RELIABILITY OF MECHANICAL SYSTEMS—AN ATTEMPT TO APPLYING CROSS-IMPACT METHOD

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Summary

This article deals with reliability problems of mechanical systems. For reliability calculations a multiperiod probability model is introduced. Interactions among non-independent elements are derived from qualitative expert estimates. The example of a tower crane serves for the illustration of reliability analysis. Based on operating failure statistics the empirical outfall curve and the fitting theoretical distribution function are established. The effect of interactions modifying the reliability of the system is illustrated by considering external environmental parameters.

Introduction

Mechanical systems are exposed to unfavourable influences during operation, as a result of which their value in use is decreasing, and their operational characteristics are gradually worsening. These damages caused by physical and external factors appear as changes of the geometrical size and shape of material structure and surface quality and also of other characteristics. The technical—economical aging leads to depreciation of machines. The fall-off in operational efficiency is a time-dependent process, caused by wearing out, overloading and aging. Wearing out—which can be measured best—appears as physical wear, corrosion and fatigue. Among the reasons of overloading improper use and great significant, unexpected environmental changes can be mentioned. Finally, aging means the irrevocable changes in material structure.

The number of impairing states arising during the lifecycle of a mechanical system is infinite. The various effects causing impairment are frequently closely interdependent. One should know their origins, motives and forms when organizing both preventive maintenance and repairing.

The reliability of mechanical systems

Mechanical systems are loosing their productive capacity in a random manner. It can generally be explained by one of the following facts:

— the operational conditions of the system can be characterized by randomly changing load, temperature etc.,

— all the external parameters are constant, but there are random changes and processes within the structure of the material, or around joints etc.

One of the most important criteria of a mechanical system is the ability to work reliably during a given period of time, and to meet all the technical parameters defined for its proper use. Reliability is the ability of an object to meet (within given limits) those requirements of practical use which are in accordance with its characteristics. Reliability is 100%, when no failure can be observed among very many objects, during nominal workshop load. Obviously, such an absolute reliability can not be reached, since a significant part of impairments is random, and not all the failures can be avoided by preventive maintenance. However, having all the necessary reliability parameters, the ideal situation can be approximated by systematic planning. The level of technical reliability has a significant influence on safety of life and property, on repairment costs and idle time.

The impairing behaviour of a mechanical system is defined by the impairments of the system elements. There are very many factors influencing impairments; that is why system elements fall out stochastically. Operating time is the very working time during which the whole machine, unit or component reaches the limit of its productive capacity [2]. Fig. 1 shows that the operating time of a system is determined by the very element with the shortest operating time. The next outfall is caused by the element with the next longer operating time etc. (It is assumed that impaired elements are immediately replaced).

When many elements fall out at the same time, a total overhaul is needed. This is a favourable solution from reliability's point of view. The situation on Fig. 1 is disadvantageous, since all the elements have different outfall times, consequently maintenance costs and idle times are high.

Reliability requirements can, however, be very easily defined, but to meet them in the practice is a little bit harder. It is, therefore, a more feasible solution to raise reliability level of the single elements. Dimensioning for life is quite unmatured, and that creates difficulties in planning.

In the literature very useful statistics are to be found on the distribution of the various failure factors [1]. The largest share is held by external environmental conditions (36%), technological aspects (23%), and operational circumstances (13%). These are all more or less due to insufficient planning.

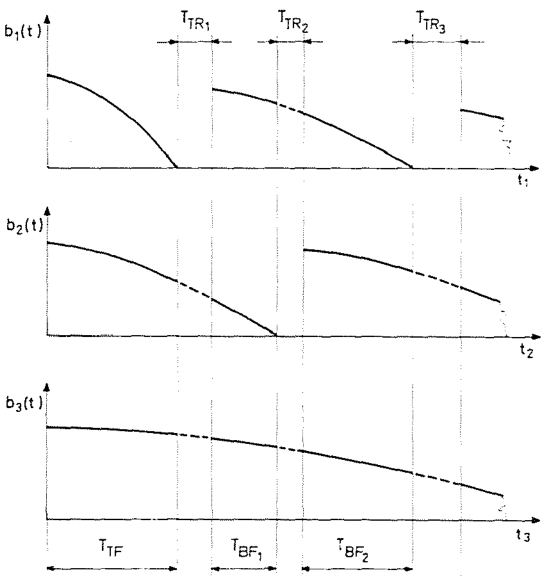

Fig. 1. Outfall process of system elements
T_{TR} = time to repair,
T_{BF} = time between failures,
T_{TF} = time to failures

Parameters of failure and reliability

First of all the interpretation of parameters used are given:

