More Reliable Multi-Function Wood-Harvesting Machines In the Future?

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PREFACE

This paper was originally written in 1978 as an internal discussion paper within FERIC to aid in the evaluation of new tree harvesting machine concepts. Consequently, the examples referred to in this paper are for machines designed in 1965-1975. Nonetheless, the theory and conclusions are still valid and thus the paper has been published with only a few minor changes in the text.

Reliability theory is a young science. Its implementation has been slow in mechanical engineering. This paper has been written as a simplified introduction to parts of the reliability theory applied to wood harvesting machine systems.

ABSTRACT

This paper explains why it has been difficult to get high mechanical availability with multi-function-machines. Simplified reliability theory is applied to demonstrate the relationship between Mean Time Between Failures of components and mechanical availability for machines of various complexities. The design engineer should reduce the number of components and find the right compromise between high reliability and low weight/low cost, thereby designing more reliable and cost-effective multi-function machines.

INTRODUCTION

The enormous distances between the users of wood harvesting machines and the manufacturers make the operation and maintenance of complex harvesting machines more difficult in a large country like Canada than in smaller countries like Finland or Sweden. To further compound the problem, the logging operations are normally located far from populated areas. Years of practical experience have proven that it is difficult to get economic mechanical availability with complex multi-function machines under such conditions.

The objective of this paper is to explain the reasons why it is so difficult to get high mechanical availability, to formulate better guidelines, and to sound a word of caution to the design engineers and the users selecting future logging machine concepts. Through simplified reliability analyses, I will try to illustrate the tight rope balancing act that designers have to perform when they try to design a reliable multi-function machine.

WHY MULTI-FUNCTION MACHINES?

The users have always expressed logical reasons for their preference for multi-function machines:

1. Simplified planning, supervision and administration. "Go and cut in this area and pile at theroadside". There are less interdependence problems between the machines. It is easier to move one multi-function machine between sites than several single-function machines.

2. Better overall productivity per productive machine hour per man. Example: The cycle times of 3-function machines are normally less than 3 times the cycle times of 1-function machines.

3. Better materials handling flow. Once a machine holds a severed tree, why not also delimb and transport it?

4. The limbs and tops remain in the stump area which may help maintain better site fertility, and will eliminate the transport of unusable fibre, as well as the resultant roadside slash problems.

During the last 20 years, the forest industry and the equipment manufacturers have spent great amounts of engineering resources and millions of dollars on the development of multi-function machines. A common frustrating problem with all complex machines developed between 1965-80 has been the difficulty in obtaining high mechanical availability, in spite of the fact that the level of design and engineering has been high. It is logical that multi-function machines are more complex than single-function machines. Design engineers have intuitively been well aware of the risks associated with complex machines, but they have been confident that they can find reliable design solutions to their problems. In retrospect, it is obvious that the

reliability problems have been underestimated or not attacked in a systematic way in most cases. One important reason may be that the reliability theory is a young science and that its application has been delayed or weak in mechanical engineering, whereas it was adopted earlier in electrical engineering. Because of their complexity and the great number of components in series, reliable color T.V., electronic equipment, space crafts, etc. would not have been possible without the use of the reliability theory and practice.

RELIABILITY IS THE PROBABILITY OF SUCCESS

Reliability is the capability of an equipment not to break down in operation. When an equipment works well whenever called upon to do the job for which it was designed, such equipment is said to be reliable. The equipment may be a simple component such as a wire, hose, fitting, hydraulic cylinder, pump or motor, or it may be a complex machine such as a loader, skidder, wood harvester, etc. The reliability of complex equipment depends on the reliability of its individual components. An exact mathematical relationship exists between the reliability of the components and the reliability of a complex machine as shall be discussed further on.

The measure of the reliability of an equipment is the frequency at which failures occur in time. If there are no failures, the equipment is 100% reliable; if the failure frequency is very low, the reliability is usually still acceptable.

A well-designed, well-engineered, thoroughly tested and properly maintained equipment should never fail in operation. However, all our experiences show that even the best design, manufacturing, and maintenance efforts do not completely eliminate the occurrence of failures. There are three characteristic types of failures (Figure 1).

