

# THE PROBLEM OF EVALUATING THE EXPIRATION OF THE SERVICE LIFE OF THE SUPPORTING STRUCTURE OF SECONDHAND CRANES

Włodzimierz ROSOCHACKI

West Pomeranian University of Technology Szczecin, Faculty of Maritime Technology and Transport, Szczecin, Poland

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## **Abstract:**

The right to safety of purchased goods is one of the most important consumer rights. Therefore, an accurate analysis of safety of machinery and equipment purchased on the secondary market is an extremely important issue. One of its elements should be the assessment of the degree of service life usage. In the case of cranes, the subject of such an assessment covers both the supporting structure of the device and its mechanisms and installations. Information on evaluation of the service life expiration of the secondhand cranes may be necessary and support the decision-making process associated with the purchase of the device. The paper deals with the problem of evaluating the expiration of the service life of the supporting structure of cranes coming from the secondhand market. The result of such evaluation makes it possible to determine whether the production capacity of a device has been exhausted. This forms the basis for the decisions on any possible further operation of the crane. The work presents an approach based on the provisions of standard ISO 12482: 2014. This document is the basis for service life evaluation for cranes. The approach presented in it makes the way of analysis dependent on the method used to collect operational data. In this paper the evaluation of service life expiration was prepared on the example of a ship to shore gantry cranes. These devices are characterized by particularly large dimensions and weight. Damage of their supporting structure can lead to the significant losses. Some of these devices change the location during operation. Therefore, it is important to know the current level of their service life usage. A case, in which the operational history of a device is not known, was considered. In the paper the special attention was paid to the methodology of estimating the load distribution coefficient. In order to describe the hypothetical load spectrum, triangular distribution was proposed. The results of the calculations for the structure of port cranes are presented and discussed.

**Keywords:** crane, supporting structure, service life, container

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## **Contact:**

1) [wlodzimierz.rosochacki@zut.edu.pl](mailto:wlodzimierz.rosochacki@zut.edu.pl) [<https://orcid.org/0000-0001-5275-0848>]

## 1. Introduction

One of the elementary activities that ensure the proper operational safety level for cranes is effective monitoring of their operational conditions. This is of particular significance given the activities observed in recent years on the secondhand machinery market. The economic crisis of the first decade of the 21st century and the following recession have forced entrepreneurs to search for new solutions, to make it possible to achieve satisfactory profitability along with minimized expenses for the suprastructure development. One of the effects of such actions in the case of the Polish economy was a significant increase in the import of handling equipment, including cranes from the secondary market. Considering the parts from these devices, the operational data concerning their operational history were incomplete or even not available. In such situations, it is particularly important from the new owner point of view, to find a credible answer to the question: can such a device be operated safely, how long, and in what load conditions it could be used.

In order to assess the current technical condition of cranes, primarily non-destructive testing methods are used (Büyükoztürk et al., 2011, Wang et al., 2012, Sapieta et al., 2014). However, they do not give grounds for estimating the period during which the crane can still be safely used. This approximate assessment is possible under certain assumptions, using probabilistic methods (Yan, 2015) supported primarily by knowledge of fatigue phenomena (Ligaj et al., 2014). In the case of supporting structures the fatigue life estimation process (Qi et al., 2013; Starykov et al., 2018) is possible. This is especially important in case when metal structure of a crane reaches its allowable safe life, then it must be retired from service. The abovementioned approaches to service life assessment are usually very labor intensive and expensive.

In Poland, a crane is approved for operation by an authorized technical inspection authority after conducting the technical tests required by the regulations. However, it should be emphasized that the legal regulations in Poland regarding the operation of cranes binding from 29 November 2018 (Regulation of the Minister for the Economy, Labor and Social Policy 2003) does not require the operator to check whether the device's production capacity has been exhausted.