Defect: Not permissible deviation of a parameter.
Deviation: Difference between real and nominal value of a parameter.
Change: The deviation from nominal value in various instances.
Failure criteria: Deviations of given elements with given limits caused by changes after initial load.
Reliability: At least one of the failure criteria of an initially perfect element is violated.
Blackout: All functions of the object fall out.
Partial failure: Some operational functions of the object fall out.
Secondary failure: Failure, caused by a failure of another object.
Life (t): Time interval is expressed in working hours from the beginning of the load till the moment of the failure causing not repairable defect. Life is treated as a continuous probability variable.
Probability of failure (Outfall probability): The probability of an object's falling out within a given $T_f < T$ interval. It can be expressed with the following

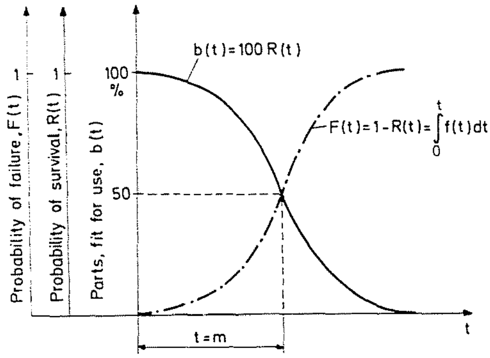

Fig. 2. Empirical curves of survival and failure probability

distribution function:

$$P(T_f < T) = F(t) = \int_0^t f(t)\,dt\,. \tag{1}$$

Probability of survival: is the complementary function of $F(t)$, which is monotonously decreasing in case of non repairable, non regenerative systems:

$$P(T_f > T) = R(t) = 1 - F(t) = 1 - \int_0^t f(t)\,dt\,. \tag{2}$$

Survival probability curve: shows the percentage distribution as a function of time of elements ready for working (Fig. 2):

$$b(t) = [1 - F(t)]100 = 100\left[\int_0^\infty f(t)\,dt\right] = 100\,R(t)\,. \tag{3}$$

The reflected curve is the failure curve showing the empirical distribution of relative outfall frequency:

$$1 - b(t) = 100 - \sum_j h_j\,. \tag{4}$$

Failure frequency: It is the quotient of failure density and survival probability:

$$\lambda(t) = \frac{f(t)}{R(t)}\,. \tag{5}$$

$\lambda(t)$ is constant when the distribution is exponential. Its value is estimated as follows:

$$\lambda \approx \frac{c}{n\Delta t}, \tag{6}$$

where c = number of failures,
Δt = measuring period,
n = number of elements in the sample.

Failure quota: The quotient of periodical frequency and measuring period; it's an empirical value of failure frequency for the given interval:

$$P(t_{i-1}, t_i) = \frac{N(t_{i-1}) - N(t_i)}{N(t_{i-1})}, \tag{7}$$

where $N(t_i)$ = number of elements ready for working at t_i time,
$N(t_{i-1})$ = the above number at time t_{i-1}.

Mean life: is the mean value of life:

$$m = T_m = \int_0^\infty R(t)\, dt, \tag{8}$$

Mean time between failures: is a mean time interval between two failures occurring during the analysis of many repairable units. When λ = constant, then $m = MTBF$. It's value can be estimated with different methods. The more elements we consider, the smaller is the value of $MTBF$. (Fig. 1) Examining a finite number of system components, the time till the first failure (m_i) can be defined for all the units. It should be divided by the number of components (N):

$$m = \frac{m_1 + m_2 + \ldots m_i + \ldots + m_N}{N}. \tag{9}$$

m and $MTBF$ contain less information than the distribution function. The number of working elements in $t = m$ time is depending on the type of distribution.

Reliability parameters can be derived by:

— laboratory observations of system elements using a model of operating conditions;
— making use of failure statistics, based on usual workshop control.

The first method gives exact information within reproducible laboratory conditions. It is suitable for studying failure types and grounds. There are no disturbing moments due to interaction between elements. The laboratory examination of elements by simulation is, however, very expensive.

In the case of large mechanical systems only the second method may come into question. Its advantage is the larger sample size (depending on product type) obtained from processing user documentation. Besides sample size, sample independence and representativity are of utmost importance, as well as exact definition of failure, outfall and operating time.

Reliability of systems with independent elements

According to the common practice of reliability theory, systems can be so long reduced, until their components, as secondary failures arise. Elements considered independent from the reliability's point of view are called structural elements. The reliability of the mechanical system is defined by the number and individual reliability of these, however, their connecting scheme has certain influence, as well. In the practice, there are serial and parallel connecting schemes.

In a series connected system, the failure of any element leads to the outfall of the whole system. Further criteria are the followings:

— the system contains finite number of elements,
— the system is non-regenerative,
— only total failures can be examined—partial analysis is not possible,
— all the failures are of stochastic nature,
— the failure frequency of the elements is constant,
— the elements each are of identical importance.