Early Failures

In most cases, early failures result from poor manufacturing and quality control. When we buy a new car, we often experience a high failure rate or a short Mean Time Between Failures = MTBF = m during the first hours of operation.
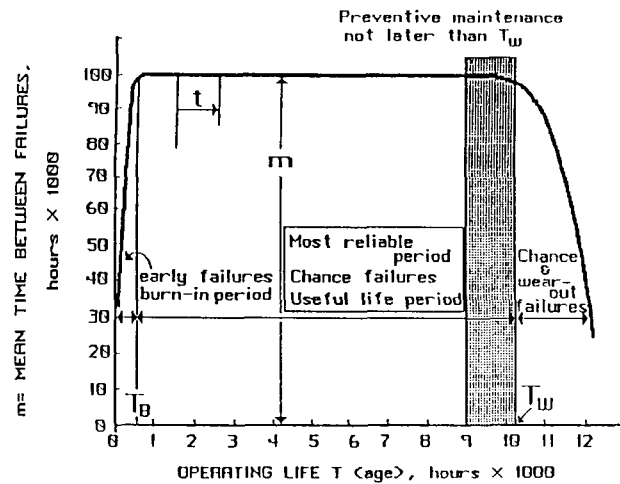

Figure 1. Component Mean Time Between Failures. MTBF = m as a function of age
T_w = Wear-out time, hours

Early failures can be eliminated by a "debugging" or "burn-in" process which consists of operating the components for a number of hours under conditions simulating actual loads or stresses.

Wear-out failures (late failures)

These are caused by the wearing out of parts. Typical wear-out parts are tires, brake-linings, V-belts, piston rings, valves and bearings. Preventive maintenance rules based on statistics prescribe replacement of such parts before they reach their wear-out time T_w (see Figure 1). As an example, the major overhaul of a diesel engine may be scheduled after 10 000 hours of operation which is the operating life at which, according to experience, the increased risk of wear-out failure can cause expensive, unscheduled shutdown of operation. Component replacement is essential if reliable operation is required beyond the components' wear-out time T_w.

Chance Failures (Useful life period)

When a component is subject only to failures which occur at random intervals, and the expected number of failures is the same for equally long operating periods, its reliability is mathematically defined by the formula:

$$R(t) = e^{-\frac{t}{m}}$$

In this formula, e is the base of the natural logarithm (2.718), t is an arbitrary operating time-during the useful life period, and m = MTBF (Mean Time Between Failures). The reliability R(t) is then the probability that the component which has a constant Mean Time Between Failures m, will not fail in the given operating time t. This reliability formula is correct for all properly debugged components which are not subject to early failures, and which have not yet suffered any degree of wear-out damage.

Let us take a concrete, simplified example to illustrate the point (Figure 1). If we take a large sample of components, say 100 hydraulic hoses with fittings, and operate them for 1000 h on a test bench under simulated, constant conditions, say 10 MPa pressure with one short shock pressure up to 20 MPa every minute, and replace them as they fail, then approximately the same number of failures will occur during each fixed period. If we assume 5 hoses will fail during the 1000 h test period, the Mean Time Between Failures for the 100 hoses will be:

$$m = \frac{100 \times 1000}{5} = 20\ 000\ h.$$

If we lower the pressures 25%, we may have only one failure in the batch of 100 hoses during the 1000 h and m = 100 000 h, which is the value illustrated in Figure 1. The designer has to use this de-rating technique to get the right m = MTBF for each component. This is an example which is over-simplified to make a point. We require that the quality of the components be approximately equal at the beginning of the test and that they do not deteriorate during the test. The reliability, or chance of survival, of this hose with a Mean Time Between Failures m = 100 000 h over the period of t = 1000 h would thus be:

$$R = e^{-\frac{1000}{100\,000}} = e^{-0.01} = \frac{1}{e^{0.01}} = \frac{1}{1.0101} = 0.99\ or\ 99\%$$

Note that the same hose would have only a

$$R = e^{-\frac{10\,000}{100\,000}} = 0.9048\ or\ 90\%$$

chance to survive over 10 000 h.

