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DIESEL LOCOMOTIVE EFFICIENCY AND RELIABILITY IMPROVEMENT AS A RESULT OF POWER UNIT LOAD CONTROL SYSTEM MODERNISATION

POPRAWA EFEKTYWNOŚCI I NIEZAWODNOŚCI LOKOMOTYW SPALINOWYCH W WYNIKU MODERNIZACJI UKŁADU STEROWANIA OBCIĄŻENIEM ZESPOŁU NAPĘDOWEGO*

The article presents an idea of modernisation of a diesel locomotive power unit load control using SM31 locomotive. In the proposed solution an electronic rotations and power governor of a8C22W diesel engine is applied, developed in cooperation with Lokel (the Czech Republic) and Newag S.A. (Poland), in which a new optimal operational characteristic is realized in the locomotive. This characteristic was selected following optimization calculations using a mathematical model mapping the real conditions of the motor-generator work in a diesel engine. Test stand experimental investigations together with an over three-year supervised observation of the locomotive equipped with the electronic governor have proved its correct and reliable operation. Based on the data collected in supervised observation the efficiency of the proposed solution has been assessed, supported by an LCC (Life Cycle Cost) analysis.

***Keywords**: reliability, operation, modernisation of locomotives, LCC analysis.*

W artykule przedstawiono koncepcję modernizacji układu sterowania obciążeniem zespołu napędowego lokomotywy spalinowej na przykładzie lokomotywy serii SM31. Proponowane rozwiązanie polega na zastosowaniu elektronicznego regulatora obrotów i mocy silnika wysokoprężnego a8C22W, opracowanego w wyniku wspólnych prac autorów z firmą Lokel (Czechy) i Newag S.A. (Polska), realizującego na lokomotywie nową, optymalną charakterystykę eksploatacyjną. Charakterystyka ta została wybrana w wyniku obliczeń optymalizacyjnych z wykorzystaniem opracowanego modelu matematycznego odwzorowującego rzeczywiste warunki pracy zespołu silnik-prądnica na lokomotywie spalinowej. Badania stanowiskowe oraz ponad trzyletnia eksploatacja obserwowana lokomotywy z zamontowanym regulatorem elektronicznym wykazały poprawne i niezawodne jego działanie. Bazując na danych zgromadzonych podczas eksploatacji obserwowanej, przeprowadzono ocenę efektywności proponowanego rozwiązania w oparciu o analizę LCC (Life Cycle Cost).

***Słowa kluczowe**: niezawodność, eksploatacja, modernizacja lokomotyw, analiza LCC.*

1. Introduction

In the projects targeted at enhancing the efficiency of rail transport an important role is occupied by activities aimed at reduction of traction vehicles operation and maintenance costs. One of the ways to reach this aim is to modernise diesel locomotives, including additionally exhaust emissions control. The basic objectives of diesel locomotives modernisation include:

- reduction of fuel and operational materials consumption costs,
- availability of new sub-assemblies and spare parts,
- increase of technical availability,
- increase of mileage between downtimes,
- improvement of driver's work conditions,
- reduction of negative effect on the natural environment.

In recent years rail transport agencies have shown interest in the modernisation of diesel locomotives. In the years 2006 – 2014, as a result of the cooperation between the Institute of Rail Vehicles of the Cracow University of Technology and rail transport agencies various projects have been developed, including the modernisation of both railway line locomotives e.g.: ST44, SU45, SU46, SP32 and shunting locomotives: SM48, SM42 and SM31 [54, 55]. The majority of these projects have been fully implemented in practice.

The present paper presents an idea of SM31 locomotive power unit load control system modernisation by the implementation of a new operational characteristic of a8C22W diesel engine, executed by a modern electronic rotational speed and power governor. The new operational characteristic was selected on the basis of optimisation calculations using a mathematical model mapping the real working conditions of the locomotive in operation. To assess the efficiency of the proposed solution an LCC (Life Cycle Cost) analysis has been carried out including the reliability properties of the vehicle.

2. Characteristics of the study object

Diesel locomotives SM31 have been used in Poland for over thirty-five years. As of the end of 2014, in the operative use there were about 150 locomotives of this series. SM31 locomotive was designed mainly for the heavy job of shunting at stations and humps, but also for tractive work. The vehicle is equipped with a supercharged a8C22W engine (produced by HCP Poznań plant) built on the basis of the a8C22 engine. The basic technical parameters of the two engines are shown in Table 1b.

SM31 locomotives were manufactured based on the technology and technical solutions dating back to the early 1970s. Since their pro-

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(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

Table 1. SM31 diesel locomotive and technical data of a8C22 and a8C22W engines

Engine parameter	a8C22 (loc. SM42)	a8C22W (loc. SM31)
Piston stroke [mm]	220/270	220/270
Number od cylinders in system V	8	8
Effective (rated) power [kW]	590	885
Rated/idle running rotation [rpm]	1000/500	1000/500
Mean effective pressure [MPa]	0,88	1,32
Compression ratio	13,5	12
Supercharging pressure (absolute) [MPa]	0,15	0,20
Peak firing pressure [MPa]	10	11,5
Unitary fuel consumption [g/kW h]	235	225
Temperature of exhaust gases in front of turbine [K]	780	850
Supercharger revolutions [rpm]	14500	17700
Supercharging air cooling	none	cooler

[Photo: http://woziarze.cal.pl]

duction the design of the locomotives has practically not changed. No modernisation works have been done. The analysis of operation indices together with an assessment of the reliability of SM31 engines, performed at the Institute of Rail Vehicles, Cracow University of Technology, has proved the necessity of their modernisation with the focus on the most unreliable units and systems of the locomotive [7].

3. Analysis of SM31 locomotive failures

The reliability of SM31 diesel locomotives in operation is chiefly limited by the reliability of a8C22W supercharched diesel engines. For the analysis of the operation data obtained from PKP Cargo S.A., a sample of 36 SM31 locomotives, collected in the years 2010-14, it follows that about 56% of all the failures found in SM31 locomotives are related to the diesel engine (Fig. 1a). The reliability of a8C22W diesel engine is determined to the highest extent by the piston-cylinder system, and the majority of failures occurs in the fuel system (Fig. 1b) [4, 7]. This results from the considerable increase of thermal stresses which for the piston-cylinder system of an a8C22W diesel engine are generally several times higher than mechanical stresses.

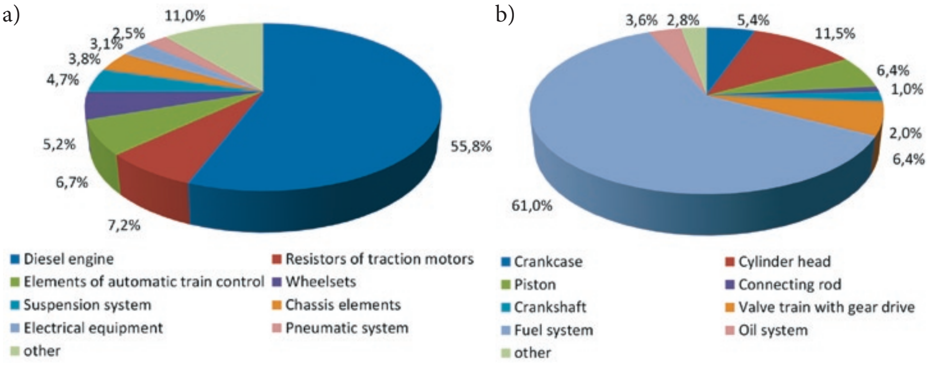

Fig. 1 a) Structure of failures of SM31 locomotive; b) Structure of a8C22W engine failures

The results of investigations prove that in order to improve the reliability of railway diesel engines in operation it is necessary to improve the quality of their work in transient states which for shunting locomotives are 50% of the overall time of engine working under load. The quality can be improved by implementing an optimal operation characteristic of an engine, selected using a specified criterion.

4. Mathematical model of diesel locomotive engine

The improvement of the reliability of some systems and units of diesel locomotives in operation is an optimisation task which cannot be solved by experimental methods. It requires mathematical modeling of power unit work conditions, i.e. creating a model of an object: motor-generator together with a simulation model mapping the work conditions of a locomotive in operation.

Some components of a traction vehicle LCC analysis have a temporary character and depend on operation conditions. The author's proposal is to calculate these components using a mathematical model of work processes in the locomotive power unit during operation.

