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Life Cycle Costs of passenger transportation system. Case study of Wroclaw city agglomeration

Keywords

Life Cycle Costs, transportation system, rail cars

Abstract

In the article authors are interested in the issues of LCC analysis implementation in the area of passenger transportation systems performance. In the first step of research analysis, there is provided a briefly literature overview of the analysed research area. Thus, the applicability of LCC analysis is investigated on the existing passenger transportation system located in Lower Silesia, Poland.

1. Introduction

Rapid changes in the market of regional passenger services forced major carriers to verify the current model of doing business and make the necessary changes, often aimed at lowering their performance costs.

The carriers' main activity, in which they seek costs savings, is a means of transport maintenance performance. Such a decision is connected with the fact that the costs associated with technical objects maintenance represent a significant percentage of the total cost of their Life Cycle Costs (LCC) [10]. According to [27], LCC are estimated at approximately 40% of the total costs of the facilities. Therefore, even a slight change in maintenance management area can therefore lead to improvement of carrier's business model performance in technological or organizational way [10].

The improvement actions are mainly focused on searching for savings (e.g. connected with reduction of labour costs, spare parts purchasing, spare parts allocation optimization). On the other hand, there are expected some activities in the area of increasing facilities dependability or providing resources availability and efficiency of their use [25], [32].

Additionally, one of the fundamental mistakes made during technical facilities maintenance decision-making process performance is considering the future renewal and operational costs without taking into account the aspects of their reliability/availability, or carrying out an incorrect identification of future performance costs (e.g. some relevant costs omission).

One of the possible solutions which may help maintenance managers to properly analyse the costs of an object over its entire lifespan and effectively invest money on dependable technical objects is Life Cycle Cost analysis [6].

In addition to LCC there can be found in the literature other methods which take a wide perspective on product life cycle. Most notable are Total Cost of Ownership (TCO) and Life Cycle Assessment (LCA). However, TCO does neglect operations and maintenance costs, LCA is focused on environmental impacts instead of being a costing tool [13], and according to [15] LCC analysis is a method that can be used to evaluate alternative asset options or/and assets maintenance management strategies.

Following this, the main objective of this article is to present a LCC analysis implementation for the case company. Thus, in the next Sections, the concept of LCC is investigated. Later, there is presented the discussion about analysis results of LCC analysis implementation in the case company maintenance decision processes performance.

The article is the continuation of authors research in the area of means of transport maintenance management issues (presented e.g. in [19], [21]-[23], [30]), and possibilities of LCC analysis implementation in the area of passenger transport systems performance (see e.g. [6]-[8]).

2. Life Cycle Costs analysis – a literature review

The concept of Life Cycle Cost is widely used in the literature and practice since 70s. of the XX century (see e.g. [16], [18]). According to [18], the Life Cycle Cost is defined as the total sum of the direct, indirect, recurring, non-recurring and other related costs incurred, or estimated to be incurred in the design, research and development (R&D), production, operation, maintenance, and support of a product over its life cycle, i.e. its anticipated useful life span. It is the total cost of the R&D, production, O&S and, where applicable, disposal phases of the life cycle. This definition was later extended in international standard IEC 60300-3-3:2004 [12], providing more detailed definition of object life cycle phases which are considered in LCC analysis. The typical areas of costs which are included in the process of estimation of object's life cycle costs are given e.g. in [6].

Additionally, according to [15], the LCC analysis can be defined as a systematic process of technical-economical evaluation that considers, in a simultaneous way, economic and reliability aspects of an asset, quantifying their real impact along its life cycle cost. Thus, the total costs of non-reliability are classified into two groups: costs for penalization and costs for corrective maintenance [15].

The literature review in analysed research area is provided e.g. in [3], [17], [24], [29]. The work of Asiedu and Gu [1] should be underlined here. Authors investigated the issues of LCC analysis and tools that have been developed to provide engineers with cost information to guide them in design. They presented e.g. a comprehensive analysis of cost issues in life cycle design, and define three main cost estimating approaches: parametric models, analogous models and detailed models. This problem was later developed by Korpi and Ala-Risku in their work [13]. Authors provided there a discussion about life cycle costing methods and presented a review of literature focused on LCCA implementation.

Durairaj et al. in their article [5] present and compare different life cycle cost analysis methods.

Following the literature known mathematical models of life cycle costs can be classified into three basic groups [3], [17], [24], [29]:

- models dedicated for technical objects' manufacturers, that are designed to minimize the costs occurred in the early stages of its lifetime,
- models aimed at minimizing the lifetime cost of the facilities being already in operation,
- models oriented to customers wishing to purchase a new technical object.

The main area of authors' interest is the last group of models, which is useful to define the future costs of technical objects lifetime and to make a proper investment decision. In this group of models, there can be defined two subgroups [9]:

- basic LCC models without technical objects reliability issues consideration,
- LCC models with technical objects reliability issues implementation.

The first group of models is focused on proper identification of technical objects costs incurred in its main life cycle phases, see e.g. [3], [11], [26], [28], [31].

The second group of models takes into account the technical objects reliability costs bearing. Following [3], there can be defined four reliability costs categories:

- prevention cost,
- appraisal cost (i.e. inspection/review cost),
- internal failure cost,
- external failure cost.

For more information we recommend reading e.g. [3], [4], [6], [9], [17], [24], [29].

Taking into account the customer purchasing decision problems, and following the literature, the most commonly lifetime costs of a technical object can be divided into two categories of costs (e.g. [28], [14], [20]): the costs of acquisition (purchase) and operating costs. Their proper identification can be the base for investment decisions.

