THE AGEING OF SIGNALLING EQUIPMENT AND THE IMPACT ON MAINTENANCE STRATEGIES

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SUMMARY

Research projects of SNCF (French railway) aim at reducing the costs of infrastructure possessions and improving the operational equipment availability and safety. This permanent search for a better regularity led the SNCF to analyse the maintenance approach of signalling equipment in detail. Until now, it was commonly acknowledged that signalling equipment, which consists of many electronic devices, is not subject to ageing. In this study, a Weibull lifetime model, able to describe an ageing phenomenon, is used and it can be shown that the deterioration is statistically significant. The validity of the model is tested. We also analyse the influence of environmental covariates. We simulate different scenarios in order to investigate the impact of several maintenance strategies as well as on future maintenance costs, on the amount of components to replace based on the mean age of the network. It can be shown that in most cases a systematic replacement strategy offers the best solution.

1. INTRODUCTION

The purpose of this study is to estimate the lifetime distribution of signalling equipment. We investigate if there is an ageing phenomenon. If signalling equipment deteriorates, the current maintenance strategy, based on curative replacements, is perhaps not optimal. We developed statistical models to estimate lifetime and maintenance costs. These methods are applied to the maintenance of signalling equipment especially to electronic units (electronic fail-safe devices). Even though the mathematical models are basically used for an economic optimisation of the infrastructure maintenance, we specify for every chosen maintenance strategy the expected number of defects and failures.

In 2006, RFF (the French infrastructure owner) and SNCF analysed the consequences of a significant effort of renewal of the French network without being able to agree on its possible consequences in terms of decreasing maintenance costs and of the ageing of the network.

The present work is based on methods accepted by both partners that were developed in order to answer, at least qualitatively, the following questions:

– Is it possible to find an economic optimum between maintenance and renewal for the current network?

– What would be the consequences on the quality of the French railway network if the current expenses remain unaffected or if they change significantly?

Generally, the former studies of the SNCF are based on estimates of the national average costs of maintenance with the implicit assumption that the level of renewal avoids any ageing of the network. They are simple to use but they estimate imperfectly the variation of maintenance costs due to the network ageing.

The development of the economic model described in this article is based on the failure models. Unit costs for every replacement and every renewal are then associated with the failure model. Sometimes it is possible to repair components. A repaired component is less expensive than a new component but it does not have the same failure distribution.

We construct the failure model as follows: we are first interested in the lifetime distribution for an unreplaced component, we analyse the impact of environmental variables on the lifespan (ageing), and we then calculate the expected number of components to be replaced. We then describe the construction of the cost model and finally we describe the different scenarios that were created in order to analyse the impact of several maintenance strategies on the network development.

2. NOTATION

In this article, we will use the following definitions:

The term maintenance is used to indicate the replacement of a component by another component, only when it is necessary.

The term renewal is used for a massive replacement making it possible to concentrate the effort and to limit the encumbrance on the network due to work. The replacements costs are lower, but the components could still have lasted several years.

3. DATA

A database containing information of all signalling equipment on the French network is used for the analysis. This database contains the state of every component including the date of installation, of repair, of replacement, of storing and of re-employment.

4. METHODS

4.1. Lifetime Estimation

We define the survival model for unreplaced components by fixing the failure rate $\lambda(t)$. The failure rate represents the probability of observing an instantaneous failure given that the component has not failed before time t. If the components are subjected neither to wear nor to ageing, it is possible to consider a distribution with a constant failure rate. In that case the exponential distribution is obtained. The failure of the signalling equipment treated in this study is usually modelled using an exponential model. One of the aims of this analysis was to show that even equipment with electric components can deteriorate.

For mechanical or electric components, if they are a part of a large system, the standard distribution commonly used is a distribution with a power failure rate: it represents reality very well. One then obtains a class of failure distribution: the Weibull distributions. They can be described by:

- failure rate $\lambda(t) = 1/\eta^\beta \cdot t^{\beta-1}$
- density function $f(t) = \beta/\eta^\beta \cdot t^{\beta-1} \cdot \exp(-(t/\eta)^\beta)$
- cumulated density function $F(t) = 1 - \exp(-(t/\eta)^\beta)$

where $\beta > 0$, $\eta > 0$ and $t > 0$. The Weibull distribution depends on two parameters (there is also a version of the

Weibull distribution depending on three parameters but this distribution is not treated here):

- The shape parameter β which determines the distribution of the failures on the time axis:
    - If it is small, the failures are distributed over a large time span,
    - If it is high, the failures appear within a short time interval,

– The scale parameter η defines the time scale.