The essential requirements for the application of a mathematical model in optimisation calculations include: adequacy to the object of research, conciseness and universality of the processes description for various types of diesel engines and supercharging systems. The need for developing mathematical models of diesel engine work processes in the conditions of operation has been a live issue for years. Numerous studies on the subject have appeared. In the field of motor-car IC engines the majority of investigations are related to IC engine systems control including dynamic states [10, 14, 15, 25, 36, 61]. In [11] an interesting mathematical model of transient processes in locomotive diesel engines was proposed. The model is based on the solution of a system composed of "n" differentia equations for the piston part and six equations describing the processes in the exhaust manifold in the case of pulsatory supercharging system. The same principles were applied in the mathematical models of transient processes in diesel engines presented in [60, 62]. It should be noted, however, that the applicability of these models is rather limited in solving optimisation tasks. This is because a significant number of calculation operations and subprograms are necessary and the calculation precision depends on the selection of the mode of differential equations solutions, which makes the calculations time-consuming.

The mathematical model of the work processes in a8C22W diesel engines in steady and transient state conditions, developed by the authors of this article, takes into account the joint work of a piston engine with a turbine, compressor, induction and exhaust systems in the locomotive as well as the operation properties of engines in shunting diesel locomotives. The mathematic model imitates the functional connections used in the crankshaft rotational speed and engine power control systems. The details of assumptions, requirements and mathematical equations related to the model are given in [5, 6, 31, 33]. The most important ones are presented in what follows.

1. The final control units of control systems work in such a way that at each moment the rate of change of controlled value A is proportional to the value of divergence and in inverse proportion to time constant:

$$\frac{dA}{dt} \cong \frac{A^* - A}{T_A} \tag{1}$$

where:

A*, A – assigned and actual values of controlled value,
TA – time constant of A control system.

2. At any moment power balance is maintained:

$$b_T \cdot H_u \cdot \eta_i = P_M + P_B + P_P + J_\Sigma \cdot \omega_g \cdot \frac{d\omega_g}{dt} \tag{2}$$

where:

P_P – power transmitted to tractive generator,
P_M, P_B – power of mechanical losses in engine and auxiliary devices in locomotive,
J_Σ – cumulative moments of inertia of diesel engine and locomotive units, reduced to diesel engine crankshaft,
$d\omega_g/dt$ – angular acceleration of diesel engine crankshaft.

In the calculations, to select the values db_T/dt, $d\omega_g/dt$ and dP_P/dt equation (2) is used in the differential form:

$$J_\Sigma\left(\omega_g \frac{d^2\omega_g}{dt^2} + \left(\frac{d\omega_g}{dt}\right)^2\right) = \frac{db_T}{dt} H_u \left(\eta_i + \frac{\partial \eta_i}{\partial b_T} b_T\right) + b_T \frac{\partial \eta_i}{\partial \omega_g} \frac{d\omega_g}{dt} H_u - \left(\frac{dP_M}{dt} + \frac{dP_B}{dt} + \frac{dP_P}{dt}\right) \tag{3}$$

For the SM31 diesel locomotive motor-generator dPP/dt component is a sum of two components:

$$\frac{dP_P}{dt} = \frac{dP_C}{d\omega_G} + \frac{d\omega_G}{dt} + \frac{dP_{RM}}{dt} \tag{4}$$

where:

$dP_C/d\omega_g$ – diesel engine power change in the function of crankshaft rotational speed at a constant travelling,
dP_{RM}/dt – assigned diesel engine power change, controlled by power regulator, in the function of field rheostat regulator position (servo-motor).

3. Initially, the fuel charge possible increase (db_T/dt) calculated from diesel engine thermal cycle parameters boundaries is substituted in equation (3) and crankshaft angular acceleration at constant power P_P transferred to the tractive generator is calculated. On reaching the allowable crankshaft angular acceleration ($d\omega_g/dt$), assigned on the basis of restrictions or other conditions, the possible rate of fuel charge increase (db_T/dt) and the assigned crankshaft angular acceleration) ($d\omega^*_g/dt$) are substituted in equation (3) and the value of the possible tractive generator power increase (dP_P/dt) is determined. If the value of power increase rate is lower than allowable (dP_P/dt), the variables (db_T/dt) and (dP_P/dt) are the control values searched. If (dP_P/dt) is higher than the allowable value, allowable ($d\omega_g/dt$) and (dP_P/dt) are substituted in equation (3), and next fuel charge change rate (db_T/dt) is calculated. The variables (db_T/dt) and (dP_P/dt) are the control values searched.

If ($d\omega_g/dt$) and (dPP/dt) are expressed as components functionally dependent on time, crankshaft rotational speed, supercharging compression etc., this method can be used for the imitation of logical functions in the existing control systems. This approach enables excluding the effect of the control systems operation quality on the transition processes indices and developing new control principles when the variable interrelations in equation (3) are changed.

Diesel engines of a8C22W type are characterised by the use of pulsatory supercharging system. In creating the model it was assumed that a change of exhaust pressure in the exhaust manifold in the function of time or crankshaft rotation angle ω_g is a time periodic function of the period:

$$T = \omega_g \cdot \phi^* \tag{5}$$

The phase of exhaust pressure change in the manifold φ* will be equal to the value of cylinders work phase shift. Let us assume that the cyclic process in the manifold can be presented a series of processes of time duration Δφ, restricted by boundary conditions. The number of such series processes can be relatively large, but, connected with the processes in the suction manifold, there are two characteristic periods: the phase of exhaust escape (angle φ_b, φ_s) and phase of scavenging (angle φ_s, φ_{be}), Fig. 2a.

In a diesel engine with pulsatory supercharging system the exhaust escape is completely separated from the processes in the suction manifold and can be calculated after commonly known methods if the parameters of the working medium in the cylinder are assigned. The scavenging process is directly connected with the processes in the suction manifold. The scavenging process is calculated together with the calculations of the processes in the induction pipes including elements of a diesel locomotive, i.e. air filter 1, compressor 2, supercharging air cooler 3, piston part 4, turbine 7 and elements of outlet system 8 (Fig. 2b). Pressure drops in the suction and compulsory escape were

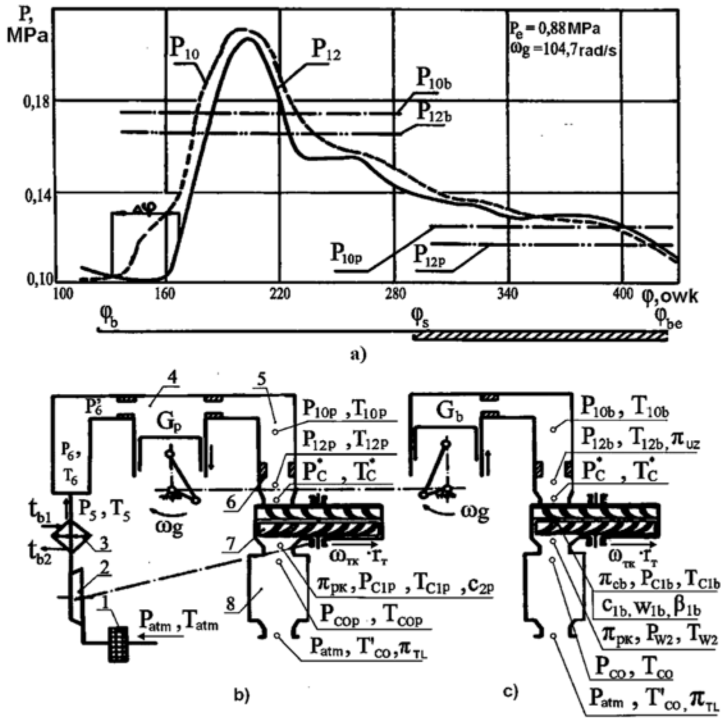

Fig. 2. Pressure modification in exhaust manifold [4]: a) calculation model of model a8C22W diesel engine with pulsatory supercharging system during scavenging b) and exhaust escape c)

calculated separately. Both processes are described with a system of nonlinear algebraic equations representing the quasi-steady flow of the working medium in the scavenging and escape phases were performed on the basis of mean values of pressure, temperature and rate of working medium flow in respective phases with an adopted duration time Δφ (Fig. 2a). The initial parameters for the calculation of the processes in the exhaust manifold, in the case of compulsory escape, were the values of the parameters defined during the calculation of the processes in the exhaust manifold during scavenging. The gas dynamics calculations of the turbocharger turbine in the transition process included modifications of the angle of exhaust flow between the rotor vanes [3, 5, 31].