Following this, in the next Section, the case study for LCC analysis implementation is provided as a base for definition of purchasing procedure for buying new means of transport with taking into account the objects unreliability.

3. LCC analysis implementation – case study

3.1. Railcar operation system

The applicability of LCC analysis is investigated on the existing passenger transportation system located in Lower Silesia, Poland. The system covers several routes operated daily by Lower Silesian Railways Company on mixed-traffic railway infrastructure which is partially single and double track. The network is of irregular form with central station in Legnica, supplemented by the only service depot for the car fleet located nearby. *Figure 1* presents the rail network.

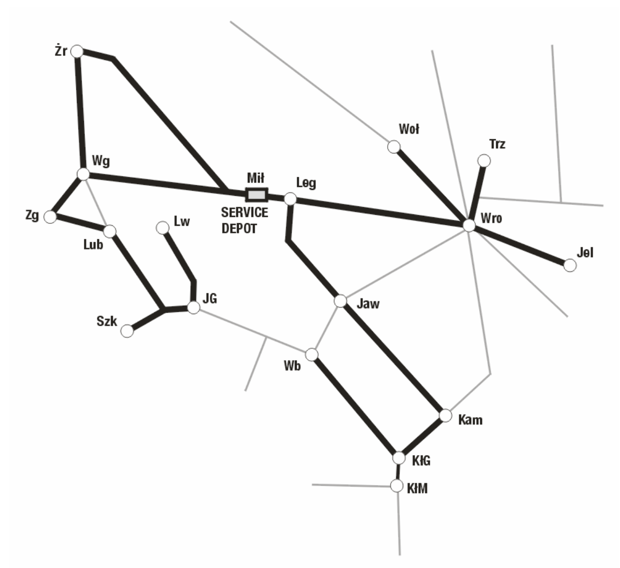

Figure 1. Schematic representation of track layout in Lower Silesia with bold lines marking out the operated routes and the service depot located in the centre of network [2]

The operator puts into service small- and middle-sized diesel rail vehicles, running mostly as single train sets, rarely coupled. Currently 21 rail buses dating from 2004 to 2011 are used, being built mostly by one manufacturer or his subsidiaries. The fleet comprises a homogeneous set of objects in terms of design solutions.

The rolling stock remains the property of local province government, being spared to the operator which is fully responsible for all maintenance activities. Therefore it is especially important for the rail company to introduce optimal maintenance strategies to meet the service and cost levels expected by the car fleet owner.

The process of railway operation is strictly determined. In short, the publicly announced timetable consists of trains servicing routes with stations. The set of trains to be run during the day are then combined to form the so called circulations which may be detailed by requirements like allowed railcar types. One circulation may also cover several trains during one or more consecutive days in schedule.

Available railcars are then assigned by dispatcher to specific circulations, provided that the permissible parameters like e.g. remaining number of kilometres to revision, are met. Disruptions and failures cause instant changes in the railcar assignment.

The maintenance process of the railcar is also precisely defined in service manual, including obligatory maintenance revisions of several different levels of complexity. Depending on the latter, the vehicle is excluded from regular operation for certain period of time.

The identification of the important aspects and possible data sources in the operation process is shown as the entity-relationship-diagram in *Figure 2*.

3.2. Maintenance data analysis for the case company

The research analysis covered 8 single car rail buses of particular type X. The analysed rail cars include these, which were handed over to the rail carrier from previous railway operator, as well as new ones were being bought by the regional province government and directly sent to the rail company. These vehicles were owned by a company at different times of their life, as illustrated in *Figure 3*.

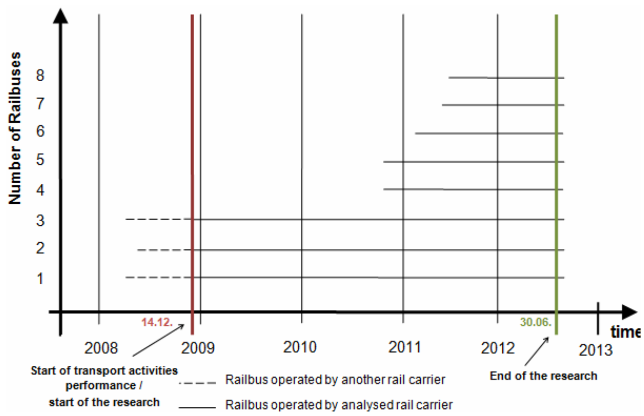

Figure 3. Time schedule of performed research analysis [7]

The period of research analysis encompasses 43 months (152 568 working hours) of rail carriers performance, from December 2008 to June 2012. The mileage of analysed rail buses made before and during the research period of time is given in the *Figure 4*. The data about rail buses' operational process performance are taken from their operational books which are prepared by department of tram maintenance employees. These operational books are located in every rail buses, and are filled in by engine drivers, warehousemen, and service engineers.