The necessity of such actions with regard to the cranes has been justified and described in international standards (ISO 12482: 2014). These documents state that the crane's operator should monitor – and in fact – evaluate the expiration of the crane's design working period. The purpose of such an approach is i.a. to develop reliable foundations to estimate for any operation moment the probable number of work cycles that the device can still perform at the assumed load condition until its production capacity is exhausted. The obligation of applying such an approach, with regard to all the handling equipment used in Poland, was introduced at the end of 2018 in the document (Regulation of the Minister for Entrepreneurship and Technology 2018). In it, among others, the notion of the service life was introduced, understood as the limit values used to assess and identify the technical state, defined on the basis of the number of work cycles and the loading conditions of handling equipment throughout the foreseeable lifetime, taking into account its actual operating conditions.

According to the aforementioned draft, the service life should be defined, and its expiration has to be monitored both for the supporting structure, and for other equipment elements of a device.

In this paper, an attempt to evaluate the service life expiration of a crane purchased on the secondhand market is presented. In particular, a case is considered, in which the operational history of the device is unknown. The evaluation was prepared on the example of the supporting structure of a port container crane. Among the port container cranes three basic groups can be distinguished: ship to shore gantry cranes, hereinafter referred to as STS, rubber tired gantry cranes, and rail mounted gantry cranes. Their main common feature is being intended for handling ship containers. The way of evaluating the service life expiration will be presented on the example of an STS crane.

The STS cranes (Fig. 1) are used for the direct handling of container ships, namely vessels specially designed to transport containers. Those cranes are characterized by their specific shape, overall dimensions, and mass (Rosochacki, 2010; Hann et al., 2009). Their construction makes it possible to lift up containers located in any place of a vessel's cargo space. For this reason, the length of the crane's jib above the water side depends on the maximum width of the vessels being operated.

With the dimensions of the largest presently operated container ships, it is possible to place 24 containers in a row widthwise. This means that the length of the crane's jig above the water side intended for handling such vessels should be more than 60 m. The second important parameter that affects its dimensions is the lifting height that allows to handle the highest located containers within the vessel's hull. For instance, the state-of-the-art STS cranes used at the DCT Gdańsk terminal are about 90 m high, 130 m with the jig raised – 130 m.



Fig. 1. STS Crane

The lifting capacity of typical STS cranes are about 400÷500 kN and depend on the number (usually one or two) of containers being hoisted at the same time. However, there are also cranes designs for simultaneous handling of even four containers. To achieve the objective (lift on/lift off a container with a weight of about 30000 kg at a crane jib of 60 m) the construction of cranes with a relatively large mass (1.5 ÷ 2 mln kg) is required.

The STS cranes play a particularly important role in the port transport chain because of the fact that they are used for direct containers transshipment. Their failure may disorganize the whole handling process, and certainly have an adverse effect on the unloading time of a container ship. Placing a crane directly near the ships creates the possibility of mutual negative interactions, and with its size decides that within the device's area of operation there are not only ships, but also elements of the port's infrastructure and additional equipment located at a distance exceeding even 100 m.

Most of these devices is transported to their destination by sea, with the use of special vessels (Fig. 2).



Fig. 2. Transporting an STS crane (photo: Piotr B. Stareńczak / PortalMorski.pl)

During such an operation, the supporting structure of the device is exposed to variable loads, as a result of sea waves. They can result in accumulated fatigue damage. In the paper by (Starkov and Van Hoorn, 2017), it was demonstrated that in the case of transporting an STS crane from China to Ukraine, the fatigue damage in the structural elements can reach from 5% to 10% of the critical value, and the crane's service life can be reduced by as much as 200000 work cycles. This means that at the beginning of their operation, these devices can be already worn out to some extent, and their production capacity can be smaller than designed.