The working conditions of a diesel engine in steady states and in the transition processes are calculated with one program, whose block diagram is shown in Fig. 3. Using this diagram a program for calculating the indices of a8C22W engine performance in steady-state conditions and in the transition processes was developed [5].

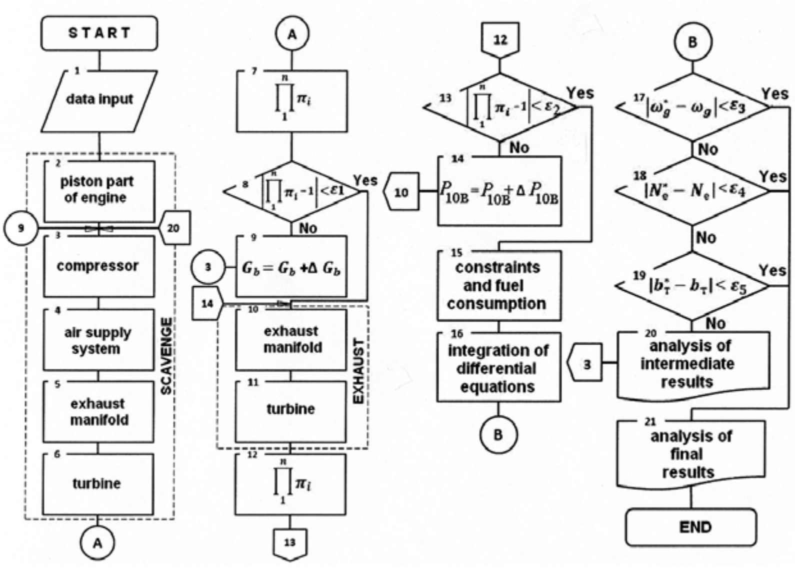

Fig. 3. Block diagram of algorithm of diesel engine transition process calculation [3]

5. Optimal operation characteristic of SM31 locomotive power unit

A comparison of the calculation and experimental indices of a8C22W diesel engine performance for the operation characteristic – Fig 4a and transition process in the function of time – Fig. 4b, has shown a good convergence of results [3].

Notation in Figs 4a and 4b:

T_s, T_T – temperature of air in suction manifold and exhaust manifold in front of turbine; P_s, P_T – pressure of supercharging and exhaust in front of turbine (overpressure); ω_g, ω_{TK} – angular speed of diesel engine crankshaft and turbo-rotor; G_b – air; g_c – fuel charge per cycle; N_e – diesel engine effective power; —— – result of experiments; - - - – result of calculations.

The satisfactory compatibility of the mathematical models of working processes between a8C22W diesel engines and the actual curves makes it possible to formulate a strategy of selection of the motor-generator optimal full-load characteristic, including the diesel locomotive working conditions, on the basis of a selected criterion, which is proposed to be the product minimum:

$$W_\Sigma = \left(K_P + K_{NP} + K_{NN}\right)\cdot T_L \qquad (6)$$

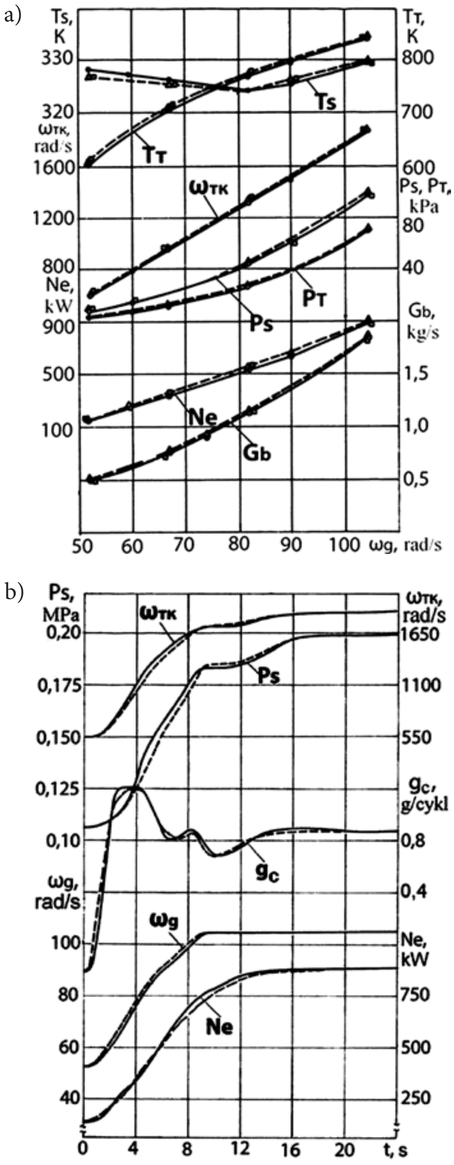

Fig. 4. Indices of a8C22W motor-generator operation: a) for operation characteristic, b) in transition process [3]

where:

- K_P – costs of fuel consumed over period T_L of assigned tractive work A_T performed by the locomotive,
- K_{NP} – costs of predicted overhaul and repair works of a diesel engine in the period of one repair cycle,
- K_{NN} – costs of unpredicted repair works (e.g.: piston-cylinder unit elements) resulting from emergency failures taking place in operation.

The calculations of engine and locomotive work indices over the period T_L of the tractive vehicle work are a result of modelling of the SM31 locomotive power unit in operation conditions. The costs of planned repairs K_{NP} are calculated according to the engine crankshaft mean operation angular velocity at a known cumulative cost of repairs and overhauls during one repair cycle. The value of costs K_{NN} is in linear dependence on the life of piston-cylinder unit elements, which in turn depends on the amount of failures. The quantitative assessment of the life of a8C22 engine piston-cylinder unit elements (cylinder heads) is done approximately using the grey cast iron fatigue curve and the linear hypothesis of fatigue failure summation according to the maximum calculated values of exhaust temperature in front of the turbine depending on [3].

Using the developed mathematical models optimisation calculations were performed, which resulted in, based on criterion (6), an optimal operation characteristic selection for a8C22W diesel engines of SM31 locomotives (Fig. 5).

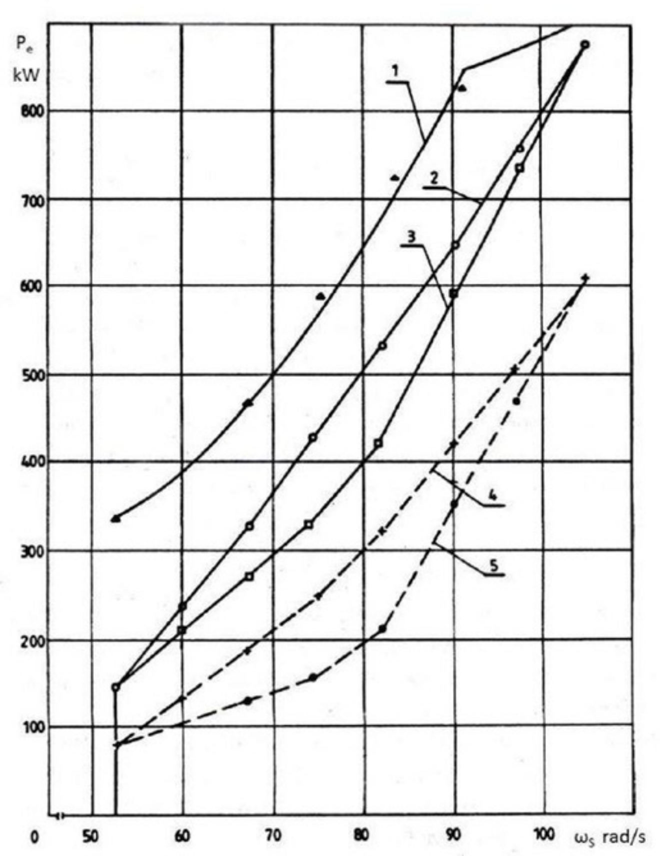

Fig. 5. Characteristics of locomotive SM31 a8C22 engine [3]: 1 – boundary characteristic – exhaust allowable temperature in front of turbine [TT] = 850 K; 2, 3 – operation characteristics – present, compatible with the technical-motion of locomotive and proposed on the basis of cost minimum criteria; 4, 5 – selective characteristics – present and proposed for characteristic 3

The performed calculations indicate that the implementation of an optimal operation characteristic of the a8C22 engine may result in:

- significant reduction of thermal stresses in engine piston-cylinder unit elements, which leads to a threefold reduction of the rate of failures of cylinder heads and pistons, i.e. reduction of unplanned repairs costs,
- reduction of fuel consumption by about 3%.

