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Mathematic modelling of reliability, safety and risk indicators related to equipment elements existing at iron and steel enterprise

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Abstract. This article describes mathematical modelling of reliability, safety and risk indicators related to load bearing structural elements. The number of this type of cranes used at a modern iron and steel enterprise constitutes more than half of the total number of cranes. Therefore, the concerned issue and the problems addressed in this case represent current interest. Due to the impossibility of conducting a laboratory or a full-scale experiment, a numerical experiment is conducted using model distribution. Benchmark data used for calculations and based on previous studies performed by the author and available statistical data about incidents and damages are systematized and proposed. Hypotheses about addition and multiplication of damages related to elements of the equipment under study are made. Modelling adequacy is observed when the experiment findings match with available data. Classification of incidents arising when metallurgical cranes are operated beyond the expiry of their warranty period is identified. These calculations and procedure develop the theory of structural risk analysis of complex technical systems and allow making correct engineering-related managerial decisions.

1. Introduction
An iron and steel enterprise consists of a large number of potentially hazardous facilities. These facilities are not only operated under extreme conditions but also their significant portion is operated beyond the expiry of their warranty service life [1,2]. Records of reliability, risk and safe operation indicators of such facilities are far from perfect at the moment [1-21]. Mathematical modeling of such parameters represents the issue of the day. Let us examine the load bearing structure of a metallurgical overhead crane as equipment elements existing at an iron and steel enterprise.

2. Materials and methods
The load bearing structure of a metallurgical overhead crane, which is structurally represented in figure 1, is examined in previous studies [9,10].

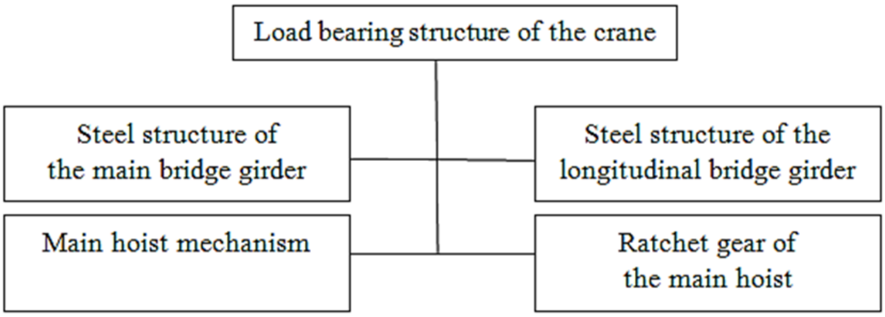

Figure 1. Structural diagram representing the load bearing structure of the overhead crane.

We have four units (subsystems) at the first level and ten elements at the second level including three elements in the first unit, two elements in the second unit, two elements in the third unit and three elements in the fourth unit. Second-level elements constitute local units grouped together based on multiple varying parameters specifying criterial functions.

We shall investigate two limit cases – addition and multiplication of damages during the damage escalation process [1,2,10]

$$R_{\Sigma}=\sum_{i=1}^{4}a_i\sum_{j=1}^{10}a_{ij}\sum_k R_{ijk};$$

$$R_{\Pi}=\prod_{i=1}^{4}\left\{\prod_{j=1}^{10}\left(\prod_k R_{ijk}^{a_{ijk}}\right)^{a_{ij}}\right\}^{a_i}.$$

Coefficients a represent the importance level of all structural subsystems and elements. They must meet the following conditions:

$$\sum_{i=1}^{4}a_i=1;\ \sum_{j=1}^{10}a_{ij}=1;\ \sum_{\mathrm{k}}\mathrm{a}_{\mathrm{ijk}}=1.$$

R with different indices represents integrated evaluation of risk, reliability and safety both for a single element in the system and for the whole structure.

When investigating such model we make allowance for the following: analysis is conducted on highly improbable events; strong uncertainty resulting from the random nature of external impacts and processes occurring in structural elements as well as the absence of clear safety objectives and criteria; time limitation, i.e. the time of response to an emergency or an incident. Besides, all the four subsystems will represent potential zones of damage.

In this case, the criterial function of risk can be presented in the following form:

$$R_{\Sigma}(t)=P\left\{t:H\,|\,\mathrm{var}\left[Z_k\right]\notin\Omega_s\right\},$$

where: H refers to the vector of hazards, Z refers to potential zones of damage and Ω refers to the safety zone.

Considering the fact that the risk depends on the type of incident and is not associated with probability of the incident, and regarding the damages of potential damage zones as equally possible events, we can proceed to modelling the indicators under study.

3. Results

The difficulty, and in some cases the impossibility, of conducting a full-scale or a laboratory experiment for verifying the adequacy of mathematical modelling findings, suggest that a numerical experiment should be conducted. As benchmark data we shall use table 1 of weighting coefficients and – for structural elements of a metallurgical crane – first to fourth units of two levels [9,10].

Table 1. Values of weighting coefficients of structural elements.

Number of elements	First level	Second level
3	3/10	1/10;1/10;1/10
2	2/10	1/10;1/10
2	2/10	1/10;1/10
3	3/10	1/10;1/10;1/10
Total: 10	Total: 1	Total: 1

Values of weighting coefficients are proposed based on the equal possibility of potential damage to any subsystem or structural element of the crane under study, which is operated at an iron and steel enterprise beyond the expiry of its warranty period. By linking reliability, safe operation and risk indicators of equipment elements we shall input the benchmark data to evaluate the risk of emergency operation – please refer to table 2.

