APPLICATION OF RELIABILITY AND ECONOMIC ANALYSES TO THE SELECTION OF A REFUSE SHREDDING SYSTEM

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ABSTRACT

Reliability as a function of failure rate, mode of operation and man-machine interactions, redundancy, and serial and parallel shredding was introduced to provide an analytical approach to the evaluation of a refuse shredding system. Various economic factors were combined with the reliability analysis to optimize the selection of system components and arrangement.

INTRODUCTION TO REFUSE SHREDDING SYSTEMS

Since the advent of solid waste resource recovery, refuse particle size reduction through shredding has been an integral part of solid waste processing facilities, with the exception of the proprietary wet pulping system. A refuse shredding system consists of an infeed conveyor, shredder, outfeed conveyor, ancillary equipment and controls. In case of multi-stage shredding, intermediate material handling and processing equipment are usually incorporated. In addition to the basic components of a shredding system, devices to minimize or eliminate safety and health hazards are an essential part of the system [1].

SHREDDERS

All shredders on the market today have been adapted and innovated from equipment originally designed and developed for applications mainly in salvage, mining, and their related industries. Consequently, there are a number of types available for refuse shredding, e.g., pulverizer, chipper, hammermill, crusher, grinder, shredder, etc. Only a few types, however, have received extensive testing in refuse size reduction.

In view of diversified design and confusion of names, the Waste Equipment Manufacturers Institute has designated the terms “shredder” and “shredding” as the means and the process of refuse size reduction.

The most commonly used shredders are of the hammermill type which consists of either a horizontal or vertical rotor with attached hammers. Due to the popularity and the apparent continual usage, only hammermill-type shredders will be the subject of discussion in this paper.

The mechanism in breaking up refuse is basically by impact, shearing, and attrition effected by the hammer, breaker plate or wear liner and grates. Shredders can be classified into a number of categories. Table 1 contains the summary of shredder classifications [2].
TABLE 1
SHREDDER CLASSIFICATIONS

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Classifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor arrangement</td>
<td>Vertical, Horizontal</td>
</tr>
<tr>
<td>Reversibility</td>
<td>Nonreversible, Reversible</td>
</tr>
<tr>
<td>Feed</td>
<td>Free-fall, Forced feed</td>
</tr>
<tr>
<td>Hammer attachment</td>
<td>Swing, Rigid</td>
</tr>
<tr>
<td>Input material</td>
<td>Municipal refuse, Bulk refuse</td>
</tr>
</tbody>
</table>

The performance characteristics of a shredder can ultimately be translated into functional and physical parameters; namely, net shredder weight, feed opening size, capacity, product size distribution, drive, hammer geometry and characteristics, speed, inertia of rotor, shaft diameter and bearing supports, liners and grate design, etc.

SHREDDER ANCILLARY EQUIPMENT AND CONTROLS

The shredder ancillary equipment and controls are required in order to facilitate maintenance, eliminate occupational hazards, and assure the reliability of the shredder. The devices and their functions are summarized in Table 2.

MATERIAL HANDLING EQUIPMENT

Material handling equipment used in solid waste shredding systems may involve various types of conveyors, e.g., apron, vibratory, belt, drag, etc. [3].

SYSTEM RELIABILITY ANALYSIS

Refuse shredding is an emerging technology which has a relatively low reliability as compared with other accepted standards of industrial products or systems. Heterogeneity, uncertainty and variability of refuse composition have contributed to most technological problems. Many of these problems are directly linked to the mechanism of size reduction and the inherent physical properties of refuse.

In many areas of a refuse shredding system, the old try-fix-try method has still been used in searching for immediate solutions, which is not only time consuming and uneconomical, but also of little scientific significance to future quality assurance. To facilitate the understanding of availability and the economic impact, the reliability analysis should be conducted so that quantitative or comparative component reliability can be obtained for optimizing the system arrangement. The spin-offs from such an analysis include the identification of system weak links and relative importance of the components.