6. Testing of modernised power unit load control system

The implementation of an optimal characteristic in SM31 locomotive requires modernisation works in load control and fuel charge systems. The power unit control system used in SM31at present is composed of the driver-operated controller, crankshaft rotations governor and main generator excitation system. The electrohydraulic controllers used in these locomotives have a very limited capacity for shaping the characteristic. They realise practically linear dependence between the assigned position of the fuel injection pump strip (of engine effective power Pe) on the crankshaft rotational velocity– curve 2 in figure 5. The selected optimal operation characteristic 3 is nonlinear. The implementation of this characteristic in SM31 locomotive requires an advanced electronic rotation governor and the power of the microprocessor technology-based a8C22W engine. In this type of control all the logic connections between the control system input and output state have the form of a control program. No alteration or correction introduced into the functions requires changes in the control system of the locomotive. To develop an electronic rotational velocity and power governor for a8C22 engines of SM31 diesel locomotives the following requirements had to be satisfied:

- to adapt the existing electromechanical equipment and apparatus of the main generator power control to the electronic controller;
- to ensure the interaction between the electronic governor actuator (servo motor) and the system of fuel charge control levers of injection pumps, existing in the diesel engine;
- in the construction of the electronic governor use Woodward or Heinzmann manufactured elements as tested and reliable in operation.

In cooperation of the authors of the article with Lokel firm (the Czech Republic) and Newag S.A. (Poland) a rotational speed and power electronic governor was built for a8C22 and a8C22W diesel engines. The governor consists of [7]:

- ProAct III Woodward electrical servo-motor;
- ProAct Driver Woodward servo-motor control module;
- INTELO 144 Lokel microprocessor controller;
- 110V/24V transducers, sensors of current and voltage of the main circuit, indicators of crankshaft rotations, oil pressure and cooling medium temperature.

The installation of the electronic governor in the a8C22W diesel engine (Fig. 6) enables the realisation of a selected operation characteristic in the power control system (capacity) of the SM31 locomotive. The complete assembly of the governor in the locomotive can be performed during preventive maintenance service: extended periodical inspection (level P3) or preventive repair (level P4).

The test stand examinations and over three-year supervised operation of the locomotive with the fixed electronic governor showed its failure free and reliable operation. The performance of the rotations and power control system in the locomotive is stable in both steady states and in the transient processes. The results of a trial operation indicated the major benefits of the modernisation of the locomotive power control system in the aspects of [3, 32]:

- reduction of locomotive ownership costs connected with the repair of electro-hydraulic governors worn in over the 35-year operation;
- reduction of locomotive servicing costs owing to eliminating the necessity of time-consuming regulation and setting of the operation characteristic in the resistor over the total operation period of the locomotive;
- improvement of accuracy and stability of power control, which reduces fuel consumption by about 5%.

7. Evaluation of efficiency of power control system modernisation using LCC analysis

To evaluate the efficiency of the proposed solution in the cost aspect an LCC (Life Cycle Cost) analysis has been performed. The idea of LCC analysis dates back to the 1960s. Information on its applications can be found in several projects run by U.S. Department of Defense which introduced calculations in various areas of activity of the American military [39-41]. LCC was used for, for instance, the evaluation of handling and maintenance of military equipment, armament and defense systems. The analyses indicated that in many cases the costs of handling and maintenance are at least 75% of the total costs, and in the period of 10 – 15 years of handling the costs exceed many times the initial acquisition costs [1, 8, 34, 42]. After that the application of LCC analysis was widely used in other branches of industry, e.g. aircraft industry [2], power industry [17, 49], oil and

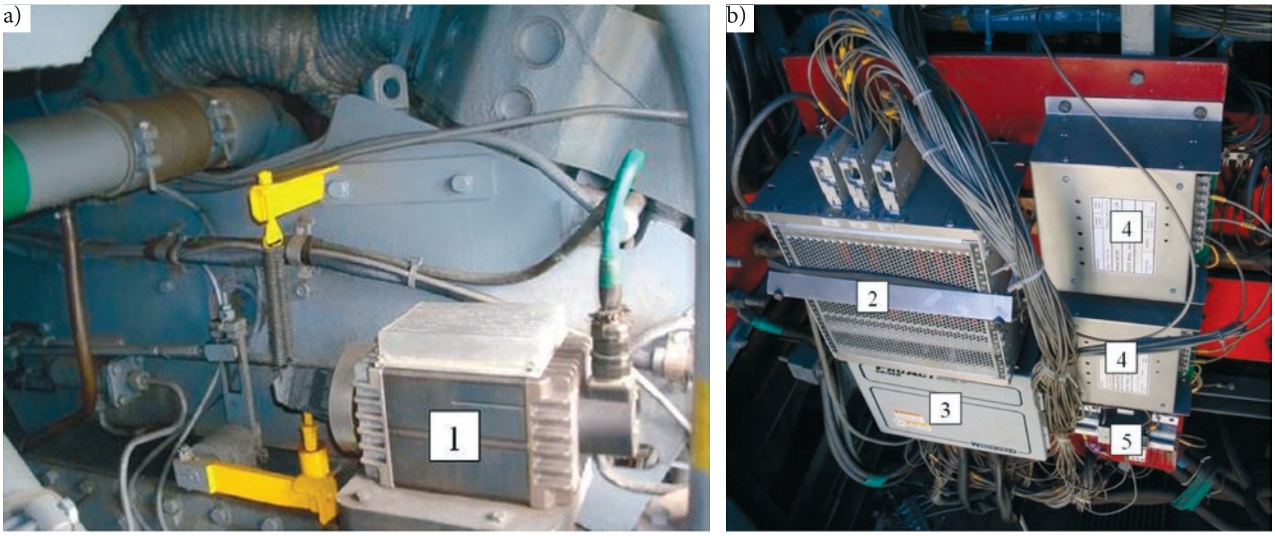

Fig. 6. *Electronic governor of a8C22, a8C22W diesel engines rotations and power [7]: a) 1 – electrical servo-motor; b) 2 – microprocessor controller; 3 – electrical servo-motor control module; 4 – Voltage transducer; 5 – current and Voltage sensors*

chemical industries [30, 46], building industry [16, 18] and transport [12, 43, 52].

In the literature and norms many methods of LCC calculations are proposed [9, 21, 23, 24, 28, 30, 35, 47, 49, 53, 56, 63]. For instance, in [15] the author compares nine models of LCC costing. The selection of an adequate model depends on available resources, input data, time horizon covering the analysis and the object itself of the analysis. In the case of modernisation of SM31 locomotive, which is the subject matter of the present considerations, LCC costing based on PN-EN 60300-3-3 (Reliability Management. Application Guide – Life Cycle Cost Estimation) *Dependability management. Application guide – Life cycle costing* was proposed. The method consists of six stages [58]:

1. Assumptions and aim of analysis;
2. RAM analysis;
3. LCC model development;
4. LCC model analysis;
5. Reporting the results;
6. Verification of analysis.

As a measure of efficiency LCC over a 25-year operation of the locomotive was adopted.

7.1. Assumptions and aim of analysis

It was assumed that the analysis is comparative. The aim of the analysis is to compare the economic effects reached in modernised operation of the locomotive with those before the modernisation. Two variants therefore were adopted:

1. **SM31 variant 0**: non-modernised SM31 locomotive with a8C22W engine,
2. **SM31 variant 1**: modernised locomotive SM31 with a8C22W engine, equipped with an electronic governor realising a selected optimal operation characteristic of the power unit.

In the first stage of the analysis a set of output data was developed for both variants. The data of the non-modernised locomotive included:

- determination of locomotive load distribution for actual operation conditions,
- measurement of actual fuel and engine oil consumption,
- calculation of mean service time, mileage, transport work per year,
- determination of periodicity, time consumption and cost of preventive maintenance resulting from the maintenance cycle,
- preparation of operation data connected with the periods of failure-free work, recovery time, necessary for reliability analysis.