Bearing the above in mind, the following conclusion can be drawn that the safety of the macro system, in which the main technical function is served by STS cranes, depends to a large extent on the current technical condition of the supporting structure of these devices (Iwańkiewicz et al., 2015). The periodical evaluation of their technical state is mandatory (Regulation of the Minister for the Economy, Labor and Social Policy 2003), and is the basis for approving a crane for further operation. From the operator viewpoint, an evaluation of the time, in which further operation of such a device can be still safe, should be quite important. In the case of the load bearing structure, this can be expressed by identifying the probable number of work cycles at the planned load spectrum until the service life expires. One tool that may be used to evaluate the expiration of the service life, and at the same time that supports the decision-making process of formulating the conditions for further operation of the supporting structure of port cranes, can be the procedure formulated in standard (ISO 12482: 2014). Its elements were

used in this paper to develop the criterion of so-called structure's service life limit status. It is assumed that this supporting structure ceases to meet this criterion at the time, when the crane has completed the limit number of work cycles typical for the preset load conditions. However, this situation does not necessarily mean that the structure's carrying capacity has been exhausted, or that the deformations have achieved the limit value. The expiration of the service life signals that any further operation of the load bearing structure shall be subject to the results of an assessment of its current technical condition. The paper presents an approach intended to meet the aforementioned criterion with regard to port container cranes using triangular distribution to identify the load spectrum.

## 2. Methodology

The operational process of the load bearing structure of an STS crane with known classification group of the crane as a whole is considered. The expiration of the service life of the device's supporting structure is analyzed. It is assumed that the crane has been purchased on the secondhand market. Two cases will be analyzed. The first one is a situation when it is possible to evaluate approximately the previous operational conditions of the crane (based on the available information). The second one assumes that there is no grounds for such estimations (the cranes operational history is unknown).

Considering the crane's intended usage, it is assumed that the structure's condition is significantly affected by time-changing variables of the load generated by the weight of containers being handled.

In the presented approach according to (ISO 12482: 2014) it is also assumed, that the service life of the crane's supporting structure is reached, that means that the actual duty has reached the design limit in respect to crane classification, when:

$$\alpha \cdot \sum_{i=1}^N \left[ \left( \frac{P_i}{P_{\max}} \right)^3 \right] = N_C, \quad (1)$$

where:

$\alpha$  – the safety factor taking account of the operational data particularization level, defined according to Tab. 1,

$N$  – the actual total number of work cycles until the evaluation,

$i$  – the index for an individual work cycle,

$P_i$  – the handled payload in an work cycle  $i$ ,

$P$  – the rated value of the payload for the crane,

$N_C$  – the design limit for converted number of work cycles for crane classification group according to Tab. 2.

Table 1. Safety factor  $\alpha$  for duty counting

No.	Methods of duty according	$\alpha$
1.	Crane operation data are fully available (e.g. the crane is equipped with a fully automated system for recording the operational conditions and the times of its operation, or with counters for needed data evidence).	1,0
2.	The crane duty history is calculated based on a regular transshipment process, in which the crane participates. The crane is an integral part of the process. Process data are documented.	1,1
3.	The crane duty history is estimated based on a general documented data concerning the production process, in which the crane participates.	1,2
4.	The crane duty history is incomplete. The data are estimated based on the approximated assessment of the crane's previous operating conditions.	1,3
5.	The crane duty history is unknown. Data are estimated or based on the assumption of compliance of the operating conditions of the crane with those adopted in the design process.	1,5

Table 2. Design limits for converted number of work cycles depending on crane class

Crane class	Work cycles, $N_C$
A1	$8 \cdot 10^3$
A2	$16 \cdot 10^3$
A3	$32 \cdot 10^3$
A4	$63 \cdot 10^3$
A5	$125 \cdot 10^3$
A6	$250 \cdot 10^3$
A7	$500 \cdot 10^3$
A8	$1,0 \cdot 10^6$

Fulfilled requirement (1) means that this structure has reached its service life limit. This requirement is easy to verify only when the data describing the previous operational conditions of the crane are fully

known, namely when the actual cargo load per each completed operating cycle is identified. In any other case, both the number of the work cycles completed by the crane, and the load value - for each of them separately - should be evaluated. In the case of first one of those values, this could be only possible e.g. based on an analysis of the indications of the lifting mechanism working time counter, commonly used in container cranes. Meanwhile, the estimation of individual cargo load values  $P_i$  becomes unfeasible. Bearing the above in mind, it is proposed to transform the formula (1) receiving (2):

$$\alpha \cdot N \sum_{i=1}^N \frac{1}{N} \left[ \left( \frac{P_i}{P_{\max}} \right)^3 \right] = N_C . \quad (2)$$

After introducing the expression (3):

$$\sum_{i=1}^N \frac{1}{N} \left[ \left( \frac{P_i}{P_{\max}} \right)^3 \right] = K_p , \quad (3)$$

where  $K_p$  is the load spectrum factor (PN-ISO 4301-1: 1998), estimated for a moment of assessment.