FAULT TREE ANALYSIS (FTA) [4]

There are a number of techniques available for the reliability or availability analysis. The selection of logics and method depends basically upon the nature of the problems or the importance of specific failure effects.

The FTA is widely used because it offers a con-
trolled approach and identified interactions among system components. The analysis begins with the development of a logic map postulating top failure events, primary and secondary events, and the logical combinations of events. The fault tree is completed when all basic faults are identified or further tree construction is unwarranted or impossible. Figure 1 shows a typical FTA depicting a system failure (top event) where the particle size distribution of shredded refuse exceeds the specified limit, e.g., 95 percent less than 2 in. in size.

The FTA enables engineers or operators to compile rates and modes of failure. It also assists personnel in taking immediate remedial actions should any failures occur within the system under study.

OPERATING MODES AND MAN-MACHINE INTERACTIONS

The reliability of a shredding system is a function of operating modes and man-machine interactions. Operating modes are the methods for which the system is intended to be operated. These operational options include one-shift, two-shift, and three-shift operations; time and load sharing...
on parallel lines; five-day week or six-day week operations; temporary storage for surge of waste and emergency transfer operation, etc.

The unique nature of refuse shredding makes the human aspects of the system, man-machine interaction, an important element in securing reliability, both from engineering and operational standpoints. The man-machine interactions of a shredding system rarely receive the equal attention that the mechanistic aspects of the system do. The technical ability of operators to operate and perform maintenance and emergency treatment must be realistically assessed so that sufficient time would be allocated for maintenance work or additional instrumentation, and controls would be incorporated into design to avoid any major oversight by operators during the operation.

Combining the operating modes and man-machine interactions, a definitive unavailability of the system should be apportioned so that the intended reliability could be expected.

The apportioned unavailability (hours/day) \( -t' \) can be logically assumed to be proportional to the system reliability. The maximum system availability, therefore, becomes \( 24 - t' \). Let \( R_p \) and \( t \) be the analytical reliability of a system and the required shredding time to achieve the design capacity respectively. The system reliability as a function of operating modes and man-machine interactions can be expressed by the following equation:

\[
R = R_p + (1-R_p)(1-\lambda)e^\lambda
\]

where

\[
\lambda = t/(24-t')
\]

\( R_p \) = Analytical reliability calculated at the maximum availability

\( e \) = Base of Napierian logarithmic system = 2.71828

Equation (1) satisfies two boundary conditions, i.e., \( \lambda = 0 \) and \( \lambda = 1 \). The range of \( R \) is as follows:

\[
R_p \leq R \leq 1
\]

SERIAL AND PARALLEL SYSTEMS [5]

A serial system is one in which the single shredding line consists of a number of components connected in a series arrangement. The successful operation of a serial system depends on the successful operation of all serial components, or

\[
R_s = R_1 R_2 R_3 \ldots \cdot R_n
\]

where

\( R_s \) = Reliability of serial shredding system

\( n \) = The number of serial components in the system

\( R_i \) = Reliability of ith component

A parallel system or redundant system consists of a number of independent serial shredding lines. If the successful operation of a parallel system having \( m \) shredding lines depends on \( j \) lines in a simultaneous successful operation, the reliability of such a system can be determined from the following equation.

\[
R_p = \sum_{k=0}^{m} \frac{m!}{k!(m-k)!} R_s^k (1-R_s)^{m-k}; \lambda = 1
\]

If a shredding line has a reliability of 0.75 at the design capacity, the reliability of having 100 percent redundancy is calculated to be \( 2R_s-R_s^2 \) or 0.94, a 25 percent increase in reliability. It is obvious that when the reliability of shredding lines improves, the 100 percent redundant system would not increase as much as in the case of lower reliability.

When two lines are provided, each being sized for 75 percent of the design capacity, the reliabilities at design and 75 percent capacity will be \( R_s^2 \) and \( 2R_s-R_s^2 \) respectively. Assume \( R_s \) has a value of 0.85; then the reliabilities will be 0.72 and 0.98 respectively for 100 percent and 75 percent of design capacity.