The data of modernised locomotive covered:

- scope, periodicity of technical servicing for new systems and sub-assemblies,
- new maintenance schedule for an electronic governor equipped locomotive.

The output data for the evaluation of modernisation efficiency concern the locomotive work conditions. For the non-modernised SM31 locomotive they were obtained based on the operation of a series of locomotives in the PKP Cargo S.A. In the analysis the following operation indices were adopted:

- locomotive's mean work time in a calendar year: TZ = 5771,7 [hours/year],
- mean mileage: P = 50000,0 [km/year],
- mean transport work: PP = 9564,5 [thousand btkm/year].

7.1.1. Project execution period

For the LCC analysis the period of twenty-five year operation of the locomotive January 2015 – December 2039 was adopted, which corresponds to 144292,0 hours of power unit work.

7.2. RAM analysis

The reliability of SM31 locomotive is treated as a complex property covering the vehicle's features such as reliability, availability and maintainability. The general guidelines of RAM analysis are given in PN-EN 50126 *Railway applications. The specification and demonstration of Reliability, Availability, Maintainability and Safety* (RAMS) [22]. The literature on the subject provides detailed description, definitions and calculation formulae of various evaluation indices [29, 44, 53]. Many study projects on RAM analysis have been done in the recent decades. At present it is applied in many industrial sectors, e.g. aircraft, armament, power, processing and transportation industries [14, 19, 29, 38, 50, 55, 59].

7.2.1. Reliability data

The evaluation of non-modernised locomotive reliability was based on the operation data collected on thirty-six vehicles. These data were collected in cooperation with PKP Cargo S.A. in actual operation conditions in the years 2013 – 2014. The operation in various conditions was observed, which provided reliable and extensive information necessary for reliability analysis. For the modernised locomotive the data were collected during three-year supervised observation.

7.2.2. Reliability, availability and maintainability indices

Locomotive SM31 can be analysed on various levels of complexity with respective RAM indices assigned to each. As the scope of the presented reliability analysis was very broad, in what follows the calculations of only some RAM indices the most important for effectiveness evaluation are discussed:

- Mean time between failures *MTBF*,
- Operation availability A_o,
- Mean time to repair *MTTR*.

The definitions and notation of the indices have been adopted according to PN-EN 50126 and PN-EN 61703 norms [22, 48], in the calculations Statistica, MiniTab and BlockSim packages have been used.

The failures of SM31 locomotive can be divided into minor, for which repair time does not exceed three hours and downtime is not necessary, and major failures which make the vehicle unavailable for operation and it needs to be sent to a rolling stock maintenance plant. In the performed analysis only major failures have been considered significant. Based on the collected operation data reliability models for failure-free work time have been made. In the analysis two parameters Weibull distribution was applied for which the probability density function of failure-free work time is expressed by the formula:

$$\mathrm{f(t)} = \frac{\mathrm{a}}{\mathrm{b}}\left(\frac{\mathrm{t}}{\mathrm{b}}\right)^{\mathrm{a-1}} \exp\left(-\frac{\mathrm{t}}{\mathrm{b}}\right)^{\mathrm{a}}, \quad for\ t \geq 0 \tag{7}$$

where:

a – parameter of shape,
b – parameter of scale.

The parameters of the distributions are presented in Table 2.

Table 2. Weibull distribution parameters for the study cases

No	Variant	Parameter of shape A	Parameter of scale B
1	SM31 variant 0	1,2313	348,788
2	SM31 variant 1	1,2025	847,734

Taking into account the collected operation data, mean times between failures MTBF were computed for the analysed variants [26, 37]. The results are given in table 3.

$$\mathrm{MTBF} = \frac{\sum_{i=1}^{N(0)} TTF_i}{N(0)} \tag{8}$$

where:

TTFi – locomotive's total work time "i" during supervised operation in [hour],
N(0) – total number of locomotives.

In the evaluation of maintainability of the analysed variants distribution functions of corrective maintenance time and mean time to repair MTTR were determined. In the calculations lognormal distribution was used for which the probability density function of recovery time is expressed by the formula [37]:

$$\mathrm{g(t)} = \frac{1}{t \cdot \delta\sqrt{2\Pi}} \cdot \exp\left[-\frac{(\ln t - a)^2}{2\delta^2}\right], for\ t > 0 \tag{9}$$

where:

a – parameter of shape,
δ – parameter of scale.

The statistic assessment of MTTR was determined from dependence [26, 37]:

Table 3. Lognormal distribution parameters for the study cases

No	Variant	Parameter of shape a	Parameter of scale Δ
1	SM31 variant 0	4,0392	0,9688
2	SM31 variant 1	4,0428	0,9261

$$\mathrm{MTTR} = \frac{\sum_{i=1}^{N(0)} TTR_i}{N(0)} \tag{10}$$

where:

$\mathrm{TTR_i}$ – total time to repair of the locomotive "i" during supervised operation,
N(0) – total number of locomotives.

The determination of mean times to recovery was based on the data collected from 503 corrective maintenance performed in the years 2013 – 2014 in the rolling stock maintenance plants of PKP Cargo S.A. The results are shown in Table 3.

To compare the technical availability the operation availability index was used, defined as a mean time share over the period of one year during of the locomotive's up time. For one vehicle this index was expressed by the formula [56]:

$$A_O = \frac{\sum_{\mathrm{i=1}}^{\mathrm{N(0)}} \mathrm{TZ_i}}{\sum_{\mathrm{i=1}}^{\mathrm{N(0)}} \mathrm{TZ_i} + \sum_{\mathrm{i=1}}^{\mathrm{N(0)}} \mathrm{TN_i}} \tag{11}$$

where:

$\mathrm{TZ_i}$ – locomotive's up time "i" in [hours],
$\mathrm{TN_i}$ –locomotive's non up time "i" in [hours]:

$$\mathrm{TN_i} = MNF_i \cdot MTTR \tag{12}$$

where:

$\mathrm{MNF_i}$ – mean number of locomotive's failures "i" in the year of operation,
N(0), MTTR – as above.

Table 4 presents the calculation results for some RAM indices of the variants considered.

Table 4. Calculation results from RAM analysis for analysed variants

No	Variant	MNF [failure/year]	MTBF [hour]	MTTR [hour]	A_o
1	SM31 variant 0	13,9	416,5	90,8	0,8223
2	SM31 variant 1	6,6	874,5	87,5	0,9097

7.3. LCC model

LCC model was expressed as a sum of acquisition costs and ownership costs:

$$\mathrm{LCC} = \mathrm{KN} + \mathrm{KE} \tag{13}$$

where:

LCC – life cycle cost,
KN – acquisition costs,
KE – operation costs.

Acquisition costs Koszty nabycia (KN) are a sum of investment outlays connected with in locomotive's modernisation and are paid only in the variant of locomotive's modernisation. Operation costs (KE) are costs connected with use and maintenance of the locomotive. Since the analysis is comparative, the costing covers only those cost categories that are different for each evaluated variant. The costs breakdown structure of in the adopted model is:

1. Acquisition costs (KN)
   - Modernisation costs (KM)
2. Operation costs (KE)
   - Maintenance costs (KUT):
     - Preventive maintenance costs (KUP),
     - Corrective maintenance costs (KUB),
     - Unavailability costs (KBG).
   - Costs of use (KUZ):
     - Diesel fuel consumption costs (KZP),
     - Engine oil consumption costs (KZO),
     - Environmental charges costs (KOS).

The elements of costs were evaluated using an engineering method of cost assessment and was based on constant prices (net price) as valid in 2015. The LCC analysis was performed on non-negotiated cost values. The assumptions adopted for calculations are discussed in sections 7.3.1 – 7.3.5.

7.3.1. Modernisation costs (KM)

The modernisation costs are cumulative expenditure for locomotive modernisation. They include costs of documentation, purchase of indispensable sub-assemblies and elements, costs of obtaining operation licence and labour costs. It was assumed that the modernisation of SM31 locomotive would be executed in the framework of preventive maintenance: periodical overhaul (level P3) or preventive repair (level P4). The modernisation costs are: KM = 75000,0 [PLN].

7.3.2. Preventive maintenance costs (KUP)

The costs of preventive maintenance (KUP) constitute the expenditure for repairs and periodical overhaul of the locomotive resulting from the maintenance schedule defined in the maintenance system documentation (table 5).

