Stochastic Total Cost of Ownership Forecasting for innovative Urban Transport Systems

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Abstract - **This paper presents a financial forecasting method for innovative urban transport systems. The Monte Carlo simulation accounts for future uncertainties such as technology-related and market risks. The method is based on a total cost of ownership (TCO) approach and exemplary results are shown for the introduction of an innovative electric bus system in the city of Berlin. The input parameters are stochastically modeled including future adverse events as well as favorable scenarios for the years 2013, 2020 and 2030. In contrast to determined future scenarios which provide only discrete results, the probability distribution of future system TCO is assessed. The simulation reveals when alternative technologies reach the TCO break-even. The results can be used to derive a technology roadmap. Furthermore, using a suitable visualization the decision-making process for complex investments typical for technology changes (e. g. replacement of a complete bus fleet) is supported.**

Keywords - **evaluation of innovative bus systems, forecasting method, Monte Carlo simulation, stochastic model, TCO**

I. INTRODUCTION

Driven by ecological issues such as noise exposure and emission level as well as in view of the fact that fossil fuel becomes increasingly scarce and expensive, growing efforts to become less dependent from fossil fuels are necessary. Concerning these matters, public transport authorities are considering different options to decrease the dependency on oil and to reduce emissions caused by public transport particularly in conurbations:

a. grid bound electric trams or trolley buses
b. battery-powered electric buses

Due to the lack of acceptance towards the installation of new overhead wires in city centers and limited operational flexibility, neither grid-bound tram nor grid-bound bus operations are feasible options in many cities. The achieved progress in the battery-based electromobility in recent years facilitates new options for public transport authorities to cope with the mentioned issues. Authorities around the globe are initiating electric bus trials in order to evaluate a possible substitution of deployed diesel buses. Fig. 1 shows feasible bus system options for conurbations.

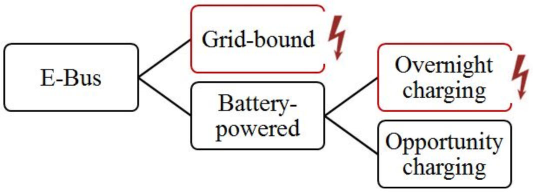

Fig. 1. Feasible electric bus systems in conurbations.

However, battery electric buses which are charged overnight (typically in the bus depot) need very large batteries which can easily add up to 5,000 kg to the curb weight. This additional mass is a “no-go criterion” for most practical applications. “Opportunity charging” during the regular operation can solve this issue but it adds extra complexity to the technology planning process.

Several research projects on electric buses with opportunity charging have been reported but commercial systems solutions are not available, yet. Battery management, battery durability and capacity as well as air-conditioning concepts and charging infrastructure have to be improved before market entry.

Additionally, bus operators and mass transit authorities are faced with high investment requirements for the deployment of electric buses. For these future investments several crucial uncertainties have to be considered which leads to a more complex decision making process. The occurrence of high investment requirements paired with future uncertainties is characteristic for innovative technologies. In the context of the electrification of urban buses the uncertainties are caused by technology-related risk such as a shortened battery lifetime causing high battery replacement costs and market uncertainties expressed by unpredictable developments of energy prices.

Nowadays, the public transport sector tends to make investment decisions based on valuation methods considering determined future scenarios without assigning a probability to the respective outcomes. The contemporary research publications reveal a lack of appropriate valuation methods acknowledging uncertainties associated with innovative electromobility technologies. This paper focus on the demonstration of a financial valuation model supporting the decision making process in context of electric urban bus systems by taking uncertainties into account. The problem of transport authorities assessing the future cost of diesel- and electric-operated buses under uncertain conditions and deriving an investment decision are addressed by this paper.