Combining equations (1) and (4) yields the following equation:

\[
R = (1-e^\lambda + \lambda e^\lambda) \sum_{k=0}^{m} \frac{m!}{(m-k)!} R_s^k (1-R_s)^{m-k} + (1-\lambda)e^\lambda
\]

ECONOMICS AND SYSTEM OPTIMIZATION

ECONOMICS

The economics of a shredding system is the unit cost of processing solid waste which consists of debt service, taxes, insurance, labor, fringes, administrative, parts, supplies, utilities, and other
costs incurred for the operation and maintenance of the system. These costs are conveniently divided into fixed costs (debt service, taxes, insurance, etc.) and operating and maintenance costs.

The debt service is basically the amortization of the initial capital investment including a small cost for the sale of bonds. Although the debt service is a fixed amount throughout the life of the bond issue, it is a function of the reliability of the system design.

The operating and maintenance costs reflect more explicitly the system deficiencies, which could directly or indirectly be linked to the system availability or reliability. In addition to the social and political factors, the outage costs, e.g., back-up and transfer operation costs, loss of revenue or penalty, liability, etc., should be fully evaluated.

Equipped with the information described above, the economic model of a shredding system could be developed.

**SYSTEM OPTIMIZATION**

The economy of a shredding system is generally expressed in dollars per ton as-received solid waste processed. The two extreme (boundary) conditions are \( R_0 = 0 \) and \( R_1 = 1 \) where shredding cost approaches infinity. A family of curves could be constructed since there are infinitive combinations of system arrangements, operating modes and man-machine interaction for arriving at the same reliability. However, the average costs for these combinations vary.

Let \( i \) be a given combination of system parameters, \( U_i \) debt service, \( V_i \) operating costs, and \( Y_i \) annual throughput. The average processing cost \( \{ A_i \} \) will be expressed as a function of \( U_i \), \( V_i \) and \( Y_i \) or

\[
A_i = (U_i + V_i)/Y_i
\]

Since \( U_i = f(R_i) \), \( V_i = g(R_i) \) and \( Y_i = h(R_i) \), the average processing cost can be mathematically related by a function \( F \) or

\[
\{ A_i, i = 1, 2, 3 \ldots \} = F_i(R_i)
\]

The optimal system selection thus becomes

\[
A = \min F_i(R_i)
\]

**SAMPLE ILLUSTRATION**

At the present time, reliability data is not available from manufacturers of equipment to make a meaningful prediction of component availability. In addition, the successful operation of a shredding system depends on factors such as man-machine interactions. However, reasonable reliability data can be developed through compilation of records of component failure, operators’ error data, and other operational experience utilizing the fault tree logic map. A hypothetical summary of records is shown below:

<table>
<thead>
<tr>
<th>Components</th>
<th>Operation Hours/Year</th>
<th>Unavailability Hours/Year</th>
<th>Reliability ( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Infeed Control</td>
<td>3,000</td>
<td>60</td>
<td>0.980</td>
</tr>
<tr>
<td>2. Infeed Mechanical</td>
<td>&quot;</td>
<td>80</td>
<td>0.973</td>
</tr>
<tr>
<td>3. Breaker Plates</td>
<td>&quot;</td>
<td>112</td>
<td>0.963</td>
</tr>
<tr>
<td>4. Hammers</td>
<td>&quot;</td>
<td>300</td>
<td>0.900</td>
</tr>
<tr>
<td>5. Reject Chute</td>
<td>&quot;</td>
<td>40</td>
<td>0.987</td>
</tr>
<tr>
<td>6. Outfeed Conveyor</td>
<td>&quot;</td>
<td>75</td>
<td>0.975</td>
</tr>
<tr>
<td>7. Hydraulic Unit</td>
<td>&quot;</td>
<td>200</td>
<td>0.943</td>
</tr>
<tr>
<td>8. Lube Oil System</td>
<td>&quot;</td>
<td>58</td>
<td>0.981</td>
</tr>
</tbody>
</table>

