DOCTORAL THESIS

# Traceable Temporo-Spatial Performance Measurement Concept for Network Industries

Kristjan Kuhi

TALLINNA TEHNIKAÜLIKOOL
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**Declaration:**
Hereby I declare that this doctoral thesis, my original investigation, and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Kristjan Kuhi

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# Tõestatav ja ajas ning ruumis jälgitav tulemuslikkuse mõõtmise kontseptsioon võrguettevõtetele

KRISTJAN KUHI

KIRJASTUS

# Contents

## List of Publications

The list of author's publications based on which the thesis has been prepared.

I **Kuhi, K.**; Kõrbe Kaare, K.; Koppel, O. (2015). A concept for performance measurement and evaluation in network industries. Proceedings of the Estonian Academy of Sciences, 64, 4S, 536–542.

II **Kuhi, K.**; Kõrbe Kaare, K.; Koppel, O. (2015). Using Probabilistic Models for Missing Data Prediction in Network Industries Performance Measurement Systems. Procedia Engineering, 100, 1348–1353.

III **Kuhi, K.**; Kõrbe, K.; Koppel, O.; Palu, I. (2016). Calculating power distribution system reliability indexes from Smart Meter data. Proceedings of the IEEE International Energy Conference (EnergyCon), 4-8 April 2016, Leuven, Belgium. IEEE, 1–5.

IV **Kuhi, K.**; Kaare, K.; Koppel, O. (2018). Ensuring Performance Measurement Integrity in Logistics Using Blockchain. Proceedings of the 2018 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI 2018): 31 July - 2 August 2018, Singapore. IEEE, 260−265.

Copies of the publications constituting the thesis are included in the appendix and marked in Roman numbers as presented above.

**Other related publications**

V Kõrbe Kaare, K.; Koppel, O.; **Kuhi, K.** (2012). Wireless sensing in road structures using passive RFID tags. Estonian Journal of Engineering, 18 (4), 314−323.

VI Kaare, K. K.; Koppel, O.; **Kuhi, K.** (2013). Use of smartphone accelerometers for winter road maintenance improvement in urban areas. In: C. A. Brebbia (Ed.). Urban Transport XIX (253−263). Wessex Institute of Techonology Press. (WIT Transactions on The Built Environment, 130).

VII Kõrbe Kaare, K.; **Kuhi, K.**; Koppel, O. (2012). Tire and pavement wear interaction monitoring for road performance indicators. Estonian Journal of Engineering, 18 (4), 324−335.

VIII **Kuhi, K.**; Kõrbe Kaare, K.; Koppel, O. (2014). Performance measurement in network industries: example of power distribution and road networks. Proceedings of 9th International Conference of DAAAM Baltic Industrial Engineering, 24–26 April 2014, Tallinn, Estonia: Ed. Otto, T. Tallinn: Tallinn University of Technology, 115−120.

## Author’s Contribution to the Publications

Contribution to the papers in this thesis are:

I Main author. I have composed the paper. Participated in literature review and case studies. Performed the system architecture design.

II Main author of the paper. I have composed the paper. Participated in literature review and analysis. I have modelled the Dynamic Bayesian Network.

III Main author of the paper. I have composed the paper. Participated in literature review, research design and performed the study. I have implemented the case study. I have presented the paper on IEEE International Energy Conference (EnergyCon), 4-8 April 2016 in Leuven, Belgium.

IV Main author of the paper. I have composed the paper. Reviewed the literature, designed the research, and performed the study. I have presented the paper on IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI 2018): 31 July - 2 August 2018 in Singapore.

# Introduction

Network industries play an important role in society and economic development. According to latest statistics, network industries directly accounted for 15% of the value added in the EU28 countries (Eurostat, 2021). Network industries directly influence the competitiveness and sustainability of society, and they provide important inputs to all sectors of the economy. Regulatory reforms in network industries aim to address social, economic, environmental, and institutional issues in addition to economic efficiency (Uukkivi, 2021). Well-designed and trustworthy performance-measurement systems for network industries give to the organizations and regulating bodies vital information and feedback about the impact of their decisions. As the source of information for governments and regulators, therefore, such performance-measurement systems have a wide impact.