The obtained functions (represented with respect to the reduced variable tr = t/η are presented in Figure 1 and

Figure 2. In the case of signalling components the value of the parameter β should be between 1 and 3.

For the signalling components that are still in use today, we obtain censored data. We cannot observe the date of replacement for these components. The method used for the analysis has therefore to be adapted to censored data. The treatment of censored data in parametric probability models is described in Klein & Moeschberger [4].

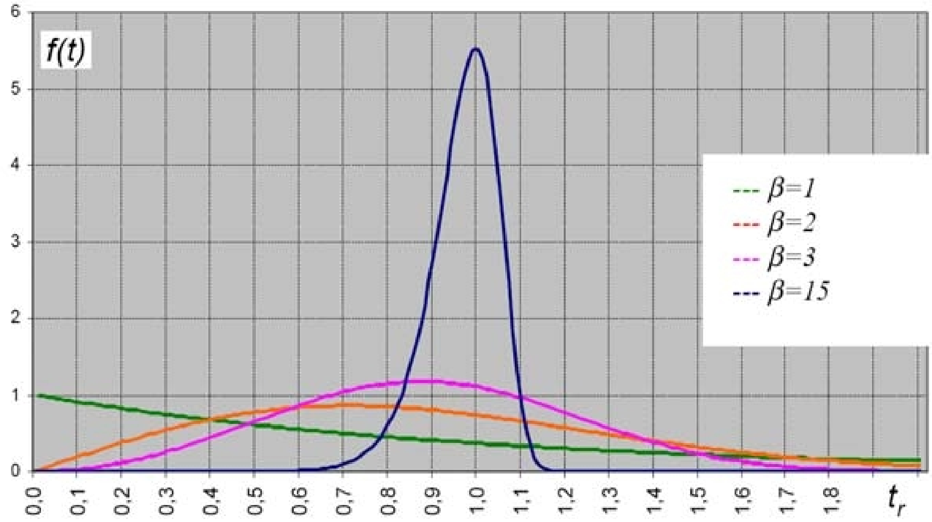

Figure 1: Density function for different Weibull distributions.

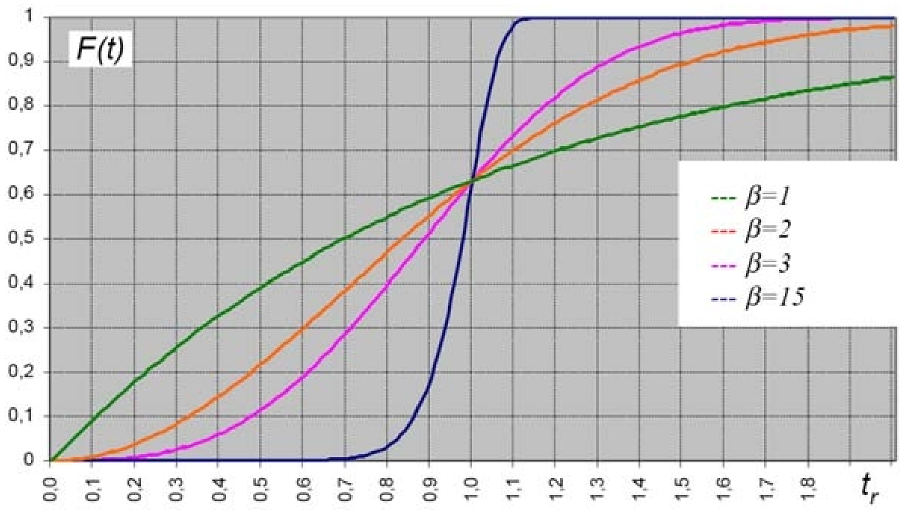

Figure 2 : Cumulated density function for different Weibull distributions.

We use the Kolmogorov-Smirnov test in order to verify if the Weibull distribution is adapted for the lifetime modelling of the specific electronic unit. In most cases, the ageing phenomenon is evident. In some cases we find ageing phenomena that seem more complex than the one modelled by the Weibull distribution. As explained in more detail in section 7.1, at the moment we are testing other distributions that remain however close to the Weibull distribution.