Reliability of Series Systems

Reliability is not confined to single components. What we really want to evaluate is the reliability of systems, simple as well as complex. The reliability of a complex system of components which forms a machine can be expressed as the product of the reliabilities of all those components on whose satisfactory operation the machine depends for its survival or undisturbed operation. If one component in a series system fails, the whole machine will fail.

For a machine of n components in series, the machine reliability is given by:

$$R_{machine} = R_1 x R_2 \ldots R_n$$

$$= e^{-\frac{t}{m_1}} x\ e^{-\frac{t}{m_2}} x\ e^{-\frac{t}{m_n}}$$

$$= e^{-t\left[\frac{1}{m_1} + \frac{1}{m_2} \ldots + \frac{1}{m_n}\right]}$$

where R_1 is the reliability of the first component in series in a system, R_2 is the reliability of the second, etc. and; m_1 is the Mean Time Between Failures of the first component, m_2 is the MTBF of the second component, etc.

Also, $R_{machine} = e^{-\frac{t}{m_{machine}}}$

where $m_{machine}$ equals the Mean Time Between Failures for the whole machine.

Thus, $\frac{1}{m_{machine}} = \frac{1}{m_1} + \frac{1}{m_2} \ldots + \frac{1}{m_n}$

To simplify our calculation for pedagogic reasons, let us assume that the designer has been so successful in the choice of components that all n components have the same Mean Time Between Failures. Thus $m_1 = m_2 = m_3 = m_n = m$

and, $\frac{1}{m_{machine}} = \frac{n}{m}$

or, $m_{machine} = \frac{m}{n}$

MECHANICAL AVAILABILITY

We can now calculate the Mechanical Availability = A of the machine. For the purpose of this exercise unscheduled non-mechanical delays (because of extreme weather, terrain, etc.) are not included. On the other hand, the waiting time for parts or mechanics is included because of its dependence on reliability.

$$A = \frac{m_{machine}}{m_{machine} + m_{service} + m_{repair} + m_{wait}}$$

where,

$m_{service}$ = Mean Time to Service, hours

m_{repair} = Mean Time to Repair, hours

m_{wait} = Mean Time Waiting for Part or Mechanics, hours

If we assume that

$m_{service}$ = 0.10 $m_{machine}$ (proportional to operating hours)

m_{repair} = 2 hours (should not vary with the number of PMH or $m_{machine}$)

m_{wait} = 1 hour (should not vary with the number of PMH or $m_{machine}$)

Thus $$A = \frac{m_{machine}}{m_{machine} + 0.10\, m_{machine} + 2 + 1}$$

$$A = \frac{1}{1.10 + \dfrac{3}{m_{machine}}} \quad \text{(Fig. 2)}$$

But $m_{machine} = \dfrac{m}{n}$

Thus

$$A = \frac{1}{1.10 + \dfrac{3n}{m}} \quad \text{(Fig. 3)}$$

The total number of components of a machine gives a good indication of its complexity. The number of components seems to be proportional to the number of functions (Fig. 4). A study of the spare parts books for some typical logging machines has provided the following figures:

Machine	Functions	No. of Functions	No. of Components
TJ 230 Skidder	Skid	1	6200
JD 743 FB	Fell-bunch	2	11500
JD 743 Harvester	Fell-delimb-bunch	3	12800
Kockum 880	Fell-bunch	2	9900
TJ RW-30 Harvester	Fell-delimb-bunch	3	8500
Koehring SW Harvester	Fell-delimb-transport-pile	5	26000

Naturally, there are a number of components which do not directly affect the reliability, e.g., washers, signs, some unimportant brackets, cover plates, etc. But the percentage of such components is fairly small, in the order of 5-10%.

CONCLUSIONS FROM THE AVAILABILITY GRAPHS

Figure 2 shows that the availability increases very slowly once $m_{machine}$ exceeds 20 to 30 hours. Consequently, A = 0.80 seems to be a reasonable economic target that we should try to reach. It would be difficult and costly to get higher availability for complex machines. For simple machines, it is always possible to reduce $m_{service}$, m_{repair} and m_{wait} because there are, e.g., fewer grease fittings, the accessability for repair is good and necessary parts can be in stock near the machine.