Table 5. Levels of SM31 locomotive maintenance [20]

No.	Maintenance level	Time interval
1	P1	max. 1300 km / max.102 h labour / max. 14 calendar days
2	P2/1	23 days ±3 days
3	P2/2	46 days ±6 days
4	P2/3	138 days ±18 days
5	P3	2 years ± 2 months
6	P4	200 000 km or 4 years
7	P5	1 200 000 km or 24 years

The preventive maintenance costs include labour costs (KUPR) as well as costs of materials and spare parts (KUPM). KUP per year is expressed by dependence:

$$KUP = \sum_{i=1}^{n} KUP_i \tag{14}$$

where:

KUP_i – preventive maintenance costs for maintenance level "i"

$$KUP_i = KUPR_i + KUPM_i = NPMA_i(\mathrm{t}) \cdot \left[\left(MMH_i \cdot CPH_P \right) + ACM_i \right] \quad \left[\boldsymbol{PLN / year} \right] \tag{15}$$

where:

$NPMA_i(t)$ – number of preventive services of level "i" over the given operation year,
MMH_i – mean time consumption of preventive maintenance service level "i",
CPH_P – cost of man-hour in preventive service: CPH_P = 53,8 [PLN/man-hr],
ACM_i – mean material consumption in preventive service maintenance level "i".

The calculations have proved that owing to the use of new sub-assemblies and elimination of the necessity of time-consuming regulation and setting operation characteristic of the resistor the modernisation of SM31 locomotive gives savings in preventive maintenance costs of about 9,6 [thousand PLN/year] compared with the non-modernised locomotive.

7.3.3. Corrective maintenance costs (KUB)

The corrective maintenance costs (KUB) are connected with running repairs of the locomotive. They include both labour costs (KUBR) and the expenditure for materials and spare parts (KUBM). The costs of corrective maintenance over a year for one vehicle are expressed as:

$$KUB = KUBP + KUBM = MNF \left[\left(MMH_B \cdot CPH_B \right) + ACM_B \right] \quad \left[\boldsymbol{PLN / year} \right] \tag{16}$$

where:

MMH_B – mean labour consumption of corrective repair: MMH_B = 10,9 [man-hour/repair],
CPH_B – cost of man-hour in corrective repair: CPH_B = 53,8 [PLN/man-hour],
ACM_B – cost of material consumption in corrective repair: ACM_B = 2324,3 [PLN/repair],
MNF – mean failure rate over a year of operation:

$$MNF = \frac{TZ}{MTBF} \quad \left[\mathrm{failures} / \mathrm{year} \right] \tag{17}$$

where:

TZ – locomotive's mean work time over a calendar year in [hour/year],
MTBF – mean time between failures in [hours].

The calculations performed using the mathematical model of a diesel engine have proved that the modernisation of the power unit load control system of SM31 locomotive reduces the cost of correc-

Table 6. Costs of corrective maintenance for the analysed variants

No.	Variant	Mean work time TZ [hours/year]	Mean time between repairs MTBF [hours]	Costs of corrective maintenance [PLN/year]
1	SM31 variant 0	5771,7	416,5	40 353,5
2	SM31 variant 1		874,5	19 210,8

tive maintenance of about 21,1 [thousand PLN/year] compared with non-modernised locomotive.

7.3.4. Costs of fuel consumption (KZP)

The costs of fuel consumption (KZP) for a non-modernised locomotive was calculated based on the actual operation data collected in the years 2013 - 2014 by PKP Cargo S.A. For a locomotive modernised as a result of modelling the vehicle tractive work and processes in the power unit realising a selected optimal operation characteristic we obtain instantaneous fuel consumption bPi in the period τj of a single regime of locomotive diesel engine. For the period of the assigned tractive work performance by a modernised SM31 locomotive the fuel consumption cost KZP was expressed as:

$$KZP = \int_{\tau_0}^{\tau_j} c_P b_{Pi} dt \quad \left[\boldsymbol{PLN / hour} \right] \tag{18}$$

where:

b_{Pi} – instantaneous fuel consumption in the period τ_j [kg/s],

c_P – diesel oil cost: 4,43 [PLN/kg].

On the basis of the collected data and performed calculations mean fuel consumption was determined:

- SM31 variant 0: 17,74 [kg/hour];
- SM31 variant 1: 16,85 [kg/hour].

Table 7 presents the yearly fuel consumption costs for the analysed variants. The calculations indicate that the modernisation of SM31 locomotive in the proposed variant reduces fuel consumption by 5,0%, i.e. 22,7 [thousand PLN/year].

Table 7. Fuel consumption costs for analysed variants

No.	Variant	Work time [hours/year]	Diesel oil consumption [kg/year]	Diesel oil consumption cost [PLN/year]
1	SM31 variant 0	5 771,7	10 2360,8	453 458,3
2	SM31 variant 1		97 242,7	430 785,3

7.3.5. Costs of engine oil consumption (KZO)

For a non-modernised SM31 locomotive the mean consumption of engine oil, according to operation data, is 0,92% of fuel consumption. For a modernised locomotive owing to the implementation of a selected optimal operation characteristic of the power unit this consumption is 0,60%. Table 8 presents the yearly costs of engine oil consumption for both variants. For the costing the price of engine oil used in a8C22W engine was adopted as 10,88 [PLN/kg].

Table 8. Engine oil consumption costs for analysed variants.

No.	Variant	Engine oil consumption [kg/year]	Engine oil consumption [kg/year]	Engine oil consumption cost [PLN/year]
1	SM31 variant 0	102 360,8	941,7	10 245,9
2	SM31 variant 1	97 242,7	583,5	6 348,0

In the qualitative approach the savings of engine oil consumption for a modernised locomotive are 38,1% i.e. 3,9 [thousand PLN/year].

7.3.6. Costs of unavailability (KBG)

The costs of unavailability (KBG) are a sum of costs resulting from the locomotive's not being in a state to perform required tasks. They include: liability costs, warranty costs, lost opportunity costs, costs of providing alternative vehicles and others. Unavailability costs are expressed by the formula:

$$\boldsymbol{KBG} = \left[\boldsymbol{8760} \cdot \left(\boldsymbol{1} - \boldsymbol{A_O} \right) \right] \cdot \boldsymbol{KPS} \tag{19}$$

where:

KBG – unavailability costs in [PLN/year],

A_O – operation availability index calculated within RAM analysis (section 7.2.2),

KPS – locomotive's downtime costs in [PLN/hour].

Assuming the yearly costs of locomotive downtime KPS = 35,5 [PLN/hour], the yearly unavailability costs are listed in Table 9.

Table 9. Unavailability costs for analysed variants

No	Variant	Locomotive downtime costs KPS [PLN/hour]	Operation availability A_o	Lack of operation availability [PLN/year]
1	SM31 variant 0	35,5	0,8223	55 261,2
2	SM31 variant 1		0,9097	28 081,5

It follows from the analysis that the proposed modernisation variant reduces the unavailability costs by 49,2%, i.e. 27,2 [thousand PLN/year] compared with the non-modernised locomotive.

7.3.7. Costs of environmental charges (KOS)

Costs of environmental charges (KOS) are connected with the charges fixed by the Ministry for the Environment imposed for emissions of hazardous substances in exhaust gases. The amount of charge depends on the indices issued by the Ministry and is proportional do fuel consumption by the locomotive. Table 10 lists charge rates per unit obligatory in 2015.

Considering the fuel consumed, following the calculations in section 7.3.4, the costs of environmental charges have been listed in table 11 for the analysed variants.

It follows from the analysis that the proposed modernisation variant reduces the environmental costs by 5,0% compared with the non-modernised locomotive.

7.4. Analysis of LCC model and presentation of results

The analysis performed using CATLOC software has proved that SM31 locomotive modernisation in the proposed version is fully economically effective. From the calculations it follows that the use of the new electronic programmer and implementation of the new operation characteristic ensures reduction of overall costs of over 2,0 [m PLN] over 25-year operation period, which equal to 10,97% less compared with the non-modernised locomotive. The comparison of overall LCC for the analysed variants over 25-year operation period is illustrated in figure 7.