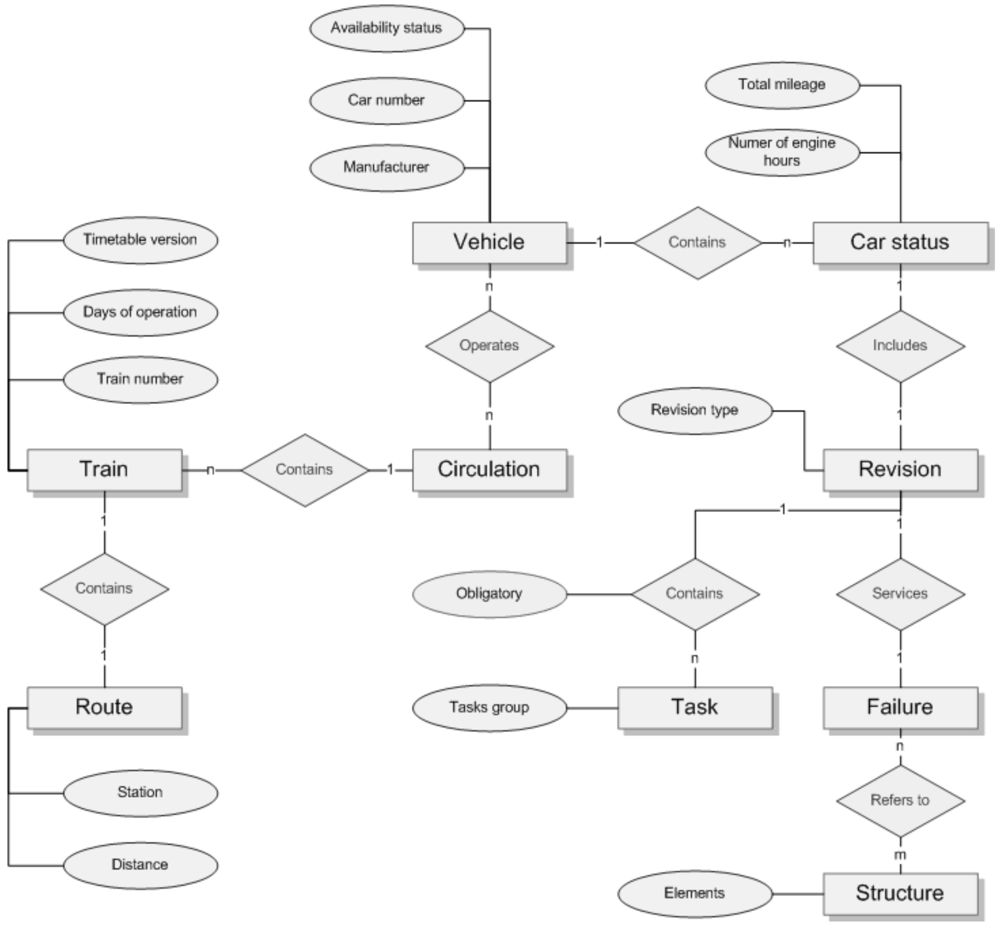

Figure 2. The model of railcar operation process shown as an entity-relationship-diagram [2]

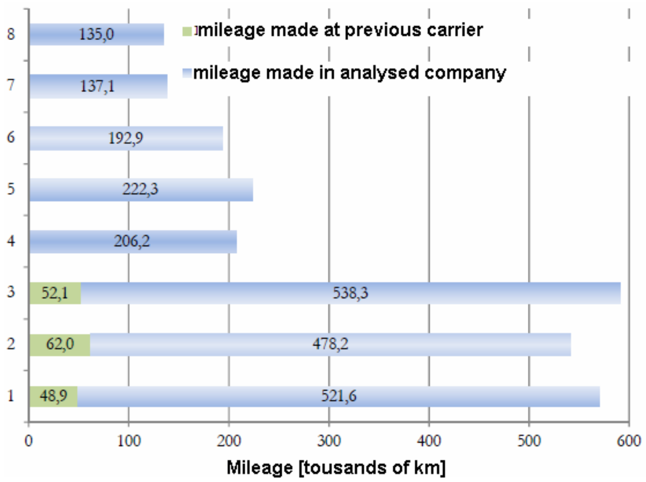

Figure 4. Working time of rail buses defined as a mileage [9]

Every engine driver should fill in the date, hour and place of beginning/finishing his work. Moreover, some additional information should be taken into account, like e.g. all failures and irregularities detected during operational process performance. More information can be found in [9]. The collected performed corrective actions (failures) during research analysis were divided into four groups depending on their impact on rail buses operational process performance (*Figure 5*):

- critical failures – which result in rail car operational unavailability,
- important failures – which require immediate maintenance actions performance,
- unimportant failures – when maintenance actions may be postponed in time,
- irrelevant failures – when their influence on system dependability is negligible.

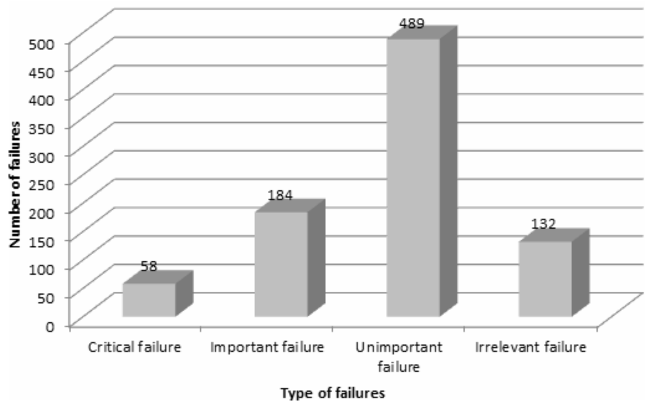

Figure 5. Distribution of failures types in terms of their influence on rail cars operational process performance [7]

This classification of corrective actions types was based on the expert opinions.

In the analysed research area, there were observed 589 current corrective actions performance, including 9 (1.5%) maintenance actions without the possibility of corrective actions type identification. During these 598 maintenance actions performance, there are made 863 remedial actions including, e.g. a damaged item replacement, repair, adjustment, or inspection. The information about the performed corrective action of rail car or its components includes eleven different maintenance actions (*Table 1*).

Table 1. Frequency of corrective actions types occurrence during rail cars operational process performance

CORRECTIVE ACTIONS TYPE	FREQUENCY OF OCCURRENCE
Repair	392
Replacement	382
Assembly	28
Seal action	23
Inspection	17
Carotid	8
Adjustment	7
Gluing	2
Tightening	2
Painting	1
Washing	1

The failures' causes were connected with operational (internal and external) forcing factors, design and manufacturing errors, or rail cars collisions and vandalism actions occurrence.