4.2. Replacement model

In practice, it is necessary to take into account the effect of successive replacement for the components in service. A failed component is replaced by a new one which, in turn, will be subject to wear or ageing. The renewal density $h(t)$, that gives the replacement due to a failure at time t, can be written as a sum of n- convolutions:

$$h(t) = \sum_{n=1}^{\infty} -[(1-F(t))']^{*n} , \tag{1}$$

where * denotes the convolutions.

There is no simple analytical expression for this function, even when considering the particular case of a Weibull distribution. The term can however be calculated numerically. Figure 3 shows the influence of the parameters β and η on the amplitude of the oscillation. The system converges more or less fast towards an asymptotic value.

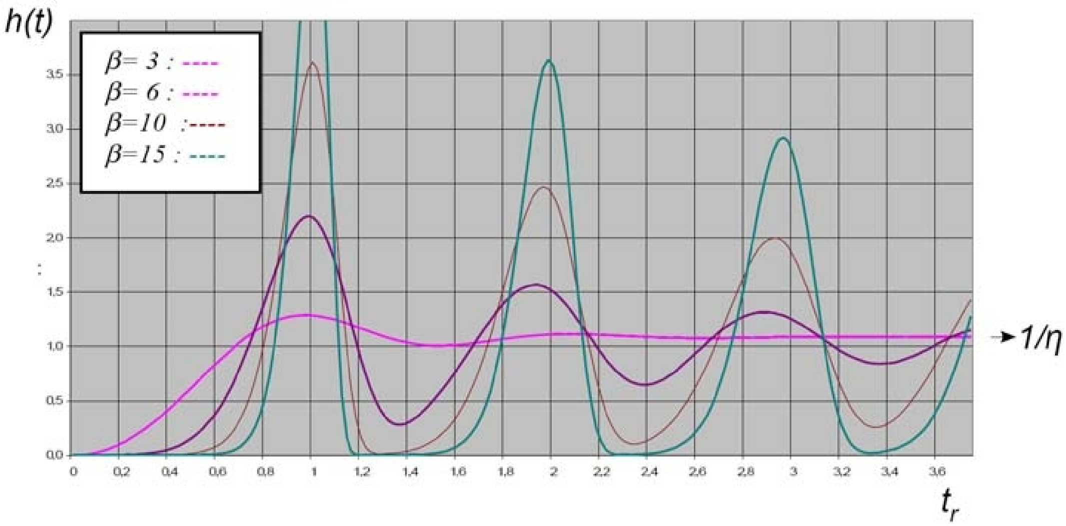

Figure 3 : The function h(t), the renewal density.

It can be seen that for a small β (this is the case for signalling units) the failures are spread over the time, and that the overlap of the successive replacements, leads to a fast attenuation of the replacement peaks. From the second cycle of replacement on, the number of failures is close to the limit value. For high β, the failures are concentrated on a time interval, the overlap between successive replacements is small and the attenuation of the replacement peaks is very slow.

We have to bear in mind that at this phase we consider implicitly that components are replaceable infinitely without reduction of their life expectancy. This hypothesis could be accepted in the case of components interacting few with other components. But it is also possible that the system, which is after many replacements very different from the initial one, influences the lifetime of the components. Every component, new or second- hand, will be stressed under conditions that are not the original ones and the lifetime will be progressively reduced in the course of time. In this article we do not treat the case of interacting components but we mention in the section 7.2 how we want to take into account this phenomenon.

4.3. Covariates

There are several covariates influencing the lifetime of the components. They belong either directly to the component or to its environment. For example, if the electronic unit is installed inside an equipment centre, it has a different lifetime distribution compared to a component next to the track without protection. The used covariates included in the study are: maximum speed on the railway track, climate, localisation but also the type of the electronic unit among all components fulfilling the same functionality and the storing time before the installation. We use two ways to treat the variables in the model: either we include them into an accelerated failure model based on a Weibull distribution or we use them as segmentation variables and estimate the lifetime for every segment separately.

For every component the most influencing covariate is determined. We find that the storing time is one of the most important covariates.

4.4. Cost model: new component

We want to optimize the global maintenance costs, including renewals and heavy maintenance (for example removal for reparation in a workshop). The real maintenance cost model is of course more complicated as compared to the following model as there are implementation constraints. However, The presented cost model considers the main expenditures.