If we assume that we have a simple skidder with n = 5 000 components and components with m = 100 000 h, we achieve A = 0.80 (from Fig. 3). If we use the same engine, transmission and hydraulic components, etc., plus other components of the same quality level for a feller-buncher with say n = 9 000 components, we drop to A = 0.73 (following the
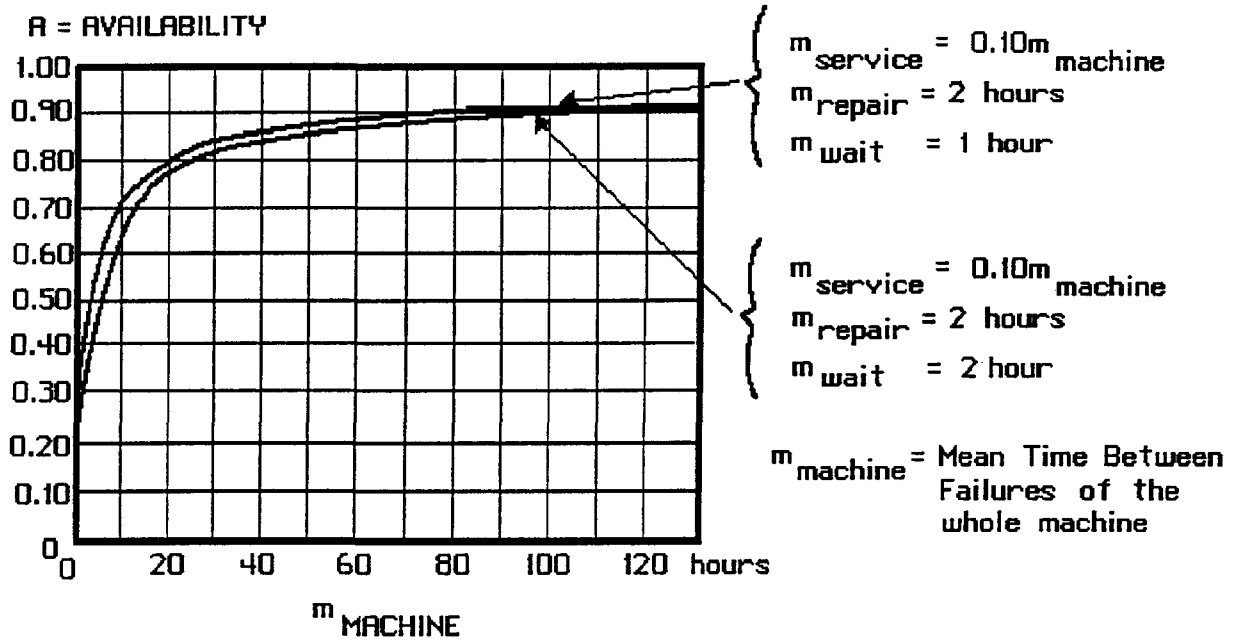
A = AVAILABILITY

$m_{service} = 0.10 m_{machine}$

$m_{repair} = 2$ hours

$m_{wait} = 1$ hour

$m_{service} = 0.10 m_{machine}$

$m_{repair} = 2$ hours

$m_{wait} = 2$ hour

$m_{machine} =$ Mean Time Between Failures of the whole machine

m MACHINE

Figure 2. Relationship between machine availability and repair frequency.