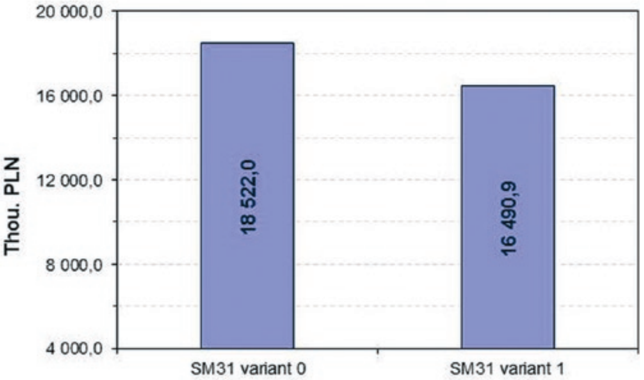

Fig. 7. Comparison of overall costs (LCC) over 25-year operation period

Table 10. Charge rates per unit for gases and flue gases emitted to air [45]

No	Emission component	Charge rate per unit [PLN/kg]	Calculation index [g/kg]
1	Sulphur dioxide	0,53	0,028
2	Nitric oxides (recalculated to NO2)	0,53	50
3	Carbon monoxide	0,11	20
4	Aliphatic hydrocarbons	0,11	2,5
5	Aromatic hydrocarbons	1,44	5,5
6	Flue gases	0,35	4,0

Table 11. Costs of environmental charges for analysed variants

No	Variant	Diesel oil consumption [kg/year]	Cost of environmental charges [PLN/year]
1	SM31 variant 0	102 360,8	3 391,1
2	SM31 variant 1	97 242,7	3 221,6

For the non-modernised SM31 locomotive the predominant costs in LCC are those of fuel consumption KZP – 61,2% and preventive maintenance costs KUP – 24,1%. The corrective repairs costs KUB and unavailabilityy costs KBG constitute over 12,9% of the overall costs (Fig. 8a).

For the modernised SM31 locomotive acquisition costs (KN) connected with the expenditure for modernisation are less than 0,5% of overall LCC (Fig. 8b). The major share in LCC is taken by fuel consumption costs (KZP) – 65,3%. The preventive maintenance costs (KUP) are about 25,6% of overall costs, while corrective maintenance costs (KUB) slightly over 2,9%. The most significant savings compared with the non-modernised vehicle are those in fuel consumption costs – 566,8 [thousand PLN]. The considerable cost reduction was achieved owing to the increased reliability and availability of the vehicle. This, in turn, led to the reduction of the corrective maintenance costs, lower costs of preventive servicing and lower costs of unavailability of the vehicle. The overall savings for these categories of costs are 1437,6 [thousand PLN] over the 25-year operation period (table 12).

8. Conclusions

The improvement of efficiency and reliability of SM31 diesel locomotive by the implementation of an optimal operation characteristic with the existing control system requires the use of an electronic regulator. As a result of joint project of the authors of the present article and Lokel and Newag S.A. firms a new electronic regulator of a8C22W engine rotations and power was developed and implemented. The efficiency of the proposed solution as applied in a SM31 locomotive was evaluated on the basis of actual operation data. To carry out the evaluation a LCC costing method developed at the Institute of Rail Vehicles, Cracow University of Technology, was used. The calculations for a 25-year operation period have proved that the power control system modernisation in SM31 locomotives is cost effective and enable reaching measurable effects at minor financial expenditure. The research and analysis performed are a basis for the undertaking the decision of the locomotive modernization.

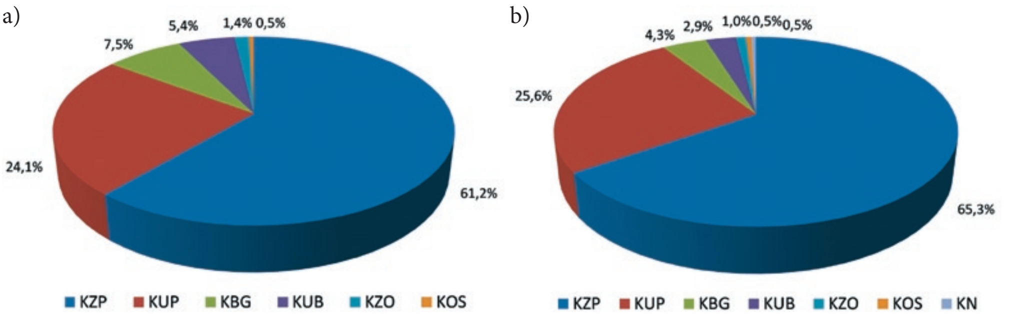

Fig. 8. LCC of analysed study cases: a) variant 0, b) variant 1. KZP – fuel consumption costs, KUP – preventive maintenance costs, KUB – corrective maintenance costs, KBG – unavailability costs, KOS – environmental charges costs, KZO – engine oil consumption costs, KN – acquisition costs

Table 12. Comparison of predominant costs for analysed variants

No	Variant	Fuel consumption costs [thousand PLN]	Preventive maintenance costs [PLN]	Corrective maintenance costs [PLN]	Unavailability costs [PLN]
1	SM31variant 0	11336,5	4454,7	1008,4	1381,5
2	SM31 variant 1	10769,6	4224,7	480,3	702,0

References

1. Augustine N R. Is Life Cycle Cost Costing Lives? Armed Forces Journal International 1978: 110-115.
2. Bååthe O. Life Cycle Management for the A/C JAS 39 Gripen. 11-th Logistics Congress Society of Logistics Engineers, Stockholm 1995.
3. Babeł M. Podstawy teoretyczne i metodologia wyboru zakresów oraz technologii modernizacji lokomotyw spalinowych w oparciu o kryterium kosztów cyklu istnienia. Rozprawa habilitacyjna. Instytut Naukowo-Badawczy Transportu Kolejowego, Moskwa, 2015.
4. Babeł M. Warunki pracy, charakterystyka eksploatacyjna a niezawodność doładowanych trakcyjnych silników spalinowych. Trakcja i wagony 1990; 9: 163-165.
5. Babeł M. Zwiększenie efektywności pracy trakcyjnych silników wysokoprężnych a8C22 na drodze dopasowania charakterystyk obciążenia do warunków eksploatacji. Rozprawa doktorska. Moskiewski Instytut Inżynierów Transportu (MIIT), Moskwa, 1989.
6. Babeł M, Kossov E E. Zwiększenie efektywności pracy lokomotyw spalinowych w eksploatacji na drodze optymalizacji warunków pracy silnika wysokoprężnego z wykorzystaniem elektronicznego regulatora obrotów i mocy. Materiały I Sympozjum Naukowego: Automatyzacja pracy silników wysokoprężnych, Poznań 1992: 69-78.
7. Babeł M, Szkoda M. Poprawa efektywności i niezawodności lokomotyw serii SM31 w wyniku modernizacji układu regulacji mocy. XXI Konferencja Naukowa POJAZDY SZYNOWE 2014, Wojanów, 26-28 maja 2014.