The final relation is obtained (4):

$$\alpha \cdot NK_p = N_C . \quad (4)$$

To verify the requirement of the service life expiration based on the above relation, it requires to estimate, apart from the number of work cycles, the value of the load spectrum factor. The approach to estimate the  $K_p$  factors values for two cases of the acquisition of operational data concerning the crane's operational conditions is shown below. The first one refers to a situation when, based on the available information on the crane's operational conditions, it is possible to determine descriptively its previous load ( $a = 1.3$ ). In the second case, a situation was considered, in which the crane's operational history data are not available ( $a = 1.5$ ). In the analysis of the first case, it is assumed that for the concerned operational period it is possible to determine its load status. To do this, standard (PN-ISO 4301-

1: 1998) can be used in which among others descriptions of four characteristic load conditions of the cranes are included together with the allocated design values for load spectrum factors. A proposal of such a description, with regard to port container cranes, is presented in Tab. 3.

Table 3. Design value  $K_p$  for load spectrum factor of a container crane (prepared based on (PN-ISO 4301-1: 1998))

Load description	$K_p$
The crane was loaded with containers having the nominal weight very rarely, and usually with low weight containers	0.125
The crane was loaded with containers having the nominal weight rather rarely, and usually with medium weight containers	0.25
The crane was often loaded with nominal weight containers, and usually with large weight containers	0.50
The crane was regularly loaded with containers being close to the nominal weight	1.00

It is assumed that the available data concerning the crane operation process make it possible to estimate the value of  $K_p$  using e.g. Table 3.

In the second case, when there is no data concerning the crane's operational history, estimating the  $K_p$  value becomes difficult. To make such estimations be realistic, it is proposed to treat the load spectrum factor as the function of a random variable, which is the actual cargo load  $P_i^*$ . In view of the above,  $(P_i/P_{\max})$  is also such a variable, denoted hereinafter by  $x$ . The expected value  $E(K_p)$  is sought. Assuming therefore that the random function describing the load spectrum factor has the form (5) :

$$K_p(x) = \sum_{i=1}^N \frac{1}{N} x^3 \quad (5)$$

its expected value can be determined in the general case from the relation (6):

<sup>\*)</sup> The symbols of random variables and their functions in this work are marked in bold.

$$E[K_p(x)] = \int_0^1 x^3 f(x) dx \tag{6}$$

where  $f(x)$  is the probability density function of random variable  $x$ .

Fig. 3. presents the empirical weight frequency distribution densities for transhipped containers in British ports based on (Knapton, 2012). Three distributions are presented there. The first one (a) is characteristic for a situation, where a transshipment only involves 40-foot containers (Class 1A), the second one (b) includes a transshipment process of only 20-foot (Class 1C) containers, and the third one (c) covers a transshipment process, in which containers of each of these classes constitute about 50% of the total number of cargo units handled.

The load spectra, presented on Fig. 3, may provide a good basis to identify the frequency distribution of the containers being handled in British ports at the end of the 20th century. On their basis, the load spectrum factor values were estimated. Considering the fact that, together with a container being lifted, its spreader is moved at the same time, the following values  $K_p$  are obtained for subsequently presented distributions: 0.29, 0.24 and 0.26 (in the calculations, a container spreader weighting 85000 N was adopted).