The financial model is based on a total cost of ownership model advanced by a forecasting approach applying probability distributions. On the basis of a current electric bus project in Berlin, Germany a financial forecasting is conducted for a diesel bus as well as for an electric bus system involving fast-charging technology [1]. The applied approach implies the determination of the main cost drivers featuring a relative high degree of technical and price uncertainty. Subsequently, a Monte Carlo simulation is conducted in order to assess the possible probability distribution of future TCO outcomes. The following sections outline how the application of Monte Carlo simulations benefits the technology assessment by considering uncertainties. The stochastic method is demonstrated for technology planning in the field of battery electric bus systems.

II. METHODOLOGY

For the TCO forecasting, a stochastic system simulation is employed. The basis of the system simulation is a stochastic model, which represents the system structure and stochastically modeled input parameters, representing the boundary conditions of the system.

As a first step the TCO model of diesel and electric bus systems is derived from the E-Bus project in Berlin, taking technical and price uncertainties of main cost drivers into account as seen in Fig. 2.

By modeling the system with its elements, relationships and boundaries in a system model [2], the structure of the system becomes more transparent and manageable. It allows finding interdependences, sensitivities and possible threshold values.

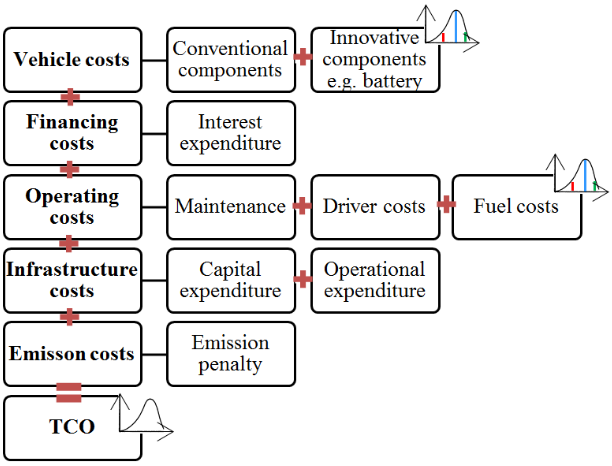

Fig. 2. Composition of the applied TCO model indicating the stochastic input parameters.

The system structure is derived from system engineering approaches such as the design structure matrix. Based on the system structure a deterministic Monte Carlo model can be defined. Input parameters are stochastically modeled variables which are driven by outside influences. The model is not static due to changing conditions and has to be updated continuously.

As a second step, three scenarios are defined, describing the input parameters of diesel and electric bus systems for a current scenario in 2013, for a possible scenario in 2020 and finally for the year 2030. The assumptions for the year 2013 and the forecasted scenarios for 2020 and 2030 are derived from the mentioned project and validated by recently published research papers [3], [4], [5], [6]. Recognizing the uncertainty within the input parameters, a price range for each input parameter is determined consisting of an optimistic (o), most likely (m) and pessimistic (p) value.

As a third step the key cost drivers, with relative high uncertainties reflected by the span of the input parameters, are identified by means of a regression analysis. It is important to state that the parameters showing a high degree of uncertainty are also main cost drivers. This circumstance underlines the necessity of assigning probabilities to possible TCO outcomes depending on the volatility of the input data. The variation of estimated parameters results from several price-affecting factors. Hence, different assumptions on production scenarios and technology readiness lead to a range of possible economies of scale and cost degressions. In particular, these technical uncertainties are in evidence considering innovative technologies such as electric bus systems. Furthermore, price uncertainties of operating cost for diesel or electricity consumption lead to forecasts with low confidence. Back-testing of oil price forecasts revealed a significant lack of accuracy [7]. In order to cope with these uncertainties the ranges of the input parameters were derived as mentioned from several different sources. The cost drivers are shown in Table I.

For modeling the input parameters, the project evaluated and review technique (PERT) [8] is used. PERT has its origin in the military network planning. The technique is widely used to plan projects under uncertainty which is typically the case in R&D programs. As an input for the PERT distribution estimations of the o, m and p-value for input parameters are carried out. With these three parameters and the factor k, which represents the weight of the most likely scenario, a beta-distribution is derived [9].