8. Barringer H P, Weber D P. Life Cycle Cost Tutorial. 5-th International Conference on Process Plant Reliability, TX: Gulf Publishing Company, 1996.
9. Barringer H P. A Life Cycle Cost Summary. International Conference of Maintenance Societies, Perth, Australia 2003: 20-23
10. Bianchi G M, Falfari S, Parotto M, Osbat G. Advanced modeling of common rail injector dynamics and comparison with experiments. SAE paper 2003-01-0006.
11. Володин А И. Моделирование на ЭВМ работы тепловозных дизелей. Транспорт, Москва, 1985.
12. Borghagen L, Brinkhagen L. LCC-procurement at the Swedish State Railways. Reliability and Maintainability Symposium 1984. Proceedings Annual IEEE, 1984: 349-358.
13. Chłopek Z. Badania zużycia energii przez samochód elektryczny w warunkach symulujących jazdę w mieście. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2013; 15(1): 75-82.
14. Chłopek Z, Piaseczny L. Uwagi o modelowaniu w badaniach naukowych. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2001; 4(11): 47-57.
15. Chłopek Z. Modelowanie procesów emisji spalin w warunkach eksploatacji trakcyjnej silników spalinowych. Prace Naukowe Seria Mechanika" z. 173. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej, 1999.
16. CILECCTA: Sustainability within the Construction Sector, Life Cycle Costing and Assessment. CILECCTA project EU 7-th Framework Programme FP7/2007-2013, grant no. 229061, 2013. (www.cileccta.com)
17. Coe C K. Life Cycle Costing by State Governments. Public Administration Review 1981; 41: 564-69, http://dx.doi.org/10.2307/976268.
18. Department of Sport and Recreation, Government of Western Australia: Life Cycle Cost Guidelines Sport and Recreation Facilities, 2005.
19. DoD Guide for Achieving Reliability, Availability and Maintainability. USA Department of Defense, Washington, 2005.
20. Dokumentacja Systemu Utrzymania lokomotywy spalinowej serii SM31 typu 411D. PKP Cargo S.A., 2011.
21. Durairaj S K, Ong S K, Nee A Y C, Tan R B H. Evaluation of Life Cycle Cost Analysis Methodologies. Corporate Environmental Strategy 2002; 9(1): 30-39, http://dx.doi.org/10.1016/S1066-7938(01)00141-5.
22. EN 50126 Railway applications. The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS).
23. Fabrycky Wolter J, Blanchard B S. Life-Cycle Cost and Economic Analysis. Prentice Hall, Englewood Cliffs NJ, 1991.
24. Garcıa Marquez F P, Lewis R W, Tobias A M, Roberts C. Life cycle costs for railway condition monitoring. Transportation Research Part E: Logistics and Transportation Review 2008; 44(6): 1175-1187, http://dx.doi.org/10.1016/j.tre.2007.12.003.
25. Guzzella L, Onder Ch. Introduction to modeling and control of internal combustion engine systems. Springer Verlag. 2nd ed., 2010.
26. Hebda M, Janicki D. Trwałość i niezawodność samochodów w eksploatacji. Warszawa: WKiŁ, 1977.
27. Herder P M, van Luijk J A, Bruijnooge J. Industrial application of RAM modeling development and implementation of a RAM simulation model for the Lexan plant at GE Industrial, Plastics. Reliability Engineering & System Safety 2008; 93(4): 501-508.
28. Hokstad P. Life Cycle Cost Analysis in Railway Systems. SINTEF Safety and Reliability, 1998.
29. Jackson Y, Tabbagh P, Gibson P, Seglie E. The new Department of Defense (DoD) guide for achieving and assessing RAM. Reliability and Maintainability Symposium 2005. Proceedings Annual IEEE, 2005: 1-7.
30. Kawauchi Y, Rausand M. Life Cycle Cost (LCC) analysis in oil and chemical process industries. Norwegian University of Science and Technology 1999.
31. Kossov E E, Babeł M. Zagadnienia modelowania eksploatacyjnych warunków pracy trakcyjnych silników spalinowych. Silniki spalinowe 1988; 2: 27-31.
32. Коссов Е Е, Нестрахов А С, Аникиев И П, Бычков Д А. Микропроцессорная система регулирования дизель - генератора. Локомотив 2002; 12: 14-15.
33. Коссов Е Е, Сухопаров С И. Оптимизация режимов работы тепловозных дизель-генераторов. Труды ВНИИЖТ. Интекст. Москва 1999.
34. Lamar W E. Review and Assessment of System Cost Reduction Activities. Proceedings NATO AGARD Conference on Design to Cost and Life Cycle Cost, 12-22 May, 1980.
35. Lynch J P, Karlaftis M G, Sinha K C, Fricker J D. The Indiana Public Transportation Management System. Report No. CE-TRA-95-1, Purdue University, 1995.
36. Ma H, Xu H M, Wang J H. Real-time control oriented HCCI engine cycle-to-cycle dynamic modelling. International Journal of Automation and Computing 2011; 8(3): 317-325, http://dx.doi.org/10.1007/s11633-011-0587-z.
37. Manzini R, Regattieri A, Pham H, Ferrari E. Maintenance for Industrial Systems. Springer, 2010.
38. Martorell S, Villanueva J F, Carlos S, Nebot Y, Sanchez A, Pitarch J L, Serradell V. RAMS+C informed decision-making with application to multi-objective optimization of technical specifications and maintenance using genetic algorithms. Reliability Engineering & System Safety 2005; 87(1): 65-75, http://dx.doi.org/10.1016/j.ress.2004.04.009.
39. MIL-HDBK-259 Military Handbook, Life Cycle Cost in Navy Acquisitions. Global Engineering Documents 1983.
40. MIL-HDBK-276-1 Military Handbook, Life Cycle Cost Model for Defense Material Systems, Data Collection Workbook. Global Engineering Documents 1984.
41. MIL-HDBK-276-2 Military Handbook, Life Cycle cost Model for Defense Material Systems Operating Instructions. Global Engineering Documents 1984.
42. Navarro-Galera A, Ortúzar-Maturana R I, Mu-oz-Leiva F. The application of life cycle costing in evaluating military investments: An empirical study at an international scale. Defence and Peace Economics 2011; 22(5): 509-543, http://dx.doi.org/10.1080/10242694.2010.508573.
43. NCHRP: Bridge Life-Cycle Cost Analysis. Report No 483. Washington DC: Transportation Research Board of the National Academies, 2003.
44. O'Connor P. Practical Reliability Engineering. John Wiley & Sons Ltd., 2010.
45. Obwieszczenie Ministra Środowiska z dnia 11 sierpnia 2014 r. w sprawie wysokości stawek opłat za korzystanie ze środowiska na rok 2015. Monitor Polski, 18.09.2014 r., poz. 790.
46. Parra C, Crespo A, Kristjanpoller F, Viveros P. Stochastic model of reliability for use in the evaluation of the economic impact of a failure using life cycle cost analysis. Case studies on the rail freight and oil industries. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability 2012; 226(4): 392-405.

47. PN-EN 60300-3-3 Zarządzanie niezawodnością. Przewodnik zastosowań - Szacowanie kosztu cyklu życia.
48. PN-EN 61703 Wyrażenia matematyczne dotyczące nieuszkadzalności, gotowości, obsługiwalności i zapewnienia środków obsługi.
49. Reiger A J. Solar Energy: The Market Realities. Real Estate Review 1979; 8: 49-52.
50. Senthil Kumaran D, Ong S K. Environmental life cycle cost analysis of products. Environmental Management and Health 2001; 12(3): 260-267, http://dx.doi.org/10.1108/09566160110392335.
51. Sharma R K, Kumar D, Kumar P. Performance modeling in critical engineering systems using RAM analysis. Reliability Engineering & System Safety 2008; 93(6): 891-897, http://dx.doi.org/10.1016/j.ress.2007.03.039.
52. Sherif Y S, Kolarik W J. Life cycle costing: concept and practice. Omega 1981; 9(3): 287-296, http://dx.doi.org/10.1016/0305-0483(81)90035-9.
53. Smith D J. Reliability, Maintainability and Risk: Practical Methods for Engineers. Butterworth-Heinemann, 2011.
54. Strategia odnowy parku lokomotyw w przedsiębiorstwie PKP LHS Sp. z o. o. Projekt nr M8/599/2007. Politechnika Krakowska Instytut Pojazdów Szynowych, Kraków, 2007.
55. Studium techniczno-ekonomiczne odnowy parku pojazdów trakcyjnych eksploatowanych przez PKP CARGO S.A. Projekt nr M8/631/2006. Politechnika Krakowska Instytut Pojazdów Szynowych, Kraków, 2006.
56. Szkoda M, Babeł M, Kossov E E. Анализ стоимости жизненного цикла (LCC) при оценке эффективности подвижного состава. Вестник ВНИИЖТ 2013; 6: 55-59.
57. Szkoda M. Assessment of Reliability, Availability and Maintainability of Rail Gauge Change Systems. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2014; 16(3): 422-432.
58. Szkoda M. Ocena efektywności ekonomicznej środków transportu szynowego z zastosowaniem analizy LCC. TTS Technika Transportu Szynowego 2012; 11-12: 64-69.
59. ten Wolde M, Ghobbar A A. Optimizing inspection intervals - Reliability and availability in terms of a cost model: A case study on railway carriers. Reliability Engineering & System Safety 2013; 114: 137-147, http://dx.doi.org/10.1016/j.ress.2012.12.013.
60. Watson N. Transient performance simulation and analysis of turbocharged diesel engines. No 810338. SAE Technical Paper 1981: 1-19.
61. Wendeker M, Godula A. Research on variability in control parameters for spark ignition engines in real-life operation. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2002; 16(4): 12-23.
62. Zellbeck H, Woschni G. Rechnerische Untersuchung des dynamischen Betriebs-verhaltens aufgeladener Dieselmotor. MTZ 1983; 3: 81-86.
63. Zoeteman A. Asset maintenance management: state of the art in the European railways. International Journal of Critical Infrastructures 2006; 2(2/3): 171-186.

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