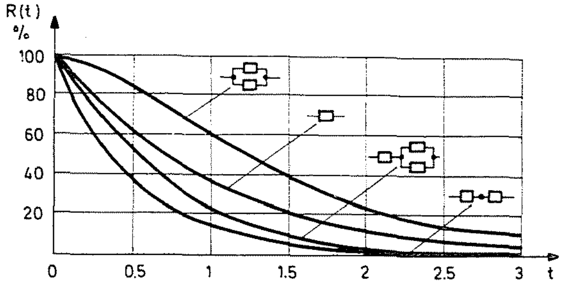

Fig. 3. Influence of different connection schemes on the system's reliability

If a system has M different elements and meets the above conditions, then its survival probability is:

$$R(t)=R_1(t)R_2(t)\dots R_M(t)=\prod_{i=1}^{M} R_i(t)\,. \tag{10}$$

It can be seen from the above formula that reliability decreases with the number of elements connected in series. To raise the level of reliability, the method of reservation can be efficiently used which is realized by parallelly connected elements. In a parallelly connected system there are redundant elements which take over the function of other elements when needed. Therefore, total system outfall occurs only when all the redundant elements drop out. The survival probability of systems with active redundancy is:

$$R(t) = 1 - \prod_{i=1}^{M} [1 - R_i(t)]\,. \tag{11}$$

On Fig. 3 the reliability of systems is shown as a function of connecting schemes (included mixed connection).

Mechanical systems are, in general, serially connected with a large number of elements.

Reliability of systems with secondary failures

The dependence criteria toward system elements can not generally be realized in the practice. That means that the failure of one element causes sooner or later the failure of other elements, or parts. There are several reliability interactions (dynamic, kinematic, electrical) between certain system elements. The question is: how to define the elements or groups with mutual dependence, and how to examine the size, direction and time function of this dependence. To answer these questions is extremely difficult. According to our present knowledge, no general method exists, and very few research reports can be found even in the literature [4]. In the followings a method is introduced which—although it implies a lot of simplifications—may contribute to the definition of survival probability in systems with secondary failures.

The failures of system elements in the course of operation will be called here as defect-events. Four types of impacts can be defined between two elements (E_i and E_j) of the event set:

1. The two elements are in mutual interaction, with the same or different intensity.
2. Only E_i impacts E_j.
3. Only E_j impacts E_i.
4. None of the elements impacts the other—they are independent defect-events from the reliability's point of view.

There are basically two types of relationships to be distinguished. On the left side of Fig. 4 there is the event pair $E_2 - E_1$ with conditional type of

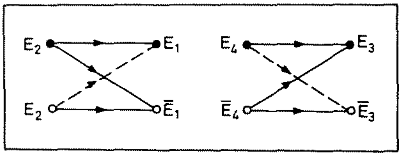

Fig. 4. Basic relationships between event-pairs

relationship, and event pair $E_4 - E_3$ with causal type of relationship. The solid line between event pairs shows strong interaction, the broken line designates a supposed weak interaction.* In technical systems failure occurs as causal interactions.

Interactions between not independent event pairs are expressed as changes in probability occurrence of impacted events. In case of mechanical systems these probabilities may obviously only increase. Since we have a whole system to be analyzed, the interactions interpreted in a pairwise manner should be defined for all the event pairs of the event set. To follow such a complex failure procedure in the practice is extremely difficult. We may use, however, some characteristics of the so-called cross-impact method here, developed for long-range forecasting [3]. Let us introduce the following denotations to use this method for our reliability problem:

— The set of defect-events consisting of M elements of the mechanical system:

$$\mathrm{D} := \{E_1, E_2, \ldots, E_i, \ldots, E_j, \ldots, E_M\}.$$

— Defect-event occurrence probabilities (for empirical analysis equal to the element failure ratios):

$$P(E_1), P(E_2), \ldots, P(E_i), \ldots, P(E_j), \ldots, P(E_M).$$

— The set of defect-events creates at every moment a total-probability system. All the different impairments of the system can be described:

$$S_1 := \{\bar{E}_1, \bar{E}_2, \ldots, \bar{E}_i, \ldots, \bar{E}_j, \ldots, \bar{E}_M\},$$

$$S_2 := \{E_1, \bar{E}_2, \ldots, \bar{E}_i, \ldots, \bar{E}_j, \ldots, \bar{E}_M\},$$

$$\vdots$$

$$S_r := \{E_1, E_2, \ldots, E_i, \ldots, E_j, \ldots, E_M\},$$

where $r = 2^M$.

There is a state probability ($P_k(S)$) attached to every impairing state:

$$\sum_{k=1}^{r} P_k(S) = 1, \qquad k = 1, \ldots, r.$$

Taking the time factor also into consideration, the input data for multiperiod cross impact method are the followings:

* *Interpretation:* when E_1 occurs within the given time interval, then there is a strong assumption, that E_2 has occurred before. At the same time, E_2 may occur without leading to the occurrence of E_1. In case of causal relationships the occurrence of E_4 results the occurrence of E_3.