The failure model defined above allows us to obtain in a simple way the cost model for the concerned component. The annual maintenance expense are, on the one hand, due to expenses related to failures resulting in the replacement of components (product of the unit expenses cu for every replacement and the number of replacement to be carried out) and, on the other hand, of expenses ci not directly related to the replacement of components (surveillance operations and common maintenance). In this way, the maintenance expense per year for a new installation are given by $Y(t) = c_i(t) + c_u \cdot n \cdot h(t)$ where n is the number of components of the installation and $h(t)$ is the renewal density at time t. The expected cumulated maintenance expenses at time T are then:

$$E(T) = \sum_{t=0}^{T-1} Y(t)\,. \tag{2}$$

The renewal expenses are chosen as constant: X = constant. The value of X is based on real costs stated over the last years. The maintenance expenses including renewal are defined as the sum of the maintenance expenses and renewal expenses over a period T. In order to calculate the expected costs during the lifetime of an installation, we define the expected annual maintenance costs that include periodical renewal by the expression:

$$C(T)/T = [X + E(T)]/T\,, \tag{3}$$

where X are the renewal expenses based on a complete renewal of the components. The minimum of these expected costs defines the optimal renewal period T_0. This period is a function of the parameters of the failure model (β , η) and of the ratio between the regeneration expenses by means of a systematic renewal X and by means of maintenance Y. For a component having a high parameter β the optimal value for the renewal period T_0 is not very sensitive with respect to the X/Y ratio. On the opposite, for low β as in our case, the optimal regeneration period exists only if the X/Y ratio is also low. The optimum period T_0 gives the date from which continuing the common maintenance is no longer the best economic solution.

For the calculation of the maintenance costs Y(t) it is important to consider all maintenance actions (repair, replacement, and re-employment). There are also costs of inspections and common maintenance. This study tries to compare the current maintenance strategy that is based on curative maintenance to a new one that includes systematic renewal. It has to be mentioned that even if we use a systematic replacement strategy there are still components that can fail between the renewal cycles. These costs have to be considered. As signalling equipment is essential for passenger safety we always analyse the number of expected failures in addition to the generated costs. The inspection intervals have to be adjusted in order to optimise the detection of failures for redundant systems and the detection of deviations from the regular mode for non redundant systems.

4.4.1. Unavailability costs

The failure of a component and its replacement often result in a limitation or a cessation of the traffic. This temporary closing of a line has consequences in terms of regularity. There can also be a financial impact (refund of the passengers). This is also true for renewal works. These “expenses of unavailability” are a function of the importance of the installation, of the robustness of the system functioning in disturbed situations, of the aptitude of the installation to manage disturbed situations. These costs are however difficult to evaluate as there are several possibilities to obtain them. Thus, the current model does not take this element into account.

4.5. Simulation: existing network

For the electronic signalling components there is currently no systematic renewal. The components are individually replaced after failure. In this case, it is not possible to neglect successive replacements of the same component, and the function h(t) (cf. equation (1)) will be used.

In order to quantify the impact of ageing on the maintenance strategies we used three scenarios:

- replacement after failure (corrective maintenance),
- replacement of a fixed number of components (fixed budget maintenance). Failed components are replaced and 10 % of the installed components are replaced preventively every year. Old components or repaired components are replaced first,
- replacement depending on the age of the component (time-conditioned maintenance). Failed components are replaced and at a given interval all installed components are replaced systematically and preventively.

The data mentioned above enables us to build a new database containing the equipment currently in use. The Weibull distribution gives us an estimation of the number of components likely to fail. Like for the cost calculations for new components (cf. section 4.4), we evaluate every maintenance action (repair, replacement, and re-employment) economically. It is then possible to simulate the impact of the ageing on the three proposed maintenance strategies. We calculate the expected number of failures, the expected number of components to replace and the development of the maintenance costs over time. It is then possible to find the optimal inspection interval.

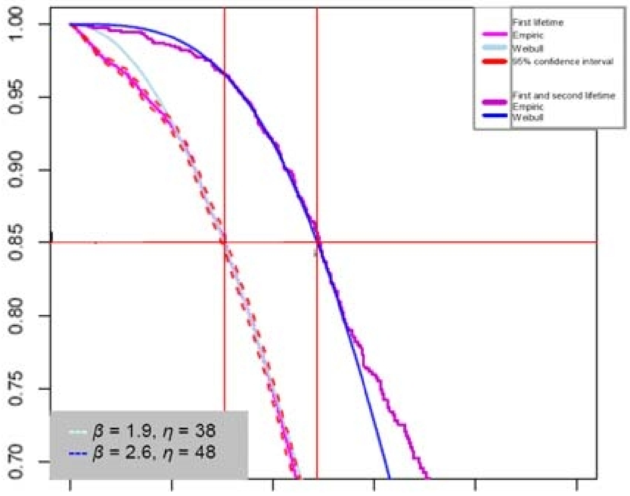

Figure 4 : Reliability estimation for signalling equipment. There are two lifetimes: the first one before reparation, the second one ignores the reparation.