Data are elemental to decision-making and accountability. Advances in information and communication technology (ICT) have made it possible to collect data through the deployment of large sensor networks or crowd-sourcing mechanisms. The collected data are beneficial only when protected from manipulations and actually used. The explosive growth of real-time sensor data requires new data-handling capabilities and architectures to process the collected data into useful traceable structured information for unbiased and transparent managerial decisions and policymaking. In the modern information society, a transparent and traceable performance-measurement system is a prerequisite for the fulfilment of the goals of organizations, regulatory bodies, and society (Gebczynska & Brajer-Marczak, 2020).

The field of performance measurement has evolved enormously in the last two decades (Lance Jacob, 2021). The development from accounting-based measurement to data-driven and objective-driven approaches has brought tremendous value through greater visibility to businesses and society. However, the current performance-measurement methods used in network industries lack temporo-spatial transparency and traceability. Current measurement architectures cannot cope with large amounts of spatial and sensor data. Moreover, it is difficult to gauge the trustworthiness of the calculated performance indicators and future predictions. The possibility of simplifying and harmonizing performance measurement across network industries has not been extensively studied.

The main objective of this thesis is to examine the similarities of performance-measurement methodologies in different network industries with the aim of proposing a harmonized trusted system for performance measurement across industries. Such a system would enable the optimized planning and operation of networks using large amounts of sensor data. The thesis investigates the different aspects of the problem and examines several industries as case studies. In addition, a proof-of-concept is developed and successfully deployed in one of the major electricity network operators in Estonia. The thesis also explores some key technical enablers, such as models for performance prediction to assist machine-aided decision-making and the role of blockchain in performance-measurement architecture as a mechanism to provide trust and validity of the indicators.

This research contributes concepts, techniques, and architecture for harmonized and validated performance measurement across network industries. The methods for collecting and analyzing data depend on the research task. In this research, mixed methods including observations, literature review, case studies, and a proof-of-concept were used to test the proposed architecture. The datasets for the two case studies contained sensor information from a power-distribution network and a logistics network.

The theoretical and practical novelty of the thesis is the following. Unifying and combining network industries performance indicators into a common framework was verified and presented. Reference architecture for performance measurement based on sensor and spatial data was suggested. An approach was proposed to predict missing values in time series and detect anomalies using Dynamic Bayesian network (DBN). A solution for traceable performance measurement data and calculations based on blockchain was recommended.

The results of the research were disseminated via scientific publications and conferences. During my Ph.D. studies, I contributed to 10 publications related to the research of performance-measurement systems for network industries. Three papers (I, V, VII) were published in peer-reviewed journals; the others were published in international peer-reviewed conference proceedings. This thesis is based on four publications (I–IV) attached to this work.

# Abbreviations

| | |
|---|---|
| AI | Artificial intelligence |
| ASAI | Average Service Availability Index |
| BFT | Byzantine fault tolerance |
| BN | Bayesian network |
| BSC | Balanced scorecard |
| CAIDI | Customer Average Interruption Duration Index |
| CAIFI | Customer Average Interruption Frequency Index |
| CEER | Council of European Energy Regulators |
| CIC/kWh | Customer interruption cost per kWh |
| COST | European Cooperation in Science and Technology |
| CPI | Combined performance indicator |
| DBN | Dynamic Bayesian network |
| EM | Expectation maximization |
| EN | European norm |
| EPRI | Electric Power Research Institute |
| ETH | Ethereum |
| EU | European Union |
| EU28 | Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, United Kingdom |
| EVITA | European Vehicle Infrastructure Transportation Alliance |
| GHG | Greenhouse gas |
| GIS | Geographic information system |
| GPI | General (or generic) performance indicator |
| ICT | Information and communication technology |
| IEEE | Institute of Electrical and Electronics Engineers |
| IoT | Internet of Things |
| KPI | Key performance indicator |
| LSTM | Long short-term memory |
| LV | Low voltage |
| MAP | Maximum *a posteriori* |
| MCMC | Markov chain Monte Carlo |
| MDCS | Meter data collection system |
| ML | Maximum likelihood |
| MLP | Multi-layer perceptron |
| NTP | Network Time Protocol |
| PI | Performance indicator |

| | |
|---|---|
| PMS | Performance measurement system |
| PQ | Power quality |
| PRIME | Platform of Rail Infrastructure Managers in Europe |
| RFID | Radio-frequency identification |
| RNN | Recurrent neural network |
| SAIDI | System Average Interruption Duration Index |
| SAIFI | System Average Interruption Frequency Index |
| SCOR | Supply-chain operations reference model |
| SmartLog | Smart Logistics and Freight Villages Initiative |
| TEN-T | Trans-European Transport Network |
| TP | Technical parameter |
| UML | Unified Modeling Language |
| VEE | Validation, estimation, and manual entry |