$P(E_i, t)$ = cumulative defect-event probability in period t. This is the probability of the i-th element's failure within the mechanical system, in period t, or earlier.

$p(E_i, t)$ = the interval probability of E_i defect-event in period t. It is the conditional probability of the i-th element's failure within the period t, given, that it has not failed previously:

$$p(E_i, t) = \frac{P(E_i, t) - P(E_i, t-1)}{1 - P(E_i, t-1)} . \tag{13}$$

C = cross impact matrix, the elements $C(E_j, E_i)$ of which express the influence of the j-th defect-event's occurrence (or non occurrence) on the occurrence of the i-th defect-event in subsequent periods. The constant values of the matrix are defined by expert estimates*—consequently they are quite subjective.

When calculating the reliability of systems containing non—independent elements with multiperiod cross-impact method, the steps to be taken are the followings:

1. The cumulative defect-event probabilities should be converted into interval probabilities.
2. Using the values of the cross-impact matrix, the influence of all the events is aggregated on the events which have not occurred.
3. Interval probabilities are modified by cross-impacts.
4. For each defect-event in each period the fact of occurrence is examined with the help of random numbers.
5. The Monte-Carlo simulation is continued until getting stable results.

Computer simulation is done for all the non—independent event-pairs. This process is illustrated in case of E_1 and E_2 defect-events by a three period probability model (Fig. 5). The non-regenerative impairing states referred to the last time of the individual periods can be described by defect-event probabilities modified by cross-impacts.

In conformity with the basic axioms of probability theory, the following formula must be valid for interval probabilities:

$$p(E_i, t) = p(E_i, t \mid E_j) P(E_j, t-1) + p(E_i, t \mid \bar{E}_j) [1 - P(E_j, t-1)] . \tag{14}$$

* It should be noted that **C** can be expressed in a form of a function, as well. *Lipinski* and *Tydeman* [5] proposed for example a new cross-impact term which is proportional to the derivated impacted variable ($\hat{y}_j$):

$$\mathbf{C} = \mathbf{C}_1 \cdot \hat{y}_j + \mathbf{C}_2 \frac{d\hat{y}_j}{dt} .$$

Other, more complex terms may also be contained by **C**. The interactions between technical elements should always be expressed by functions. In the practice, however, these functions can not be defined; therefore, we have to come up with estimates.

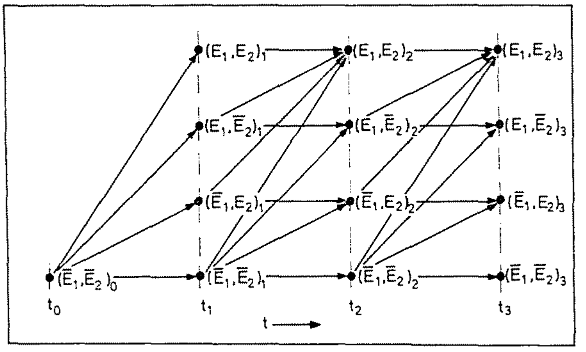

Fig. 5. Three period probability cross-impact model for E_i and E_j defect-events

Based on (14) it is obvious that the interval probability of defect-event E_i is the weighted average of the two conditional interval-probabilities. The weighting factor is the cumulative probability of the earlier occurrence of the defect-event. Note that the conditional interval probability—expressing a causal relationship—is not equal to the conditional probability known from the classical probability theory. In the course of reliability analysis interval probability should be used.*

Using the likelihood-multiplier method, the $C(E_j, E_i)$ cross-impacts are factors, the interval probability of E_i defect-event should be multiplied with, if the affecting defect-event occurred before [3]:

$$p(E_i, t \mid E_j) = \frac{p(E_i, t)C(E_j, E_i)}{1 - p(E_i, t) + p(E_i t)C(E_j, E_i)}. \tag{15}$$

After the necessary deductions the complementary interval probability is:

$$p(E_i, t \mid \bar{E}_j) = \frac{p(E_i, t) - P(E_j, t-1)p(E_i, t \mid E_j)}{1 - P(E_j, t-1)} \tag{16}$$

In summary, the characteristic features of the model are the followings:

Numberableness: The defect-event system D is a finite set of mutually interacted defect-events.

* During cross-impact analysis the following future probabilities are searched for: the probability of the occurrence of event a, if event b has occurred before the occurrence of a. In the classical probability theory the question sounds like this: assuming that event b has occurred, how probable is that event a has also occurred? When analyzing dependent elements of mechanical systems, the question is the following: when in the course of future operation one of the structural elements breaks down, has this event any relation to a former break down of an other element?

Dichotomous variables: All the elements of D defect-event system have only two possible states: absolutely in gear and out of gear.

Sequential characteristic: The defect-events have a definite occurrence sequence which is incorporated in the model.

Monotony: The defect-events do not repeat themselves: if a system breaks down in the analyzed period, it can not be active again.