The expected mean value of the Beta-PERT distribution can be obtained from:

$$\mu = \frac{o+km+p}{k+2} \tag{1}$$

With the standard deviation of a Beta-PERT distribution:

$$\sigma = \frac{p-o}{k+2} \tag{2}$$

TABLE I
KEY COST DRIVERS WITH A HIGH DEGREE OF UNCERTAINTY

	2013			2020			2030		
	Min.	Exp.	Max.	Min.	Exp.	Max.	Min.	Exp.	Max.
Battery system 60kWh [T€]	120	140	280	60	72	144	15,5	25	50
Diesel price [€/l]*	0.90	1.10	1.30	1.07	1.37	1.73	1.20	1.68	1.90
Electricity price [€/kWh]*	0.09	0.11	0.12	0.12	0.13	0.15	0.13	0.15	0.17

*industrial prices for public transport companies in Germany

Input data can be obtained from internal or external studies, as well as subjective expert estimations.

Specialized internal or external experts with specific knowledge in a particular field (e. g. battery technology) can estimate certain input parameters even if they do not have a grasp of the entire system. This is an important enabler for an effective information search. The stochastic modeling and simulation of other key performance indicators have been described in more detail by Spangenberg and Goehlich [10].

As the fourth and final step, the TCO model including the parameter variations is employed to provide the input data for the stochastic modeling. Based on stochastic input data the stochastic distribution of the TCO is iteratively compute by the Monte Carlo simulation.

III. STOCHASTIC TCO SIMULATION FOR THE E-BUS BERLIN PROJECT

The E-Bus Berlin project is quite a representative use case for the methodology presented. The project aims to electrify a complete urban bus line in the city center of Berlin as seen in Fig. 3.

Investing in new types of vehicles is a high-risk issue for public transport authorities. On the one hand the vehicles should be compatible to existing operational procedures. On the other hand the new technology should be upscalabe to a significant share of the fleet, because diversity in a fleet leads to higher cost of maintanance and operation. Therefore a long-range technology roadmap is needed to plan vehicle investments, technologies and ressources required, based on the expected market trends. Strategic decisions in the technology roadmapping process are based on the TCO forecasts. Based on the track profile, the systems parameters like energy consumption, milage and battery size are defined.

Fig. 3. Bus transportation in Berlin city center [11].

For each of the three most uncertain factors with the highest impact on the TCO three values are defined as shown in Table I.

Electricity prices show less volatility than diesel prices due to the growing share of renewable energies in electricity generation, what makes the production cost of renewable electricity quite predictable, because of their long investment cycles and the high share of initial investment cost. Moreover, investment cost and durability of batteries are quite uncertain due to unknown developments in the battery research field. In the worst case the durability of batteries is not sufficient over the whole lifecycle, and thus causes high replacement cost. This doubles the cost of batteries, represented by twice the expected cost as a maximum value.

Based on the defined input parameters the TCOs for the different technological system alternatives are computed by a Monte Carlo simulation with 10,000 iterations using the software @Risk. The results are shown as histograms with the TCO per kilometer on the horizontal and the relative frequency on the vertical axis as seen in Fig. 4, Fig. 5, Fig. 6 and Fig. 7.

IV. RESULTS

The resulting histograms for the years 2013, 2020 and 2030 as seen in Fig. 4, Fig. 5 and Fig. 6, respectively, show that standard deviation of the TCO of the electric bus systems will decrease over the years as well as the gap to the diesel bus. This results from the decreasing battery prices, relatively stable electricity prices and rising diesel prices. One major benefit of the stochastic simulation is that allows the identification of adverse events, if all input parameters coincidentally feature unfavorable events. Although they occur rarely, they can cause serious consequences for companies and have to be taken into account.