# 1 State of the art

This chapter introduces the theoretical and conceptual framework required to understand this research. The framework is based on the most recent literature. The chapter is divided into five sections. The first section sets out the research problem and objectives. The following four sections present literature reviews for network industries, performance measurement, prediction models, and blockchain. The final section summarizes the conclusions and states the main research questions.

## 1.1 Research problem and objectives

The current performance-measurement methods used in network industries lack temporo-spatial transparency and traceability. Current measurement architectures cannot cope with large amounts of spatial and sensor data. It is difficult to gauge the trustworthiness of the calculated performance indicators (PIs) and future predictions. The possibility of simplifying and harmonizing performance measurement across network industries has not been extensively studied.

The main objective of this thesis is to examine the similarities of performance-measurement methodologies in different network industries with the aim of proposing a harmonized trusted system for performance measurement across industries. Such a system will enable optimized planning and operation of the networks using large amounts of sensor data.

Network industries are economically important. Other industries interact with network industries, making their performance a vital matter. Improving the efficiency of network industries will improve resource use and increase the value added. In addition, transport and energy are among the main contributors to oil dependency and greenhouse gas emissions (Maincent et al., 2013). The European Union (EU) Green Deal (EC, 2019), Circular Economy Action Plan (EC, 2020), and Clean Energy Package (EU, 2019) all address and affect network industries. Greater efficiency in these sectors translates into lower emissions and greater sustainability and climate change mitigation.

A heterogeneous implementation of performance measurement in network industries will lead to efficiencies in terms of infrastructure interconnection, planning, operation, and the variety of services offered by operators. For these reasons, it is important to examine the harmonized performance measurement of these industries, as the impact of any incorrect conclusions can go beyond these sectors and negatively affect the wider economy, including competitiveness and growth.

The latest developments in the ICT sector, such as big data and analytics in conjunction with novel human-computer interaction design patterns, pave the way to measure all important performance parameters, radically improve the understanding of the problem domain, and translate that knowledge into management decisions (Ethirajan et al., 2020). These developments are key enablers for harmonized performance measurement based on vast amounts of collected (sensor) data.

As the system grows, it becomes necessary to use prediction models to fill gaps in the data, and the trustworthiness of prediction becomes more important. Decisions affect greater areas, and wrong decisions, based on erroneous data, may lead to unplanned and unnecessary expenditure. Accurate performance prediction with indication of its trustworthiness is important in networked industries.

Also important is the integrity of the data used in the PI calculations. It is important to ensure that manipulations of base datasets are impossible so that the calculated indicators are immutable. The trustworthiness of the base dataset defines the decision quality.

With the discussion above in mind, the following research tasks were developed:

1) Investigate similarities in performance-measurement methodologies for network industries and evaluate the possibility of harmonizing methodologies.
2) Propose a performance-measurement system architecture that can process large amounts of sensor information for network industries.
3) Conduct cases studies on selected industries to test the proposed methodology and system architecture.
4) Evaluate the suitability of a DBN for PI predictions in network industries.
5) Propose a solution for a traceable performance-measurement system.

The following sections describe the main underlying concepts of the theoretical framework of this research. Section 1.6 will summarize the main identified research questions.

## 1.2 Network industries

Network industries have evolved over the past 100 years. Depending on the approach, various definitions and interpretations can be found in the literature. Network industries can be defined as entities whose institutions or their products consist of many interconnected nodes and where the connections among the nodes define the character of commerce in the industry (Gottinger, 2003). The term *network industries* has also been used in social sciences (i.e., economy and regulation). It is appropriate to use the term in the framework of this thesis to denote the industries that have a significant impact on the welfare of societies and that are planned and operated on similar basis. Network industries provide a foundation for a society's economic performance and well-being. Figure 1 gives some examples of the most well-known network industries.