It can be seen, the characteristics of the model are in proper conformity with the real behaviour of non-regenerative mechanical systems. Therefore, the model corresponds to the Boolean reliability model, as well. Regarding the latter there is one single exception: the assumed stochastical independence of the elements. Our main aim has been, however, to express just these interconnected relations in the reliability calculations.

Example

We will consider a tower crane here to illustrate the reliability analysis of mechanical systems. A sketch is shown on Fig. 6 of the crane which is to be used in building 16-level apartment houses. Main technical data: maximum load 8 t, maximum lifting height 60 m, lifting speed 22 m/min.

The following theoretical and practical aspects have been taken into consideration when defining the connection scheme of the crane:

1. It should contain all the crane elements, important from the point of view of failures.
2. The scheme has a serially connected main branch, the elements of which represent one of the crane's main operating functions. The failure of these elements causes total system break down.
3. Failure of parallelly connected elements does not lead to total system break down, since these elements are dispensable for quite a long time; their functions are subfunctions. Operating experience shows that in case of their failure the tasks of crane in building mechanization can fully be carried out.

Connecting scheme of the tower crane is to be found on Fig. 7: there are *10 subsystems connected in series* and in total *32 structural elements* defined.

Failure data of $n=50$ cranes have been prepared for analysis, for the period 1975–82, using failure statistics. A representative sampling was made, as a result of which cranes with different age were chosen. All the cranes were used for building panel houses; the operating conditions were, therefore, nearly the same. Differences (however, quite small: 9.5–11 hour/day) of actual working hours were compensated with the help of operation statistics. The moment of