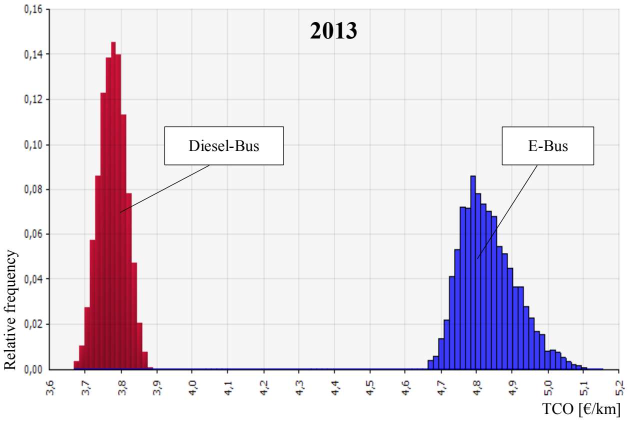

Fig. 4. TCO of diesel and electric-bus systems for the year 2013.

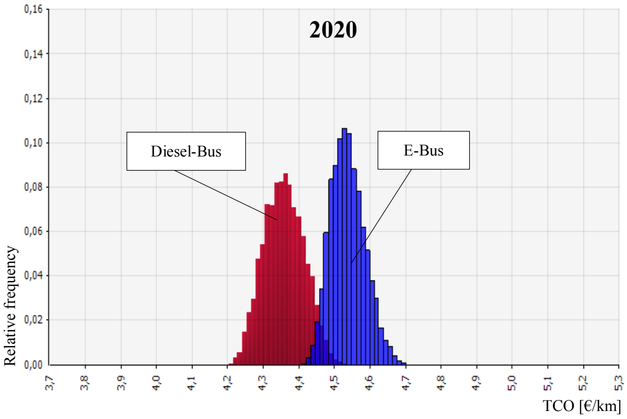

Fig. 5. TCO of diesel and electric-bus systems for the year 2020.

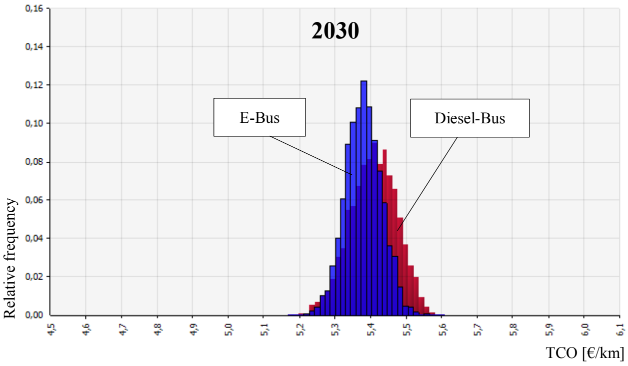

Fig. 6. TCO of diesel and electric-bus systems for the year 2013.

Furthermore the predicted TCO-Delta between the alternatives can be analyzed as shown in Fig. 7. In the year 2013 there is a financial gap of 0.99 Euro per kilometer, which is about 26%. As a result electric bus projects have to be supported by governmental grant or by company-intern cross-subsidization. The graph also shows significant potentials especially for the years from 2020 on. In the year 2030 the electric opportunity charging bus will likely be the most cost efficient alternative.

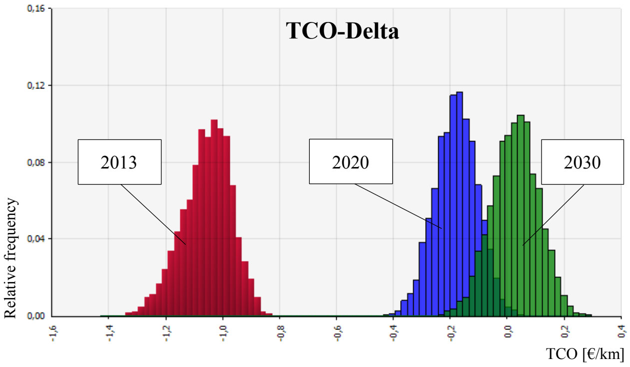

Fig. 7. TCO Delta development of an electric opportunity charging bus.