The planned maintenance actions are defined in five levels of rail bus maintenance (ML – maintenance level) [7]:

- ML1 – regards to control inspection performance level,
- ML2 – defines the average periodic inspection level,
- ML3 – regards to the average periodic inspection action with extended range level,
- ML4 – defines the revision repair process level,
- ML5 – the main repair process level.

All of the defined by ML maintenance actions are periodically repeated after a fixed work time, expressed by rail bus mileage, hours of operation, or fixed exploitation time in days, months or years. Moreover, they form a rail bus maintenance cycle.

The inspections of type ML1 and ML2 are performed in carrier's own repair department and do not demands rail bus closing down. However, the inspection of type ML3 could be performed only in rail bus manufacturer's service departments where the rail bus has to be delivered. This maintenance inspection regards rail bus closing down. Because of the short operational period of rail buses performance, the inspections of type ML4 and ML5 have not been executed yet [7].

Next, the transportation system characteristics can be obtained. The exemplary transportation system characteristics are presented in *Figures 6–7*.

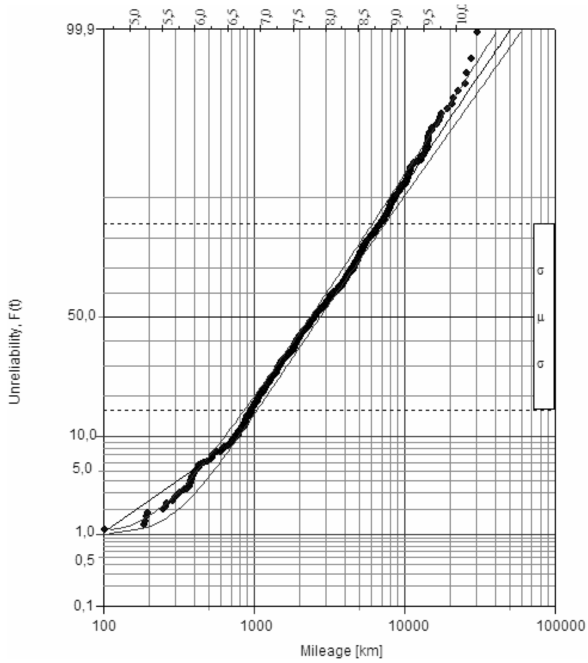

Figure 6. The cumulative distribution function of rail buses time between failures [mileage]

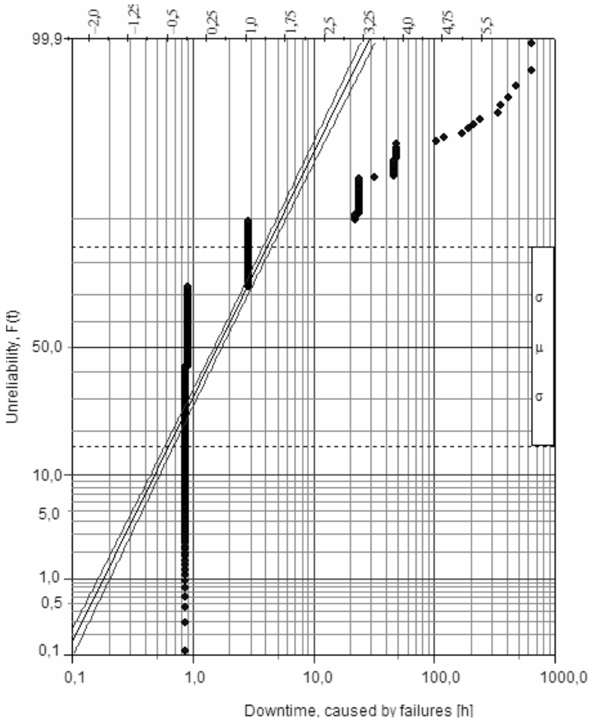

Figure 7. The cumulative distribution function of rail buses repair time [hours]

Based on the odometer, which indicated the number of kilometres being registered on consecutive days in which the damages have been observed, the time between failures can be calculated. During the calculations, all corrective actions types were included. According to the analysis results, time between failures may be defined by a log-normal distribution function with parameters μ equal to 7.8517 and σ equal to 0.9673. High compliance was achieved at ρ = 0.99 (Fig. 6). The MTBF is equal 4130 kilometres with standard deviation equals to 5107 kilometres. The calculated coefficient of variation is less than a value 1 (reaches a level about 0.86).
The time between preventive actions performance is defined in service manuals (*Table 2*).

Table 2. Time between preventive maintenance actions performance defined in Service Manuals of analysed rail cars

TIME BETWEEN MAINTENANCE ACTIONS PERFORMANCE FOR THE DEFINED MAINTENANCE LEVELS*			
Maintenance level	Mileage (km)	Engine hours	Time
ML-1	At every 1500 km ± 25%	every 50	every 3 days
ML2-1	At every 30 000 km ± 10%	every 1 000	every 2 months
ML2-2	At every 60 000 km ± 10%	every 2 000	every 4 months
ML2-3	At every 120 000 km ± 10%	every 4 000	every 8 months
ML3-1	At every 210 000 km ± 10%	every 7 000	at every 1,25 years
ML3-2	At every 400 000 km ± 10%	every 14 000	at every 2,5 years
ML-4	At every 1 200 000 km ± 10%	---	at every 9 years
ML-5	At every 2 400 000 km ± 10%	---	at every 18 years
* whichever occurs first			