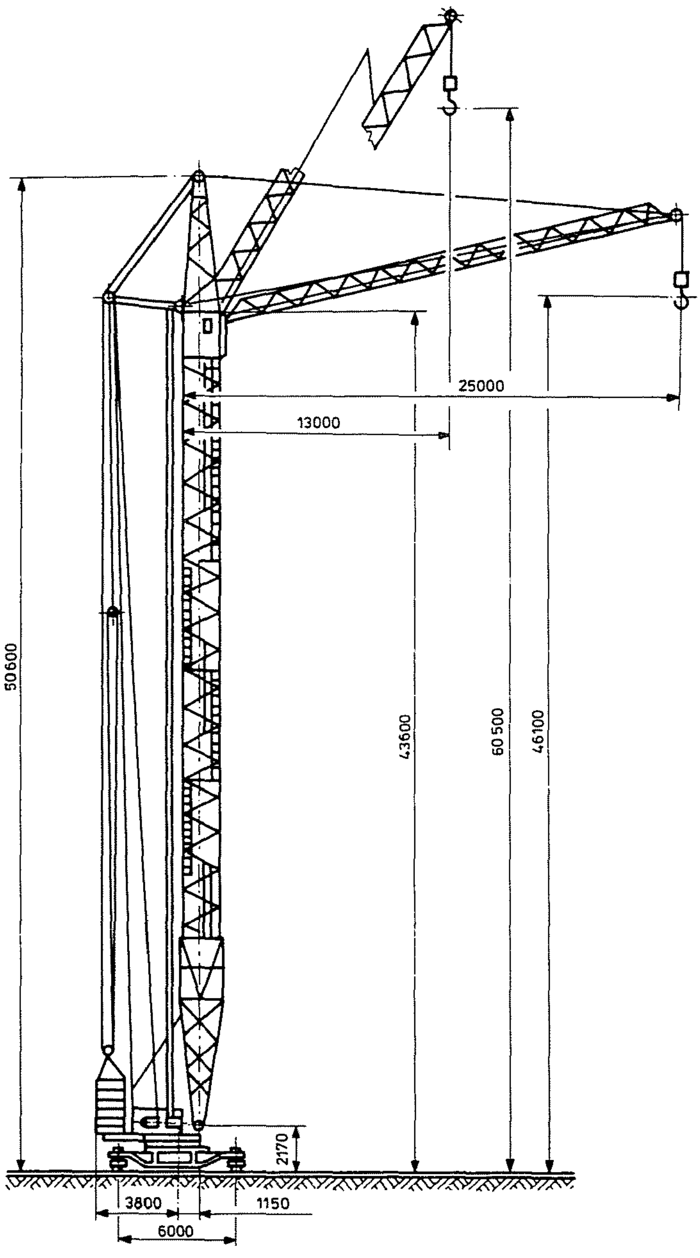

Fig. 6. Sketch of tower crane, type KB

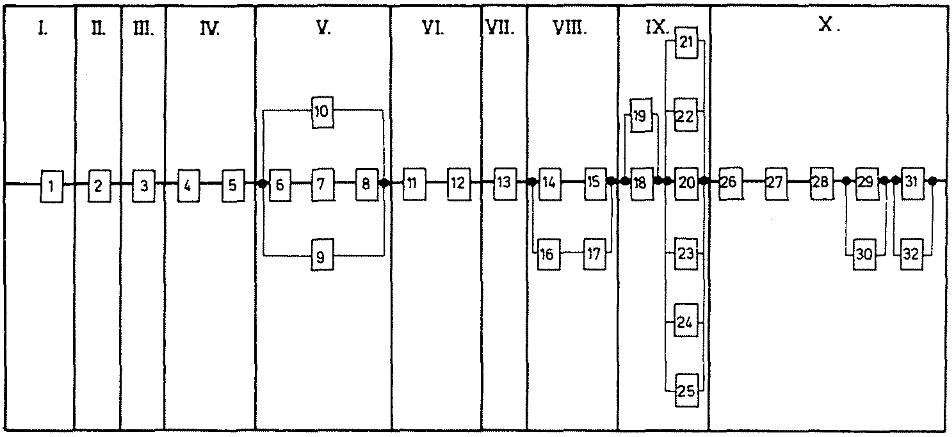

Fig. 7. Connecting scheme of the tower crane I. UNDERFRAME. 1. Under frame, spiders, stiffeners. II. WHEEL BOXES. 2. Driven and running wheels. III. TOOTH WHEEL RIM. 3. Structural elements. IV. TRUCK. 4. Frame structure. 5. Balance weight. V. DRIVING SYSTEMS. 6. Turning mechanism. 7. Load lifting mechanism. 8. Jib pulling mechanism. 9. Carriage. 10. Creeping mechanism. VI. COLUMN. 11. Portal, trunk and appliances. 12. Trunk head and appliances. VII. JIB. 13. Structural elements of gib. VIII. HANGING TRUSS. 14. Rigging for bearing load and jib. 15. Hook block. 16. Creeping rigging. 17. Rigging for frame and bracket. IX. SAFETY EQUIPMENT. 18. Moment and load limiter. 19. Load indicator. 20. Safety limit switches. 21. Limit switches for loaded state. 22. Limit switches for jib state. 23. Limit switches for driving mechanism. 24. Limit switches for carriage. 25. Limit switches for creeping mechanism. X. ELECTRICAL EQUIPMENT. 26. Magnetic switches. 27. Elements of the main circuit. 28. Subcircuit elements. 29. Service elements for crane operation. 30. Service elements for crane assembling. 31. Illuminant elements for non-crane state. 32. Carriage cables

the first failure was measured from the installation—the above mentioned compensation has been taken into consideration.

The range of the sample is the operating time difference of the crane last failed (T_{MAX}) and that of first failed (T_{MIN}):

$$R = T_{MAX} - T_{MIN} = 4137 - 20 = 4117\text{ h}\,.$$

When setting up classes, the number of gaps between them should be:

$$k \leq 5\lg n = 5\lg 50 = 8{,}49\,.$$

Choosing $k=8$, the length of the gaps is:

$$d = \frac{R}{k} = \frac{4117}{8} = 514.6\text{ h}\,.$$

Doing all the calculations according to (3), the empirical survival probability curve is given (see Fig. 8, dotted line). This is a specific exponential

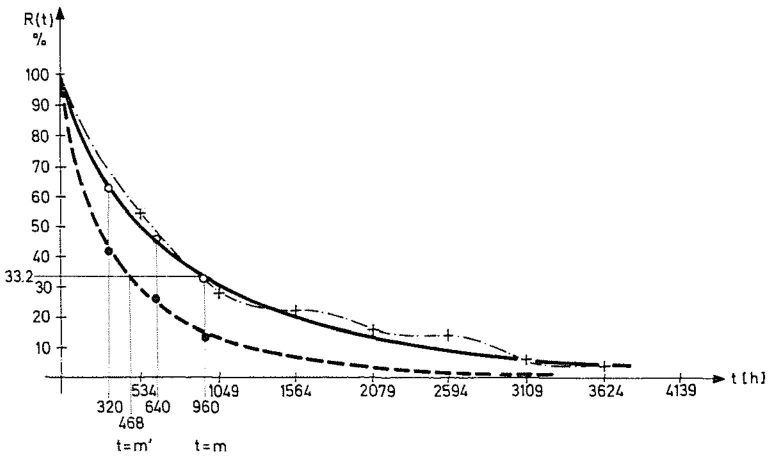

Fig. 8. Survival probability curves of the tower crane
Open circles: Calculated $R(t)$ values without cross-impacts
Black dots: Calculated $R(t)$ values with cross-impacts

curve, typical for mechanical systems. This kind of curve is characteristic for large systems, containing many elements with different mean life and variance. It is very easy to recognize, that quite large number of failures occur in the early stage of operation. Analysis shows, that these failures are due to planning and production problems. It would, however, be rash, to judge the cranes negatively on the basis of the survival diagram. The failures experienced in the beginning of the operation are namely minor ones, they can be fixed within 1–2 hours. Theoretically, however, they should be treated as failures, since they are leading to total system outfall.