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TABLE 3

HYPOTHETICAL ARRANGEMENTS AND ANALYSES FOR 500 TONS/DAY SHREDDING SYSTEM

<table>
<thead>
<tr>
<th>System arrangements</th>
<th>$R_1$</th>
<th>$R_2$</th>
<th>$R_3$</th>
<th>$R_4$</th>
<th>Capital investment $/1000$</th>
<th>Debt serv. CRF 7% @ 20 yr $/1000$</th>
<th>Yearly throughput $/ton$</th>
<th>Owning and operating cost $*$ $/1000$</th>
<th>System cost $/ton$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I One line @ 50 tons/hr 10 hours/day operation</td>
<td>4</td>
<td>0.7357</td>
<td>0.7357</td>
<td>0.8746</td>
<td>2,500</td>
<td>236</td>
<td>113,700</td>
<td>693.4</td>
<td>6.10</td>
</tr>
<tr>
<td>II Two lines @ 50 tons/hr 10 hours/day operation</td>
<td>6</td>
<td>0.7357</td>
<td>0.9302</td>
<td>0.9842</td>
<td>4,500</td>
<td>425</td>
<td>128,000</td>
<td>721.1</td>
<td>5.63</td>
</tr>
<tr>
<td>III Two lines @ 35 tons/hr 14 hours/day operation</td>
<td>6</td>
<td>0.7357</td>
<td>0.9302</td>
<td>0.9639</td>
<td>4,000</td>
<td>378</td>
<td>125,300</td>
<td>695.7</td>
<td>5.53</td>
</tr>
<tr>
<td>IV Three lines @ 25 tons/hr 10 hours/day operation</td>
<td>10</td>
<td>0.7357</td>
<td>0.8274</td>
<td>0.9282</td>
<td>5,000</td>
<td>472</td>
<td>120,700</td>
<td>836.8</td>
<td>6.91</td>
</tr>
</tbody>
</table>

*Operating costs include outage costs and loss of revenue ($12/ton) calculated on the basis of system unavailability.

Assuming a shredding system consisting of the components listed above, the operation of the system depends upon the failure-free operation of each of these components. The reliability of this hypothetical serial system is determined to be $R_s = 0.7357$, using Equation (3).

For the purpose of illustration, four different arrangements of a 500 tons/day shredding system are analyzed and shown in Table 3. The optimum selection of system arrangement under these conditions is System III.

CONCLUSIONS

The reliability and economic analyses provide a logical tool for selecting the most cost-effective shredding system. Spin-offs may develop during the course of the fault tree analysis including the weak links of the system, and the relative component reliabilities. To overcome such weak links, remedial steps may be taken by providing redundancy or specifying better quality equipment.

Equipment to eliminate occupational and safety hazards should be given the highest apportioned availability in conjunction with the reliability analysis since the failure effects of human safety versus monetary value cannot be assessed.

Although operating modes and man-machine interactions were given due consideration in this paper, further study needs to be done to arrive at a better correlation between these factors and the overall system reliability.

REFERENCES


Key Words
Analysis
Comparison
Economics
Equipment
Refuse
Refuse Derived Fuel
Shredding

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Discussion by

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Systems analysis techniques so deftly described by the authors will certainly be useful in evaluating the performance of operational plants as well as the design of future installations. They have contributed significantly to an auspicious beginning.

A backlog of dependable data from operational plants will be necessary if reliability analysis is to be effective.

The availability and candor of input data will be the most critical requirement in this approach, and the outlook has not been encouraging.

With few exceptions, this is because:

- Equipment manufacturers usually don’t really know the performance and reliability capabilities of their product and persist in euphoric promotion [1].
- Plant operators have a tendency to exaggerate accomplishment in a justification-protectionist syndrome.
- The reluctance of most private owner-operators to divulge any meaningful information at all.