For the defined research time period, the mean time between ML-1 actions performance is equal to 3.2 days (1304 km and 48.9 eh). The mean time for ML-2 actions performance equals 75.3 days (30 454 km or 1 144 eh), respectively. The mean time for ML3-1 is equal to 539 days (212 520 km and 7313 eh), and for ML3-2 – 1 009 days (427 464 km and 15 107 eh). In the analysed time period, only four ML-3-1 actions and three ML3-2 actions were performed. Moreover, there were no performances of maintenance actions at ML4 and ML5 levels.
The estimation of downtime caused by corrective action performance was based on expert opinion (Figure 7). Till January 2012, there were no data gathered about the time moments of maintenance actions (both corrective and preventive) starting/ending. This problem was solved now by introducing the new document called Service Report. Following this, the downtime and maintenance actions performance times were defined based on the Repairmen and Maintenance Department Employees conversations. The downtime includes e.g. the time necessary for disassembly, failure identification, repair/replacement time, assembly, waiting time for spare parts delivery, waiting for service arrival.
The determination coefficient (ρ = 0.75) confirmed the compatibility of downtime empirical distribution with log-normal distribution with parameters μ = 0.4750 and σ = 0.9376, the confidence level of 95%. The period of downtime connected with corrective and preventive actions performance is equal to 15 180 hours. Average downtime was 2.5 hours with a standard deviation of 2.96 hours.
It is also worth taking a note that 74% of current corrective maintenance actions have been made as an opportunity during preventive maintenance actions performance. Thus, the repair times hover around 0.86 h (that is the minimal downtime for corrective maintenance performance).
Maintenance actions of ML1 last on average 2 hours. When the repair actions were performed during ML1, this downtime was lengthened by an average of about 0.86 hours. Labour-consumption of ML1 performance is approximately 1.4 hours. Maintenance actions of ML2 require on average 12 hours. The average maintenance time of ML2-1, ML2-2, and ML2-3 equal 5.3 hours, 5.9 hours, and 6.0 hours, respectively. Moreover, it should be also included the labour-consumption of ML1 (1.4 hours), and labour-consumption of current repairs performance (approximately 0.6 hours), if necessary.
The maintenance actions of ML3 performance result in longer downtime occurrence. The average maintenance time of ML3-1 is equal to 326.4 hours with standard deviation equals to 146 hours. The average maintenance time of ML3-2 equals 1136 hours with standard deviation being equal to 14 hours. The labour-consumption of ML3-1 actions performance is as 230 hours, and for ML3-2 – is as 840 hours.
Another problem regards to economical parameters estimation. For the analysed rail cars, there are e.g. corrective and preventive maintenance actions' costs easily obtainable. The mean maintenance costs are

presented in *Table 3*. *Figure 8* presents the cost of manpower incurred during the analysed research time.

Following this, the mean downtime cost is defined at the level of 1 962 PLN. The maintenance costs are so high because the rail carrier does not have its own service departments. As a result, all the maintenance activities are performed by manufacturer's service facilities.

Table 3. Mean costs of preventive and corrective maintenance actions performance for the analysed rail cars

MAINTENANCE LEVEL	MEAN COST PER ONE MAINTENANCE ACTION PERFORMANCE (PLN)	
	Estimated by rail carrier service employees	Estimated by service employees of rail carriers' manufacturer
ML-1	331.94	
ML2-1	3 900	11 520
ML2-2	3 931	15 253
ML2-3	3 992	18 985
ML3-1	---	56 504
ML3-2	---	338 526
ML4		800 000
ML5		2 500 000
remedial action	1 729	
corrective action	2 521	

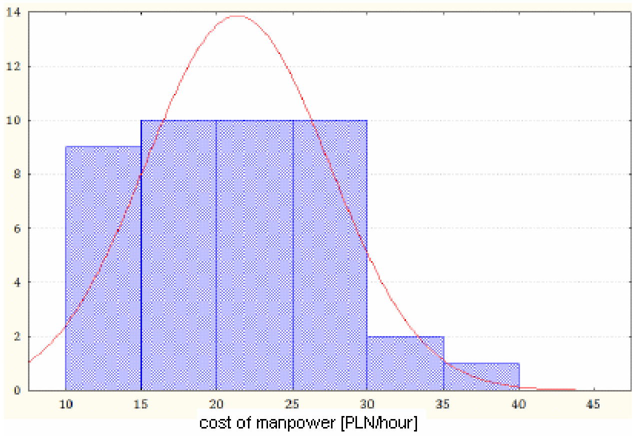

Figure 8. Probability density distribution of manpower cost [9]

To sum up, the analysis of rail cars operational processes performance gives the possibility to gather main economical, operational and maintenance data, necessary for LCC analysis carrying out.

Following this, in the next Section, there is presented the LCC analysis results for the case study.

3.3. LCC analysis results

To implement LCC analysis, there is used cost model given in *Figure 9*. This structure results from the chosen input data gathered during operational process and corrective and preventive maintenance processes performance.