In the case, when there is no statistical data that make it possible to identify the distribution of the variable  $x$ , in order to estimate the measure (6), it is proposed to use a probability model, in which the actual distribution of the variable being calculated is replaced by triangular distribution (Szopa, 2009). Such an approach requires three values to be estimated: the minimum  $x_{min}$ , the maximum  $x_{max}$ , and the most probable,  $x_s$ . It is sufficient to know those three parameters to determine the probability density of the  $x$  variable with a triangular distribution (7):

$$f(x) = \begin{cases} \frac{2(x-x_{min})}{(x_{max}-x_{min})(x_s-x_{min})} & \text{dla } x_{min} \leq x \leq x_s \\ \frac{2(x_{max}-x)}{(x_{max}-x_{min})(x_{max}-x_s)} & \text{dla } x_s < x \leq x_{max} \\ 0 & \text{in other intervals} \end{cases} \tag{7}$$

In order to estimate the  $K_p$  factor for analyzed STS cranes using triangular distribution, the minimum, the average, and maximum weight of a container should be determined.

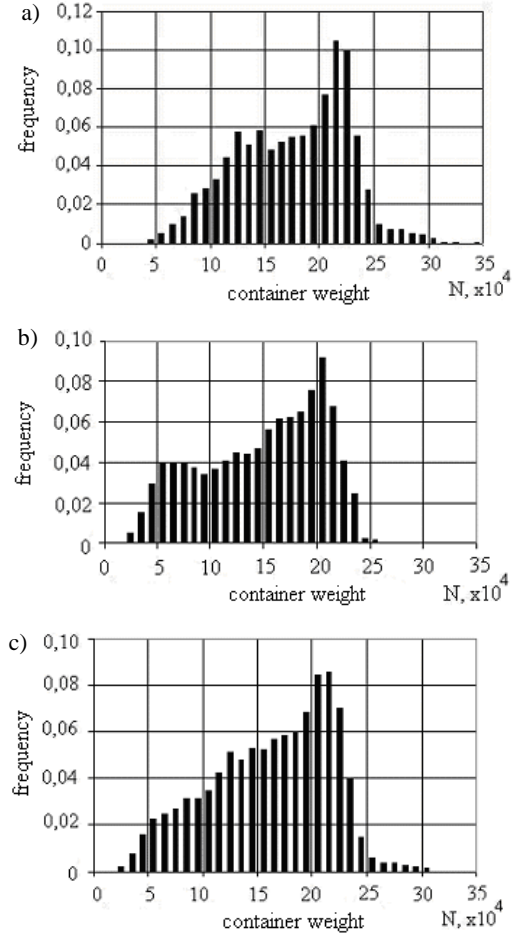


Fig. 3. Container weight distribution

**3. Calculation results**

Based on standard (ISO 12482: 2014) and proposed approach it is possible to verify whether the service life of an STS crane with unidentified load spectrum has been exhausted. It is assumed that the crane's classification group is known: A7. The crane's number of work cycles ( $N = 400000$ ) was estimated based on an analysis of the records of the lifting

mechanism working time counter, and by evaluating the average duration of a single work cycle. The crane was used to handle single Class 1A and 1C containers. The weight of the container's spreader is 85000 N.

In view of the absence of any data about the crane's load spectrum, it is assumed that the estimated value of the factor  $K_p$  shall be the expected value (6).

In the calculations the following data were assumed:

- the minimum weight of a 1C class steel container 24000 [N],
- the maximum weight of a 1A class steel container 300000 [N],
- the most likely weight of a container 210000 [N] (Fig. 1 c).

The calculations require determining the values of  $x_{min}$ ,  $x_{max}$  and  $x_s$  parameter. For this purpose, it is necessary to determine the values of the minimum ( $P_{min}$ ), the maximum ( $P_{max}$ ), and the most likely ( $P_s$ ) cargo load of the crane. These are determined taking into account the weight of the container's spreader. As a result:  $P_{min} = 109000$  N,  $P_{max} = 385000$  N,  $P_s = 295000$  N, and the corresponding values  $x_{min} = 0.283$ ,  $x_{max} = 1$ , and  $x_s = 0.77$  are obtained. For the determined parameters, the course of the corresponding density function  $f(x)$  is presented in Fig. 4. The received function extremum is 2.79.