Sobering confirmation of this contention is evident in the less than satisfactory performance of most resource recovery plants presently on stream, which have front-end processing systems—likewise, the more numerous shredding-only installations [2].

If solid waste processing is to survive, it is imperative that system designers recognize the necessity to provide adequate access to subsystems not only for retrofitting but for meaningful performance-acceptance testing. Also, a higher level of performance accountability than now exists must be established.

It is evident to this observer that divided responsibility accounts for much of the difficulty and that a single supplier responsibility for integrated mainstream front-end systems will be a significant improvement.

A recent survey [3] reveals that in most cases, solid waste processing installations do not meet specified performance requirements and there has been little or no accountability for:

- Lower average production.
- Inability to handle difficult material, requiring unexpected pre-sorting.
- Unsatisfactory product size and quality.

Referring, now, to specific headings in the paper:

**Shredders**

I would add my conviction that there isn’t very much shear force working in most shredders, especially breaker plate types [1]—an area where there is much need for improvement which would minimize the undesirable topsize output of primary and secondary shredders.

**System Reliability Analysis**

Exception might be taken to the statement that “the old try-fix-try method.....” has little value. Actually, it is the only way to determine whether or not a change is working. Perhaps the intent here is that if system reliability analysis is employed along with “the old cut and try,” there will be significant improvement.

There is strong endorsement in principle that, “The reliability analysis should be conducted so that quantitative or comparative component reliability can be obtained for optimizing the system.” As a practical matter, however, meaningful component evaluation in most existing systems is extremely difficult if not impossible.

Component performance testing access is the greatest challenge to system/arrangement designers if the aforementioned accountability is to be attained.

**Fault Tree Analysis, Fig. 1**

This appears to be a useful method provided all significant events and conditions are included. For the particle distribution fault example as shown, I would add:

- Grate edges (sharpness).
- Feed transients (rate, material inventory in mill).

Shredder design [1] has a definite effect on particle size distribution, but this would be difficult to display. And, there isn’t much you can do about it after the original equipment selection without major surgery or replacing the entire machine.
Operating Modes and Man-Machine Interactions

The assumptions and computation input data sources are difficult to follow. If this technique is for designing a new installation, then I would ask:

- How do you “assess the technical ability of operators to operate and perform maintenance and emergency treatment . . .”? 
- Does design capacity depend upon a manufacturer's rating or estimate? (This could be precarious.)
- Exactly what is analytical reliability, $R_p$, with respect to: $R$, $R_s$, $R_i$, etc.? Are they not all analytical?

Serial and Parallel Systems

Component reliability data appears to be a “missing link” and I certainly agree with the authors that this information is not yet available from manufacturers, but that reasonable data should be forthcoming if they (mfrs.) and plant operators ever get around to tracking it.

Usually, they are too busy keeping systems operating to bother with such “esoterica”.

Economics and System Optimization

Depreciation seems to have been omitted. This can vary, depending upon several factors, including public or private ownership. Ten to 20 years appears to be a reasonable range, with 10 years rather common with scrap processing shredder operations [1].

It is interesting to note that the authors include debt service in their average processing cost computation (Eq.6). It is important that inclusion of debt service be clearly shown in any processing cost citation, lest it be misleading to those who normally consider processing cost to include only the operating cost factors of power, maintenance and labor [1].

Sample Illustration

The list of components includes a reject chute, item 5. With horizontal shaft mills in mixed solid waste service, this feature has proved utterly useless [1] and should be abandoned, lest it be relied upon to protect the mill from dense, damaging material at the expense of less vigilance in raw infeed surveillance.

I would suggest that grates be added to the list and that a distinction be made in the lube oil system reliability factor depending upon a single system (pump, etc.) serving both bearings vs an individual system for each bearing of horizontal mills.