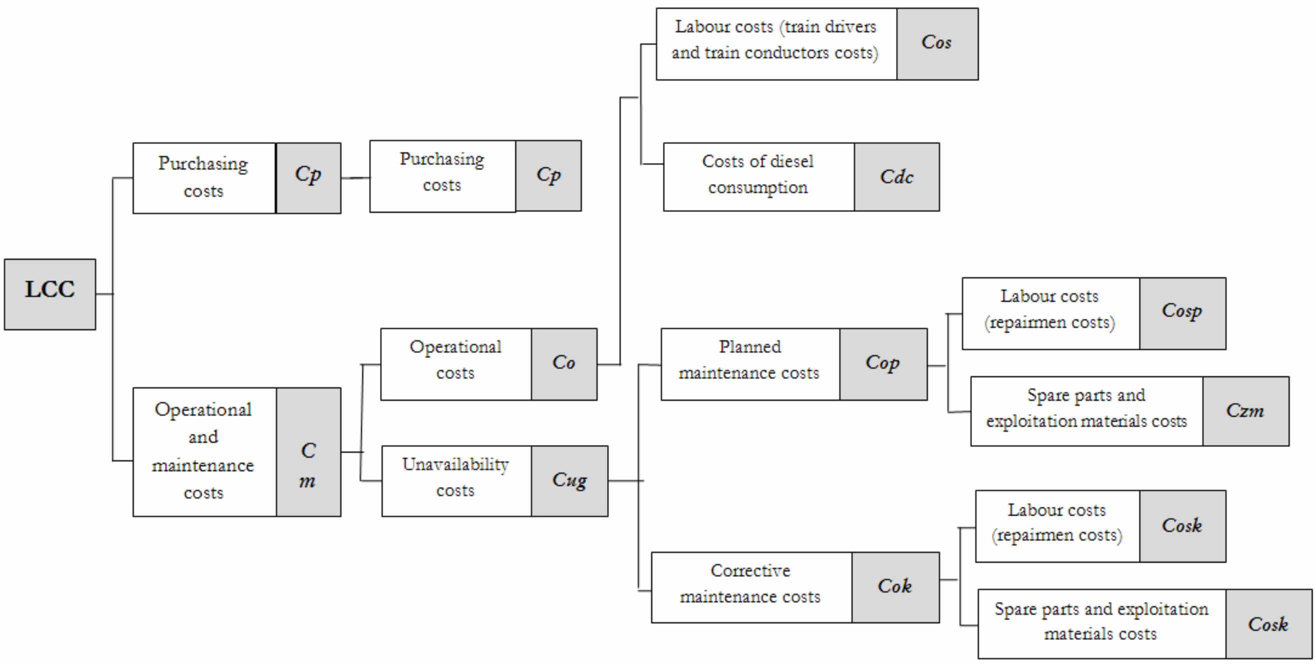

Figure 9. Cost structure used in LCC analysis of railcars [9].

Following this, the estimation of operational and maintenance costs was based on the presented formulae [9]:

- Daily operational costs c_O^d:

$$c_O^d = \left(T_E^d \cdot c_{en}^z \cdot z_{en}\right) + \left[\left(T_E^d \cdot n_{um}^{os} \cdot n_{um}^p\right) + \left(T_E^d \cdot c_{uk}^{os} \cdot c_{uk}^p\right)\right] \quad (1)$$

where:

T_E^d - daily exploitation time (km)

c_{en}^z - purchasing price of diesel fuel [PLN/dm3]

z_{en} - unit consumption of diesel fuel per unit of time

n_{um}^{os} - number of train drivers working daily

n_{um}^p - number of train conductors working daily

c_{uk}^{os} - working cost of train drivers per unit of time [PLN/km]

c_{uk}^p - working cost of train conductors per unit of time [PLN/km]

- Cost of preventive maintenance action performance c_{OP}:

$$c_{OP} = \left(c_{OP}^e \cdot n_{OP}^{os} \cdot c_{nz}^p\right) + \left(\sum_{r=1}^{R} c_{OP}^{zm^{(r)}} \cdot n_{OP}^{m^{(r)}}\right) \quad (2)$$

where:

c_{OP}^e - time of preventive maintenance action performance [h]

n_{OP}^{os} - number of repairmen who perform preventive maintenance action

c_{nz}^p - cost of repairmen working time [PLN/h]

$c_{OP}^{zm^{(r)}}$ - price of r-th spare parts or r-th exploitation material used during preventive maintenance action performance

$n_{OP}^{m^{(r)}}$ - number of r-th spare parts or r-th exploitation material used during preventive maintenance action performance

- Cost of corrective maintenance action performance c_{OK}:

$$c_{OK} = \left(c_{OK}^e \cdot n_{OK}^{os} \cdot c_{nz}^p\right) + \left(\sum_{r=1}^{R} c_{OK}^{zm^{(r)}} \cdot n_{OK}^{m^{(r)}}\right) \quad (3)$$

where:

c_{OK}^e - time of corrective maintenance action performance [h]

n_{OK}^{os} - number of repairmen who perform corrective maintenance action

$c_{OK}^{zm^{(r)}}$ - price of r-th spare parts or r-th exploitation material used during corrective maintenance action performance

$n_{OK}^{m^{(r)}}$ - number of r-th spare parts or r-th exploitation material used during corrective maintenance action performance

There also have been made some additional assumptions, e.g. [9]:

- one rail car is operated by one train conductor and one train driver,
- preventive maintenance actions are made by two repairmen,
- the purchase prices for exploitation materials and spare parts are valid for the whole replenishment supply time,
- manpower cost is monthly constant.

For more information we recommend reading [9].

Following this, the life cycle costs were estimated. Preventive maintenance costs were estimated for each type of rail bus separately, due to the different panoramic bus cycle imposed by the rail manufacturers. Other exploitation costs such as operating costs and corrective maintenance costs were estimated without division for rail buses types. Due to the fact that the occurred failures had different influence on the vehicle operation process, the corrective maintenance costs were estimated for the three different groups, namely:

- catastrophic failures – first group,
- failures that do not cause safety hazards, do not limit values utility vehicle, and do not require immediate shutdown of the vehicle of use (non-catastrophic) – second group,
- failures caused by external events (accidents, vandalism, weather conditions) – third group.