In the context of the investment cycles of circa ten years public transport authorities should include these forecast results in their technology roadmaps and should consider to introduce innovative electric buses in their fleets well enough in advance. One first step to establish electric bus technologies could be in form of pilot projects.

V. DISCUSSION

Conventional financial valuation methods of technologies are based on determined future scenarios and provide only discrete financial results. The presented approach accounts for future uncertainties such as technology-related and market risks. The stochastic simulation facilitates the valuation of complex innovative systems and provides a visualization of the outcome variation including assigned probabilities. This allows the identification of extreme TCO values if all input parameters coincidentally feature unfavorable events.

Using a suitable visualization the decision-making process is supported for complex investments which are typical for technology changes such as the replacement of conventional buses in favor of electric bus systems. Moreover, the simulation reveals when alternative technologies reach a TCO break-even.

TCO is a major decision making criterion and the results of the financial valuation can be used to derive a technology roadmap. However, supplementary approaches are required to include non-financial aspects such as social acceptance, environmental sustainability or strategic intentions such as strategic alliances which possibly also effect the final investment decision.

Applying the financial valuation method to an electric bus project in Berlin showed that electric buses can be operated without subsidies in the next decade. However, due to the long investment cycles of urban buses (typically 8-12 years) transport authorities should consider to introduce innovative electric buses in their fleets well enough in advance.

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REFERENCES

[1] D. Goehlich, F. Spangenberg, „E-Bus Berlin: Technology Planning and System Design“, in German “E-Bus Berlin: Technologieplanung und Systemauslegung,“ *10. Symposium: Hybrid- und Elektrofahrzeuge,* Braunschweig, 2013.

[2] G. Ropohl, „General Technology: A System Theory in Engineering", in German *Allgemeine Technologie: Eine Systemtheorie der Technik,* Karlsruhe: Univ.-Verlag Karlsruhe, 2009.

[3] Fuel Cells and Hydrogen Joint Undertaking (FCH JU), „Urban buses: alternative powertrains for Europe”, 2012, [Online] available at: http://www.fch-ju.eu/sites/default/files/20121029%20Urban%20buses%2C%20alternative%20powertrains%20for%20Europe%20-%20Final%20report.pdf, accessed: 25th April 2012.

[4] Boston Consulting Group (BCG), „Batteries for Electric Cars: Challenges, Opportunities, and the Outlook to 2020”, 2010, [Online] available at: http://www.bcg.com/documents/file36615.pdf, accessed: 20th April 2013.

[5] U.S. Energy Information Administration (EIA), “Annual Energy Outlook 2012”, 2012, [Online] available at: http://www.eia.gov/forecasts/aeo/, accessed: 2nd May 2013.

[6] Deutsche Energie Agentur (DENA), “Electricity prices increase by 20 procentage until 2020“, (in German), [Online] available at: http://www.dena.de/presse-medien/pressemitteilungen/dena-strompreise-steigen-bis-2020-um-20-prozent.html, accessed: 3rd May 2013.

[7] L. Tang, S. Hammoudeh, “An empirical exploration of the world oil price under the target zone model in Energy Economics,” *Energy Economics*, vol. 24, no. 6, pp. 577–596, Nov. 2002.

[8] J. D. Wiest, F. K. Levy, *A management guide to PERT/CPM: with GERT/PDM/DCPM and other networks,* Englewood Cliffs, N.J: Prentice-Hall, 1969.

[9] J. J. Moder, C. R. Phillips, *Project Management with CPM and PERT*, New York: Reinhold Industrial Engineering and Management Sciences, Reinhold Publishing Corporation, 1964.

[10] F. Spangenberg, D. Goehlich, “Technology Roadmapping based on Key Performance Indicators,” in *Proc. 23rd CIRP Design Con. - Smart Product Engineering,* Bochum, 2013.

[11] Solaris Deutschland GmbH, [Online] available at: http://old.solarisbus.pl/files/solaris_urbino_18_berlin_small.jpg, accessed: 25th May 2013.