The mean life of the tower crane according to (9) is, because cranes are naturally, repairable systems:

$$m = MTBF = \frac{20+30+\ldots+4137}{50} = 950.1 \text{ h}.$$

Failure frequency:

$$\lambda = \frac{1}{950.1} = 0.00105.$$

It is useful to find a theoretical distribution function to approximate the empirical survival curve. In case of exponential distribution, the survival probability for mean life is 37%. In our case however only 30% of all the elements (i.e. 15 cranes) are operating at this time. Because of this difference it is worth while experimenting with Weibull-distribution. Fig. 9. shows the definition of the Weibull parameters. A well fitting line can be drawn using the

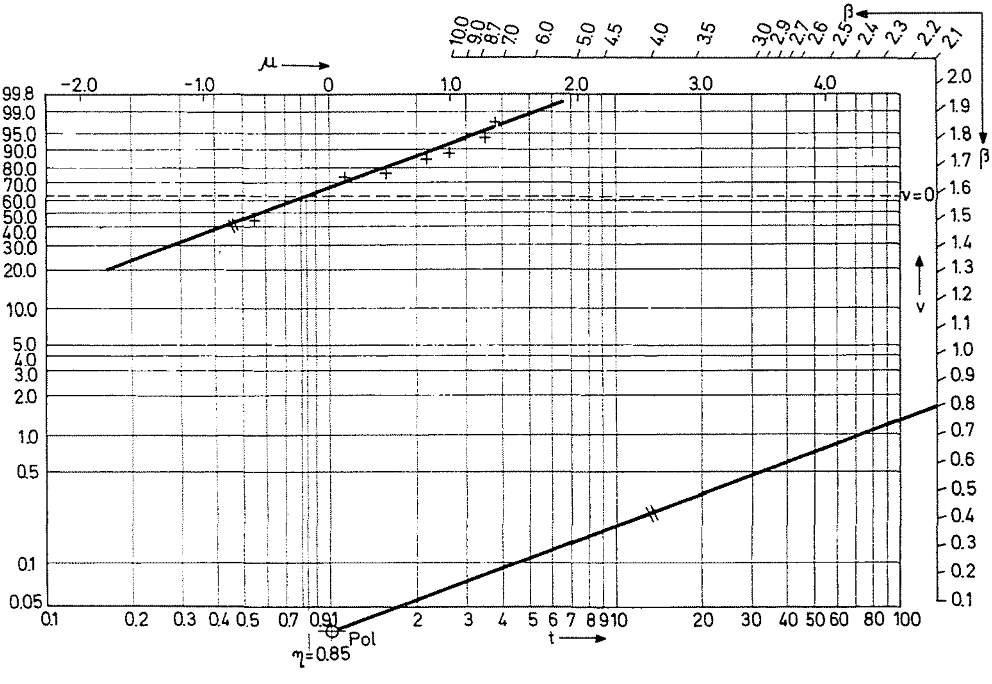

Fig. 9. Definition of Weibull-distribution parameters

characteristic points on the probability sheet which proves our assumption. This statement can be proved by a one-sided confidence analysis, not explained in detail here.

The positional parameter in the Weibull-distribution is $\gamma=0$, since failures occur already in early stage. The shape parameter $\beta=0.8$ the dimension parameter $\eta=850$ (Fig. 9). The Weibull function best approximating the empirical survival curve is (continuous line on Fig. 8):

$$R(t)=e^{-\left(\frac{t}{\eta}\right)^{\beta}}=e^{-\left(\frac{t}{850}\right)^{0.8}} \tag{17}$$

Based on Weibull function:

$$\frac{m}{\eta}=f(\beta)=1.13\,,$$

and $m=1.13\cdot 850=960.5$ h,
and with this

$$R(t=m)=0.332\,.$$

Dividing the interval *0–960 h* into three parts of the same size (Fig. 5.), defining the numerical values of the model's input data, and using (10), the survival probability of the tower crane for $t=m=960\ h$ operating time can be defined:*

$$R(t)=R_{I}(t)R_{II}(t)R_{III}(t)R_{IV}(t)R_{V}(t)R_{VI}(t)R_{VII}(t)R_{VIII}(t)R_{IX}(t)R_{X}(t)$$
$$=0.999\cdot 0.999\cdot 0.999\cdot 0.998\cdot 0.566\cdot 0.998\cdot 0.999\cdot$$
$$\cdot 0.979\cdot 0.969\cdot 0.605=0.3222\,,$$

where $R_{I}(t), \ldots, R_{X}(t)$ are the cumulative survival probabilities (failure quotas) of the independent main units (Fig. 7.) in the third part of the operating interval.

This value—like the calculated values of $R(t)$ for $t=320\ h$ and $t=640\ h$—adjusts itself without significant difference to the (17) Weibull function.