Later, there were estimated average costs for each group and for each time interval. This gave the possibility to accumulate the average values of the cost of the given time periods. The exemplary costs are presented in *Figures 10-12*.

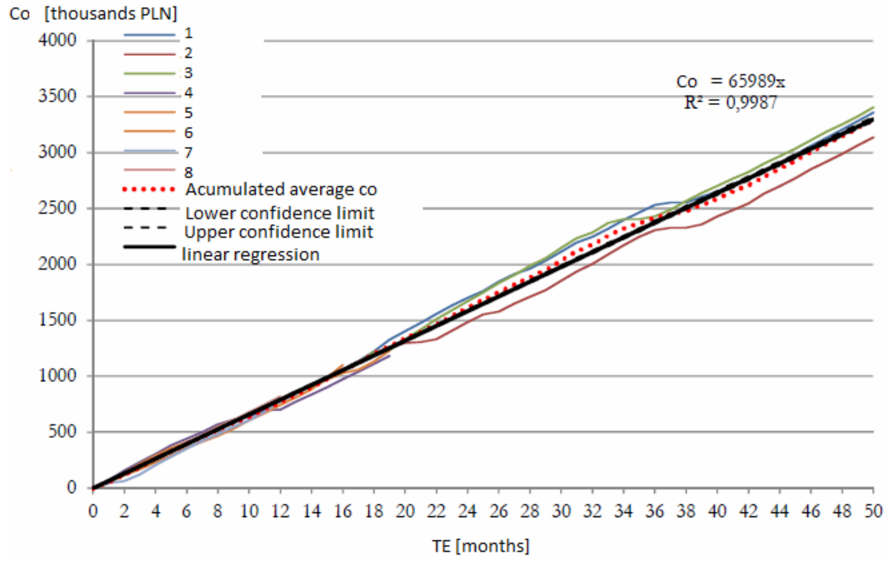

Figure 10. Operational costs of analysed rail buses [9]

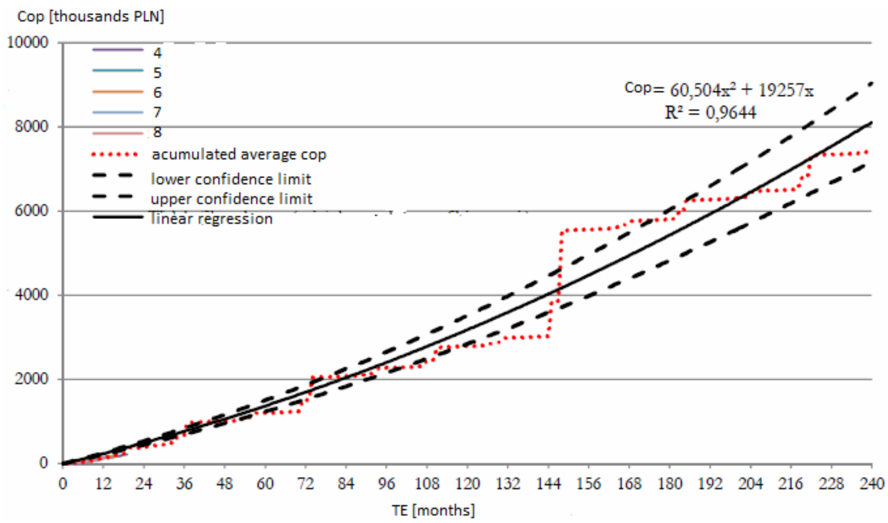

Figure 11. Preventive maintenance costs of rail buses of chosen type [9]

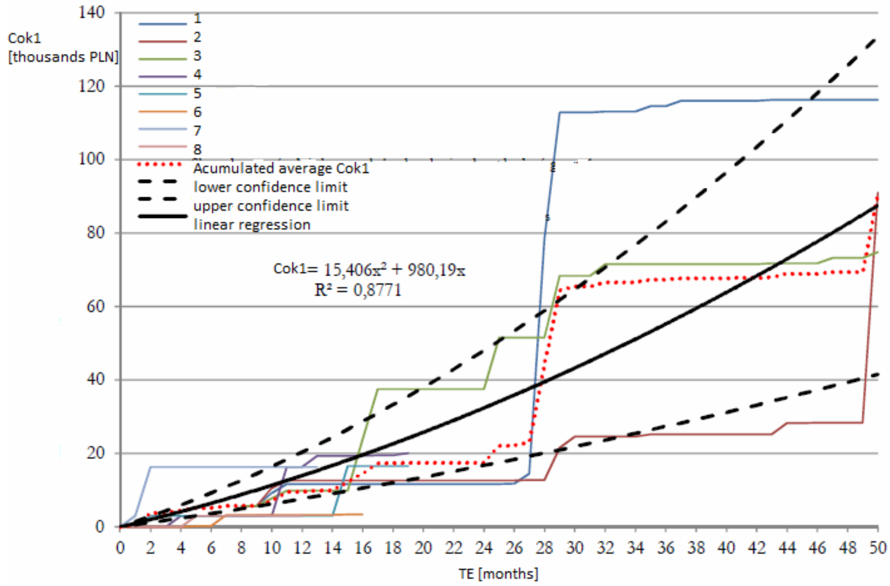

Figure 12. Corrective maintenance costs of analysed rail buses (failures group 1) [9]

Based on the obtained cost estimations, there can be the possibility to define the LCC for both types of rail buses used by regional carrier. The costs of rail buses purchase come from different moments of time. In July 2007, the first type of rail buses has been bought. The second typed rail buses have been bought in February 2010. The purchase costs of the second typed rail vehicles converted into a moment of purchase of rail buses of first type, while the calculation of future operating costs based on undiscounted cost values. Such a procedure is justified, because they were converted to the same time periods before fitting them with the line trend.