Referring to Table 3:
- Does the analysis include bulky trash of any kind?
- If so, was consideration given to the fact that minimums are then established for mill size and connected horsepower regardless of stream capacity requirements.

Discussors Conclusion

This paper is neat and concise, with an overall technical integrity worthy of cornerstone status in an important emerging analytical approach to improved solid waste processing plant design.

It is hoped that the authors will continue this work so that the industry will have the opportunity to cooperate in its advancement with, perhaps, an entire session at the 1980 conference in Washington, D.C. so devoted.

REFERENCES


Discussion by

Don Kaminski
The Heil Company
Milwaukee, Wisconsin

I disagree with the author on the following:
1. All shredders on the market today have not been adapted from other applications. Heil machines were designed specifically for refuse and we happen to have 35 to 40 percent of machines operating on refuse today.
2. Comments under System Reliability Analysis are over-stated.
3. If the system is needed only 10 hr/day, reliability should not be calculated over 24 hr, therefore, items like hammer work, etc., which are planned maintenance items, do not enter the
picture. The real life key is whether the machine will work all ten hours without a breakdown.

4. Even if a machine is down several hours a day, ultimately the refuse will be disposed of (possibly on overtime) and, therefore, revenue will not be lost.

AUTHORS' REPLY

To W. D. Robinson

The authors wish to thank Mr. Robinson for his excellent comments on current problems facing shredding systems and the industry. The lack of candor and a scientific approach in compiling useful failure data has probably been the main retardant for the future improvement of shredding system design.

Even with a single supplier responsibility and an outstanding performance-testing procedure, there is always an unaccountable refuse characteristic. To make the performance testing more meaningful, it may be necessary to create a typical municipal refuse sample by mixing the predetermined refuse components for testing purposes.

The authors realize that the component reliability evaluation, at the present time, is extremely difficult, if not impossible, to obtain. However, it is imperative that it be pursued rather than being ignored if shredding for resource recovery is to survive.

The paper was not intended to be a case history or a complete analysis of current shredding system application. It was intended to be a methodology or a logic, which one can follow and improve as the time goes by and more data become available. The mathematics are merely the presentation of such logics because it is always less ambiguous than normal language.

The depreciation is included in the debt service, which includes amortization cost. The system optimization, in a simple word, is to get the best the money can buy.

The authors share the same observation regarding the reject chute. Again, the sample is for illustration purpose and it should be included in the analysis if the shredder already has one. The fault tree analysis will prove eventually to serve no purpose other than creating trouble.

Table 3 is a hypothetical analysis utilizing the methodology contained in the paper and the assumed component reliabilities. The inclusion of special type of wastes would have definitive influence on the component reliabilities, thus affecting contents of Table 3.

The techniques introduced in this paper can be generalized to cover almost any subject. Similar techniques have been used by space technology, nuclear power plants, etc. We all have some catching up to do in our basic thinking and the approach to problems if we are to continue to advance in our profession. The authors compressed a great deal of information into a few equations; consequently, it is difficult to follow.

To Don Kaminski

The authors appreciate the comments supplied by Mr. Kaminski and our replies are numbered the same as his comments.

1. The authors are familiar with the design of the Heil machines as well as their predecessor, the Tollemache machine. However, even though these are vertical machines they are basically of the hammermill design with little shearing force and are patterned after hammermill crushers which have been in use in other industries prior to the initiation of refuse shredding and composting in Europe.

2. Mr. Kaminski states that the authors' analysis on machine reliability is over-stated. The shredding system is the key to many resource recovery facilities which also imposes tremendous burden (financial and operational) on the owner and operator. If shredding continues to be successful in resource recovery, the reliability of shredding must be emphasized and improved.

3. The authors invite Mr. Kaminski to examine Eqs. 1-5 since they explicitly show the reliability as a function of operating time, not as he pointed out, that the reliability was calculated over 24 hr. Any down time during the scheduled operation is in effect a direct or indirect loss of revenue due to overtime payment, prolonged operation and increased maintenance costs.