A = AVAILABILITY

m = 200,000 hours

m = 100,000

m = 50,000

m = 25,000

FELLER BUNCHER

SKIDDERS ◄————— HARVESTERS ————►

$m =$ Mean Time Between Failures of components
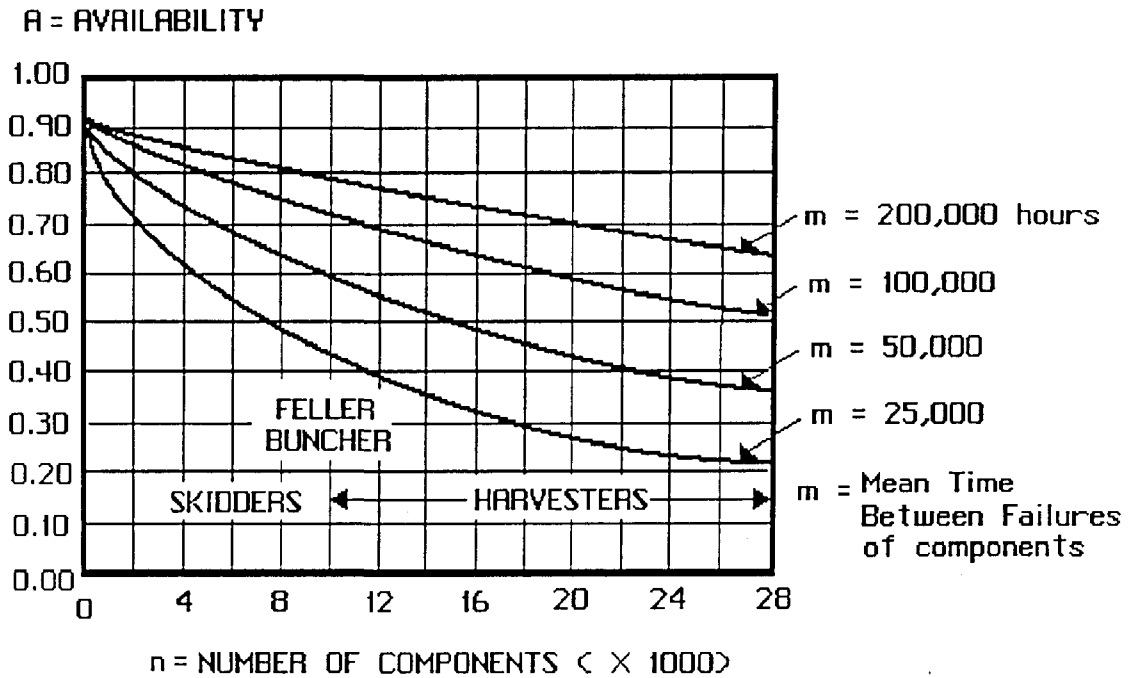
n = NUMBER OF COMPONENTS (X 1000)

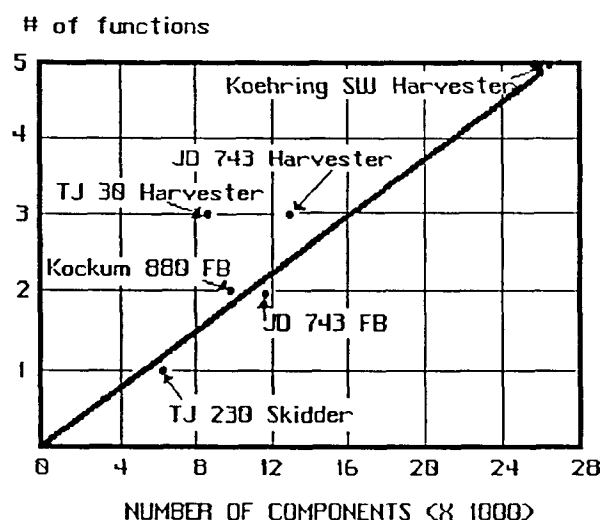**Figure 3.** Relationship between machine availability and the number of machine components.

Figure 4. Relationship between the number of machine functions and the number of machine components.

curve for m = 100 000 hours). If we use the same component quality for a complex harvester with 24 000 components, we can only get A = 0.55 (following the curve for m = 100 000 hours).

The obvious conclusions are:

To improve the availability of complex machines, we have to simplify and reduce the number of components n, and/or increase the Mean Time Between Failures m of the components by using higher quality materials or through de-rating techniques (increased dimensions, lower hydraulic pressures, lower engine rpm, etc.). However, the use of de-rating techniques may mean a weight or cost increase. That is why the designer has to compromise between high reliability and low weight or cost to achieve the goal of designing reliable multi-function machines.

Compounding Factors

There are also other factors besides the reliability that further compound the problems with complex multi-function machines:

1. Reduced stability and gradeability because of the higher weight with more components.

2. Increased weight, because of more or heavier components, increases the risk of ground disturbance and over-loading of the drive components.

3. Diagnostic times are longer because of reduced accessibility (too many components in a limited space).

4. Repair time is longer because of reduced accessibility.

5. An increased need for exotic components and service specialists may lead to longer wait times.

6. There may be problems to retain the needed skilled maintenance personnel in remote areas.

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