Figure 13 shows the life cycle costs for the both types of rail buses.

LCC analysis showed that the purchase of rail buses of first type is more cost effective than purchasing the second typed vehicle. Comparative chart showing the LCC of both types of rail buses is shown in *Figure 14*. The results of the study indicate that LCC of first typed vehicles is about 0,93-0,98 million PLN lower compared to the second typed buses. Despite the much higher vehicle purchase of first type of rail buses, there are achieved significant savings in the preventive maintenance costs - over 3.1 million PLN.

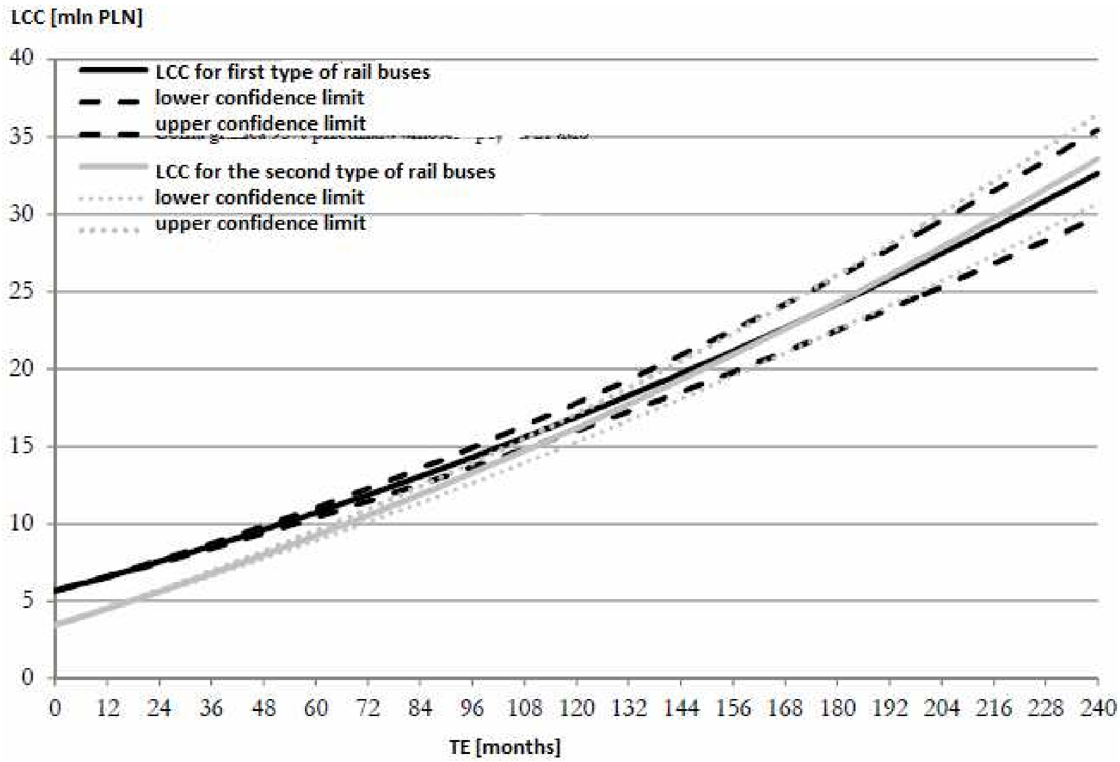

Figure 13. LCC for analysed types of rail buses [9]

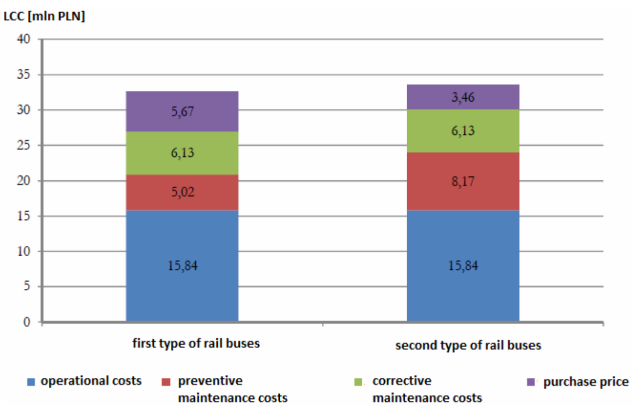

Figure 14. LCC structure for analysed types of rail buses [9]

4. Conclusion

In the available literature in the area of theory of maintenance and reliability, authors often address the question of the relationship between the reliability of an object and its economic effects, expressed in the incurred operating and maintenance costs,. However, this research analyses are rarely made from the buyer perspective. Following this, the aim of this work was to implement LCC method as a tool that supports rational purchasing/investment decision making (buyer at the time moment of technical object purchase will know what are the predicted total cost of its existence).

Based on the presented LCC analysis implementation case, it has been shown that the analysis allows for:

- estimation of operating costs of the assumed useful life of a technical object,

- comparative analysis of alternatives (variants) of purchase,
- selection of the object economically viable in terms of the lowest total costs (i.e. the total cost of purchasing and operating costs).

The presented method is the universal tool and can be used for each technical object LCC costs prediction. At the same time cost forecasts are based on models of time series with trend. Moreover, LCC regression curve depends on:

- the category of the analyzed LCC and its components,
- width of the intervals of operational time, and
- take into account changes in the value of money over time.

The development of the presented model let managers capture the time variability of technical objects life cycle cost which is connected with technical and economic parameters changes regard to technical and moral use. In the next step of authors research, there is planned investigation of railcars reliability characteristics influence on obtained level of life cycle costs.

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