Table 2. Risk of emergency operation of the structure beyond the expiry of its warranty service life.

t	0	1	2	3	4
R(t)	0.010	0.016	0.026	0.038	0.053

We assume that t refers to the number of years following the expiry of warranty service life of the crane structure. Considering that the warranty service life is fifteen years, 0 refers to the sixteenth year.

We shall make a distinction between the following three types of incidents:

- incidents that do not result in the shutdown of the crane and the production process;
- incidents that result in the shutdown and repair of the crane;
- catastrophic incidents that can result in the damage of the structure, disruption of the production process and loss of life.

We shall use MS-Excel and model distribution for the numerical experiment. Based on the conducted numerical experiment and available data [1,2,9,10], we shall calculate the damages resulting from different types of incidents, in notional currency units. We make the calculation assuming that there are 600 overhead cranes operated at the iron and steel enterprise for five years following the expiry of the warranty service life.

Damages obtained by way of addition: $R_{\Sigma} = 600 * 5 * 0.0325 * 2.1 = 204.75$ notional currency units.

Damages obtained by way of multiplication: $R_{\Pi} = 600 * 5 * 0.0288 * 2.1 = 181.44$ notional currency units.

Calculated data are interpreted as follows: probability of risk arising with the breakdown of one or several structural elements of a metallurgical overhead crane or being outside the safe operating zone is 0.0325. On the other hand, probability of risk arising with the breakdown of all structural elements at the same time and being inside the hazardous operating zone is 0.0288.

Damages will correspond to 21 incidents of the first type, 2 incidents of the second type and 0.2 incidents of the third type when adding the damages and, correspondingly, 18 incidents of the first type, 1.8 incidents of the second type and 0.18 incidents of the third type when multiplying the damages – please refer to figure 2.

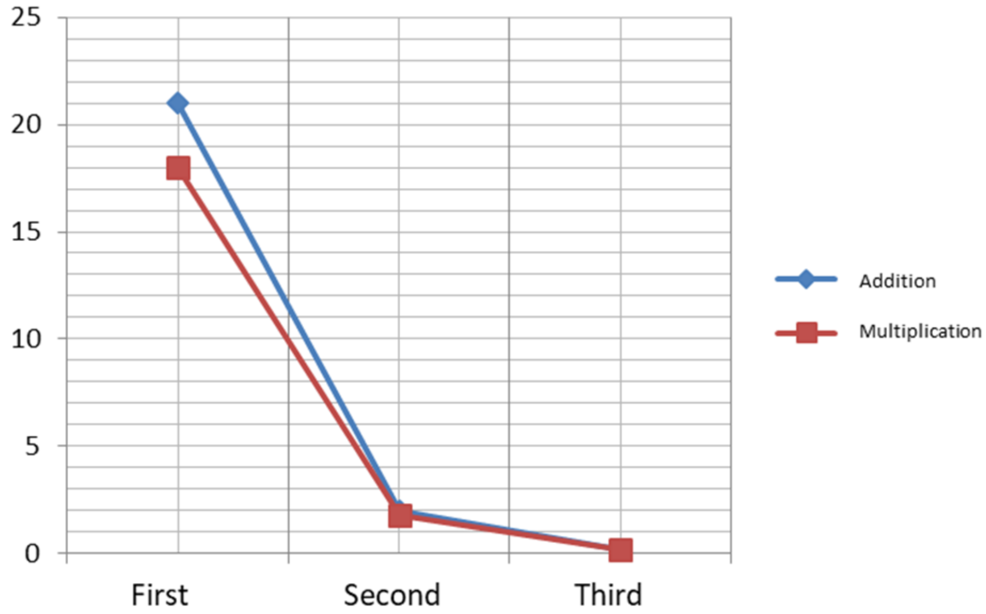

Figure 2. Added and multiplied damage resulting from different types of incidents.

The conducted mathematical modelling develops the theory of structural risk analysis and will allow to make correct engineering-related managerial decisions when operating the equipment under study, namely to consider changes in time between repairs, procedures, etc. for ensuring reliable, safe and failure-free performance of its elements.

4. Conclusion

The task of evaluating various technical systems is currently quite relevant and popular. Despite the existence of numerous approaches and software tools used to address this task, the calculation of risks and associated reliability and safety parameters for the studied elements of equipment existing at an iron and steel enterprise – the load bearing structure of a metallurgical overhead crane – is relatively new and complex, and must comprise a unified methodological line. It is suggested that this requires mathematical modelling of all these parameters.

Risk of incident occurring with a particular type of load bearing structure is calculated based on the study of two limit cases: addition and multiplication of damages during the damage accumulation process.

The conducted mathematical modelling represents a model solution for the major problem of risk assessment as well as safe and reliable operation of equipment at an iron and steel enterprise where overhead cranes are used. They are operated in heavy and extra-heavy conditions, often beyond the expiry of their warranty period. Modelling adequacy is verified by numerical modelling and its matching with available data on incidents and damages resulting therefrom.

Despite the fact that the calculations are model-based and conventional, they can definitely be applied to process calculations of real complex technical systems.

This approach can be used as follows: everything can be left unchanged when operating the studied crane elements. In other words, the deadline of the post-warranty period can be determined and then the owner can buy a new crane, without making any investments. Alternatively, the amount of investments for maintaining safe, failure-free and reliable operation of the crane at a particular enlarged operating area beyond the expiry of the warranty period, which will significantly improve its efficiency, can be calculated.

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