5. RESULTS

Figure 4 shows the results of a lifetime estimation for track circuits transmitters. This type of unit can be repaired and there are therefore two reliability curves. The dark blue one gives the sum of the first and the second lifetime.

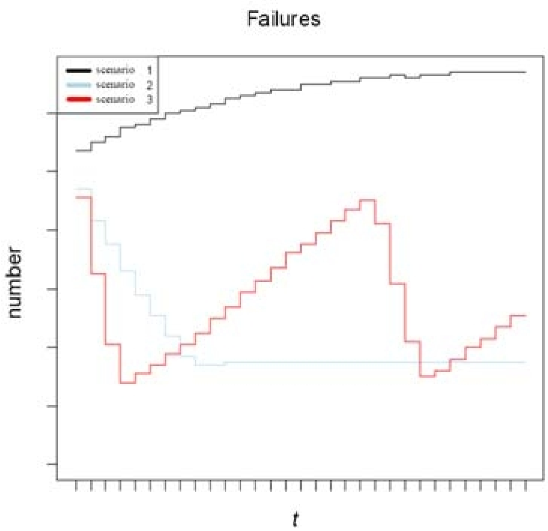

Figure 5 : Expected failures for the three scenarios.

The results of the simulations can be seen in Figure 5 and in Figure 6. As mentioned above we also consider the number of failures. From Figure 5 it can be seen that a change of the maintenance strategy does not increase the number of failures. Figure 6 gives the corresponding costs. The expenses are discounted with a rate of 4 %. It can be seen that the red scenario is more expensive at the beginning, but after a certain time, the cumulated expenses are lower than for the other strategies. It appears that a renewal strategy minimizes the global lifecycle costs.

6. CONCLUSION

The result enables SNCF engineers to adapt the current guidelines and to predict future maintenance expenditures.

6.1. Developed method

The approach is based on methods usually used in reliability. It allows a good modelling of the intuitively perceived phenomena: the more the equipment is regenerated, the lower the regular maintenance costs and conversely, regular maintenance alone does not allow a piece of equipment to last indefinitely as it ages, and finally there is often an economic optimum for the systematic renewal. The calibration of the model is based on accessible real data.

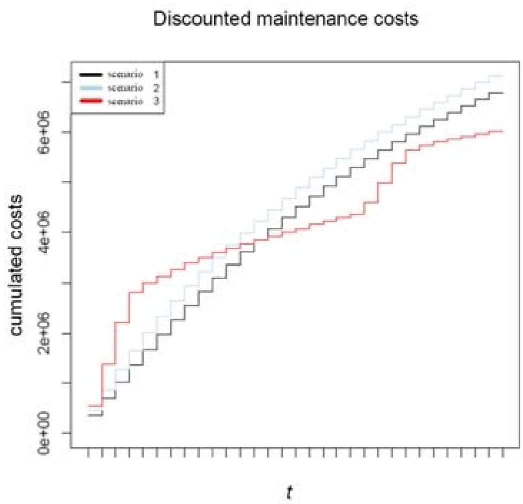

Figure 6 : Expected cumulated costs for the three scenarios.

The method is very general. The application range is very wide. All replaceable infrastructure equipments can be used for such a study. The proposed method is already used for track and overhead line components [1].

6.2. Extension to other questions

This approach can be applied to particular sub populations: high speed lines, lines with dedicated traffic. It is also possible to use this type of model on a particular line in order to predict failure trends. This knowledge allows the Maintenance Engineering Department of the SNCF to confirm in an objective way its new maintenance strategies.

7. PERSPECTIVES

7.1. Extension of the Weibull distribution

Some of the signalling components seem to follow a more complicated probability distribution. The Weibull distribution is able to model the overall behaviour but it seems that the characteristics of components at the beginning and at the end of their lifetime, change. This could be due to the different parts of the component

(electrical parts, chemical parts, mechanical parts). At the moment we are working on a more detailed modelling of the lifetime and parameter estimation. As this concerns only one sub-model of the proposed method, we can keep the cost model and the different scenarios. We only have to change the input for the calculation of the h(t) function.