Next step was to set up the cross-impact matrix. Cross-impact values were estimated by an expert group consisting of engineers and crane operating personnel. One of the most interesting experience of the analysis was to find out that this expert group failed in estimating the failure cross-impacts for the 10 main units—they succeeded only in the case of the 32 element matrix. The interpretation is that in case of technical equipment a connection scheme breaked down to subunits or to components is needed to do the estimations. This was a very complex and long task, since $N^2-N=32^2-32=992$ elements were to be defined for the whole system. It is to be noted that cca. 80% of the elements equal to zero.

Then the cross-impact values were aggregated. Fig. 10 shows the cross-impact matrix, giving qualitatively the dependence relations among the 10 main units of the crane. Note that the cross-impact matrix is not symmetrical. Between main units, there are failure connections of different intensity and direction; they are, consequently, not totally independent. Our preassumption has been proved by this fact: the more we split up a mechanical system, the more interconnected is the generated event-set from reliability's point of view. Input data—since they are service data of the whole system—contain the causal cross-impacts between main units, as well.

To make use of the probability cross-impact model, three further outside events were generated. They represent most frequent events occurring in the course of operation, thus influencing significantly the failures of main units (Fig. 10). These outside events are: *01 = additional load caused by wind (higher than permissible); 02 = operation in extraordinarily unfavourable environment (e.g. vitriol-plant, cement plant); 03 = careless assembling/disassembling when installing the crane at a new site.* The cumulative probabilities in the three

* Since the tower crane does not contain spare or substituting elements, the resultant reliability of subsystems V., VIII., IX., and X. cannot be defined with (11)—namely these elements are not redundant. Therefore, during calculation only the main line elements connected in series have been taken into consideration.

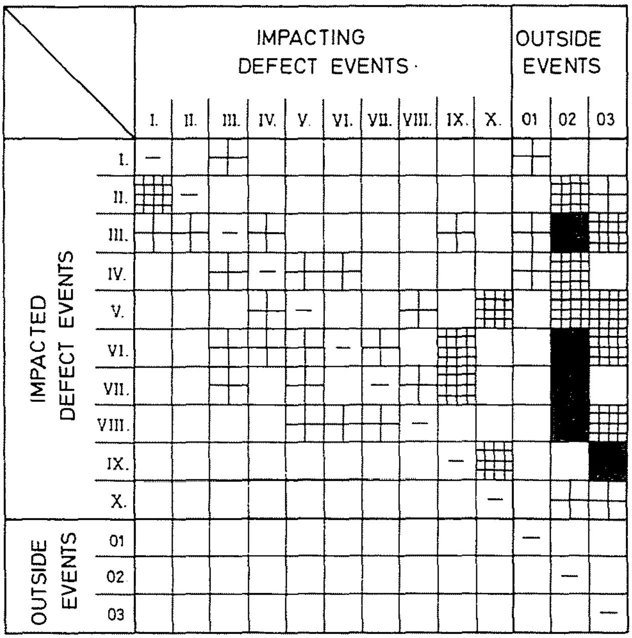

Fig. 10. Cross-impact matrix
Black square: strong cross-impact
Hatched square: moderate cross-impact
Crossed square: weak cross-impact
Open square: no cross-impact

periods examined, are in sequence:

$$P(01)=[0.04;\ 0.08;\ 0.12]\,.$$
$$P(02)=[0.10;\ 0.10;\ 0.10]\,.$$
$$P(03)=[0.10;\ 0.20;\ 0.30]\,.$$

Note, that the case of catastrophic failure has been excluded.

Attaching numerical values to the qualitative probabilities according to *Enzer* [3], and replaced the results of the computer run in (10), the following values are obtained:

$$R(t=320)=0.418\,.$$
$$R(t=640)=0.255\,.$$
$$R(t=960)=0.130\,.$$

The adjusted Weibull function (broken line on *Fig. 8*) is:

$$R(t)=e^{-\left(\frac{t}{400}\right)^{0.75}} \tag{18}$$

Mean life of the crane:

$$m' = 468 \text{ h}.$$

Regarding the curve of (18), and the value of m', the common impact of the three outside events decreasing the system's reliability significantly, can well be appreciated. The correctness of the numerical values got, equals that of expert's estimation.

Conclusions

When defining the reliability of complex systems, we can not assume independence among system elements and between system and environment. Those empirical or experimental methods should systematically be searched for, by the help of which interactions can be explored and analyzed exactly enough. To have an adequate and total idea of system operation influenced by environmental effects, is particularly important in the design phase of new machines and equipments. This knowledge may contribute to decrease failures in operating systems and to design maintenance more objectively. In the course of our analysis a lot of partial results were obtained, concerning the reliability of crane elements. All these may be used for further developments.

The procedure proposed and introduced here is general enough to be used widely. The application of methods like this, however, demands a sound background of information—it can, therefore, be proposed only for users having the necessary level of organization, and the failure statistics needed.

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