The target expected value  $E(K_p)$  is determined based on the relation (6), assuming the lower integration limit equal to the  $x_{min}$

$$E[K_p(x)] = \int_{0.283}^1 x^3 f(x) dx \quad (8)$$

obtaining value  $E(K_p) = 0.36$ . For the A7 crane classification group, the limit number of work cycles according to Table 2 is  $N_c = 5 \cdot 10^5$ . In view of the absence of any historical data on the crane's load, in criterion (4)  $a = 1.5$  is assumed, as a result (9) is gained:

$$1.5 \cdot 400000 \cdot 0.36 = 2.16 \cdot 10^5 < N_c = 5 \cdot 10^5. \quad (9)$$

The relation obtained indicates that the crane's service life has not been exhausted.

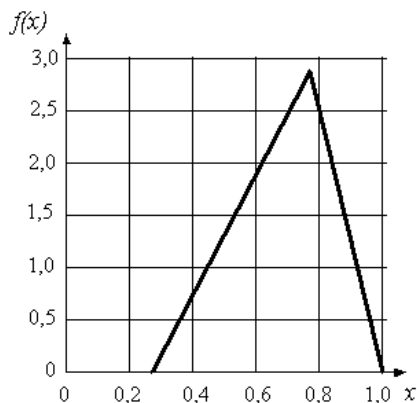


Fig. 4. The probability density of the  $x$  variable with triangular distribution

Table 4 presents the results of the crane's calculated expected load spectrum factor values set together for several other values of the most probable container weights.

Table 4. Expected load spectrum factor values

The most probable container weight, [N]	$1.2 \cdot 10^4$	$1.4 \cdot 10^4$	$1.6 \cdot 10^4$	$1.8 \cdot 10^4$	$2.0 \cdot 10^4$
$E(K_p)$	0.26	0.28	0.30	0.33	0.35

An attempt to estimate the crane's load spectrum factor values based on evaluated minimum, maximum, and the most probable container weight values is presented above. In the case, when there is an obvious doubt whether the evaluation of the third listed value is valid or not, the estimation can be performed by replacing it with the average value. For instance, for the distribution presented in Fig. 1a, the average value of a container weight is 170000 N. Assuming the engaging means weight equal to 85000 N, and the minimum weight of the 1A container equal to 38000 N, the following  $E(K_p) = 0.31$  is obtained.

#### 4. Conclusions

In the process of managing the handling equipment operation, it is important to know the period of time, in which the device can still function at the assumed load until it exhausts the production capacity. The main issue is to define, whether the limit parameters that determine the service life have been achieved. In the case of cranes, this means verifying, whether it has reached the limit number of work cycles typical for it under given specific operation conditions. This requirement can be tested using the methodology presented in (ISO 12482: 2014). Its application requires evaluating the number of the work cycles and the load spectrum factor value. The issue raises no doubts in the case, when there is full documentation necessary to identify both parameters. A problem emerges when such data are incomplete or even do not exist. This situation may take place particularly in the case of devices with unknown operational history, purchased on the secondhand market. In this paper, an attempt is made to estimate the load spectrum factor in such a case on the example of a port container crane.

The evaluation was prepared by approximating the unknown, actual load spectrum with a triangular distribution. The load spectrum factor value obtained this way is higher than the one determined for exemplary actual container loads of port cranes (Knapton, 2012). This leads to overstated evaluation of the service life expiration. The crane analyzed in the example has not exhausted its production capacity (it has not reached the end of its service life). In such a case, the relation (4) forms the basis for predicting the number of work cycles  $n$  remaining to the end of the service life at the assumed load spectrum factor  $K_{pn}$

$$n = \frac{N_c - N_z}{\alpha K_{pn}} \quad (10)$$

where:  $N_z = \alpha N K_p$ .

The forecast presented above is obviously an estimation, and can be used to support decision-making processes in the device's operation management. Prediction of the remaining operational time of a crane (expressed as the number of work cycles at an assumed load) based on the (10) relation may be burdened with an error related to ignored transport conditions. At the same time, it should be noted that in

the case of cranes coming from the secondhand market, any assessment of how transport conditions influence the remaining service life of the crane is even more vital, because it applies to at least two transport courses, which cover the manufacturer, and the first and the second buyer.

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