + 0.10(0.90)^2$$
$$= 0.9810$$

Subsystem 5. From Equation (3):

$$R_{ss(3,4)} = 0.83 + (1 - 0.83)*(0.83)^3$$
$$= 0.83 + 0.0972 = 0.9272$$

Total System. From Eq. (1):

$$R_{system} = 0.9272*0.958*0.9810*0.9272$$
$$= 0.8079$$

The iterative processes assume that the unit of highest reliability is always used first. In fact, one can see that doing otherwise might greatly diminish system reliability. The old philosophies of "I'll use the old ones first" and "I'll use the old ones 'until they wear out" simply do not pay.

Estimating Values of Individual Components

Just how does one attain the reliability values for machines, components, and functions? Absolutely the best way is to keep records on these units. Fortunately, computers and spreadsheet software make this task much easier today. Line foremen can record downtimes, as can mechanics or service managers. In the case of agricultural field machines, this is certainly "doable." One of the world's largest field production sugarcane growers actually tracks each field machine and keeps a life record via computer database. A farmer could keep uptime and downtime records on a spreadsheet. In the case of processing plants, maintenance records often exist, and data estimates can be made by "recouping" the past information on items such as blenders, mixers, conveyors, bagging machines, and chemical processes. Where no life records exist, a good manager can collect sample data using good statistical techniques. Data can sometimes be gathered from other plants or the engineering firms producing the devices. The literature in processing journals does contain some reliability data. And when all else fails, an ASM could interview users of the machines and processes to backtrack in time to find failures and downtimes. The real bottom line is that attaining accurate unit reliability data requires forward planning. However, the effort to attain the data will yield great rewards in system performance.

Estimating Human Component Values

Many situational factors affect human performance. Operator unit reliabilities can range from zero to 0.99999 reliability. It becomes quite difficult to develop generalized relationships. The trade-off considerations that can be applied are consequently qualitative. Costs, hazards, state of the technology, and other factors often influence the human role in an agricultural system. It was also shown that the reliability in a space system with a maintenance person available could be higher than that of the same system with automated devices as a monitor or "fail-safe" unit. Humans can seldom be rivaled by equipment. The following illustrates the trade-offs that exist with the use of humans.

Human long-term unit values seldom exceed 0.78. This is because there are so many time deductions one must make. Ignoring time lost for weekends and hours beyond 40 per week, the following lost time applies:

- Sick time
- Late time
- Vacation time
- Family leaves
- Strike time
- Break times
- Other

Humans are also subject to errors from repetitive tasks. The value assigned to human subjects varies greatly, depending on how they are inserted into the system. With proper managerial planning and backups, the values can be very high.

Let's take a closer look at the true value of a human in an agricultural system. Suppose a woman operates a bagging machine in a line operation that produces bags of garden mulch for the Super Duper market outlets. In a year, if she worked an eight-hour day, five days a week, she would need to be available 2080 hours per year. But she is not likely to be able to deliver this. Consider the following time losses:

Activity	Hours lost
2 weeks of vacation	80
Holidays (11 days)	88
Family leave (5 days)	40
Break times (40 min/day)	143
Late/tardy (1 hr/wk)	50
Sick (7 days)	56
Total time lost	457 hours

$$\text{Total time lost (\%)} = \frac{457}{2080} \times 100 = 21.97\%$$

$$\text{Approximate reliability} = 78.03\%$$

The first reaction would be that this is unacceptable. But, this is just being human. It would be easy to develop a much worse scenario for an employee. So how does the plant manager cope with labor on a line that might involve 20 or more employees?

First, let's assume that the manager could back up this employee with another available employee. The manager might call in another qualified [1] individual off-shift. Or maybe there is a pool of employees available. The calculation would [2] be:

$$R_{\text{bagger}} = 0.7803 + 0.7803(1 - 0.7803) = 0.9517$$

We can see that by having a backup available raises the reliability of the human component to 95.17%.

Managerial Implications

The use of parallel or redundant units becomes a very important factor in production management decisions, such as deciding what unit to replace and whether to buy new or used equipment. Reliability and machinery labor costs are clearly traded off to attain some acceptable level of performance.

It becomes clear that the use of redundant subsystems is often more economical than simply purchasing new units with higher reliability. Comparisons between ownership and operating costs of new purchases versus several older units and their maintenance and repair operating costs are necessary. Leasing and rental units must also be considered. Individuals or corporations "starting out" or with limited capital obviously have some alternatives that may be quite viable.

The human operator can be used to great advantage. If inserted properly into a system, reliability can be increased several-fold to save capital outlay.

Weighing the Cost of Attaining System Reliability

One can come to the supposition very quickly that most systems must achieve a 0.95 total reliability or better to be considered "successful." There are almost always alternatives. And each alternative has its costs. The decision could be driven by how to get an acceptable system reliability for the lowest cost. Let's consider a struggling college graduate, Bob, desiring to farm. He owns an older combine of unit reliability of 0.88. He knows this is not good enough. So what are his alternatives?

Suppose his dad is willing to allow Bob to use his new combine of 0.96 reliability as a backup, but only when he is not combining himself. The calculation would be:

$$R_{\text{combining}} = 0.88 \times (1 - 0.88)0.96^2 = 0.9905$$

Now, if good old dad is generous and does not charge Bob, this is a no brainer. Use dad's combine as a backup! (See how much smarter dad is now?) Each method of backup could have another opportunity cost. Here are some other alternatives:

Alternative	Depreciation cost
Buy a new combine	$ 45,000
Purchase a used backup	15,000
Lease a new combine	35,000
Rent a backup	?
Hire a custom operator to harvest and sell the old combine	?
Steal a new combine (maybe you would not want to do this)	?

In a processing situation, some devices might be extremely expensive, such as a reactor in an ethanol processing plant. The backup alternative may be maintaining an extensive parts inventory or even an emergency contract with an engineering firm to perform immediate services.

Another alternative is to introduce the concept of scheduled repair versus maintenance. Suppose the huge sugarcane harvest system has hundreds of tractors. Based on past records, the managers may know what breaks down and when. They might actually shut down the operation of units with higher hours and rebuild the transmissions, hydraulics, and engines before they break down. This might be expensive and require a larger pool of tractors, but it might be cheaper than buying new units or stocking even more backup units.

This concept is often used in situations where downtime is either extremely expensive or critical (no one wants their army tank to break down during battle)! Or the grain elevator operation does not want the bucket elevator to break down during a key harvest period. In any case, the ASM needs to be a true thinker!

This type of evaluation and trade-off consideration should be ongoing. Arguably, reliability planning could be the most important agricultural systems decision—but the one most often neglected.