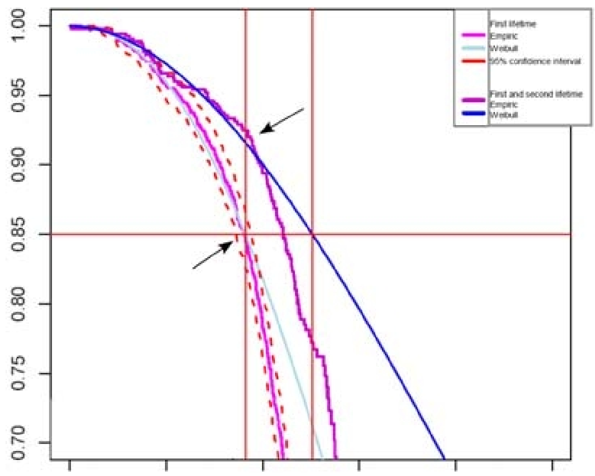

Figure 7 : Reliability estimation for signalling equipment. The Weibull model is not a very good fit. It can be seen that there is a turning point in the curve probably coming from several superposed reliability functions.

Figure 7 shows an example of a type of electronic unit that cannot be modelled by the Weibull distribution. It seems that there are two different reasons for failure: the first one is completely random. The second one should be related to wear or deterioration and increases with time. We are testing at the moment the Bertholon distribution, a combination of the exponential and Weibull distribution [2][3].

7.2. Ageing of the system

The correct functioning of an electric unit depends on the functioning of other components. For example, the transmitter of a track circuit wears more quickly if the electronic separation joint of the transmitted is not correctly electrically adjusted. Electrical fail-safe devices have characteristics that change with time: by replacing a component of an electronic board, the component will be stressed within an operating sphere different from what it would have been with a new board. The more the “neighbours” are used and were replaced, the less the system will endure. This phenomenon could be clearly detected on signalling equipment after several reparations.

In order to represent this phenomenon in an adapted way, we introduce a third parameter, the rate K. This rate represents the life expectancy reduction after each replacement of a component: $\eta_n = \eta_{n-1} \cdot K = \eta_0 \cdot K^n$, where n is the rank of replacement. This parameter K depends on the equipment and on its environment. It can be estimated from feedback data.

The introduction of a power coefficient leads to a very short life time for components that were replaced several times. This representation is satisfactory.

Figure 8 illustrates the increase of the number of replacement when the system gets older; the example uses K = 80 %.

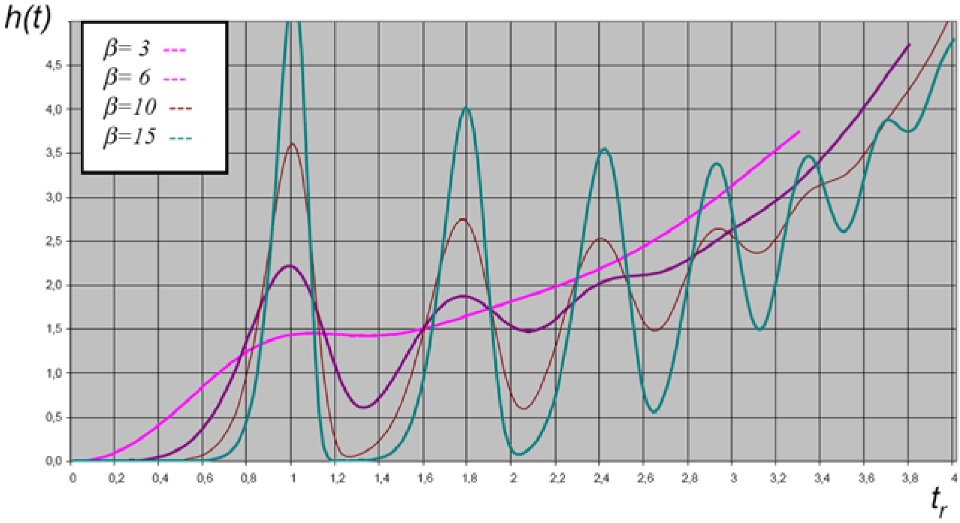

Figure 8 : Density function h(t) when including the ageing of the system.

8. REFERENCES

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