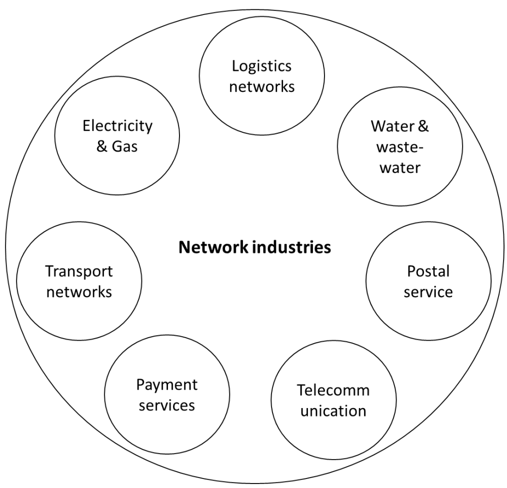


*Figure 1 Examples of network industries*

Network industries can be distinguished from other industries such as agriculture, finance, and retail by the following characteristics:

- complementarity, compatibility, and standards,
- consumption externalities (network effects),
- switching costs and lock-in,
- significant economies of scale in production (Shy, 2001).

Network industries play a key role in society from an economic and social perspective. Reforms were started a few decades ago, in 1970s (Fiorio & Florio, 2009), to modify and optimize network industries. The process was accelerated during the 1990s due to EU stimulus and later became part of the Lisbon strategy. The protected and vertically integrated national monopolies were reformed into free market entities that are open to international competition. Significant elements of the reform were vertical separation of the integrated supply chains and the retaining of control and regulation in the segments where the monopoly should remain. In many cases, monopolistic public companies were privatized. The objective of the reform was to improve the overall performance of network industries (Bogaert, 2006).

The new data layer on top of infrastructures and services improves the management efficiency of the networks. The management and data models of those industries need to be harmonized so that efficiencies can be found in planning and operational processes. The planning and operational processes share many similarities. In the past 10–15 years, intense technological transformation caused by advancing digitalization has transformed the operations of these traditional network industries and will continue to transform them for another 10–15 years if disruptive business models for managing those networks do not appear on the market.

The same force – the 4th industrial revolution and ICT development – has brought new players into the market that have disrupted other service industries. They are a new type of network industry, namely digital platforms (e.g., Amazon, Facebook, Bolt). Montero & Finger (2018) have described that a new type of social organization model is emerging in the form of digital platforms and it is causing disruption in traditional network managers as their infrastructures and services become intermediated by digital platforms. This situation is creating more powerful network effects by coordinating previously fragmented or isolated infrastructures and services. Digital platforms present the transformative characteristics of network industries: network effects, efficiency, scale, concentration, market power, to name a few.

In most societies in 2021, there are still examples of siloed planning and operation of networks. This results in inefficiencies and emotional and economic burdens on the public and governments. The removal of cost inefficiency is important to guarantee that network industries deliver services in a socially optimal way (Gillies-Smith & Wheat, 2016).

This thesis examines in detail the following network industries:

- road networks (Kaare, 2013),
- energy networks (section 2.5.1),
- logistics networks (section 2.5.2), and
- communications networks (section 3.1).

These networks were selected due to their overall contribution to the economy (Eurostat, 2021) and the availability of data for the case studies. Other networks were considered, but the deployment of sensor networks or data collection methods were not adequate. The case studies of energy and logistics networks are presented in section 2.5. The idea to perform further research on network industries emerged from Kaare (2013), who analyzed performance-measurement models of road networks.

## 1.3 Performance measurement

The field of performance measurement has evolved enormously in the last two decades. The development from accounting-based measurement to data-driven and objective-driven measurement has brought tremendous value through higher visibility to businesses and society (Figure 2). Both advancing ICT and the development of new measurement frameworks and methodologies – such as the balanced scorecard (BSC), the performance prism, economic value added, economic profit, activity-based costing, and self-assessment techniques – have enhanced performance measurement models (Neely et al., 2011; Kamble & Gunasekaran, 2020). The next innovations in sensor technology, big data, crowdsourcing, blockchain technology and machine learning will begin a new generation of performance measurement approaches.

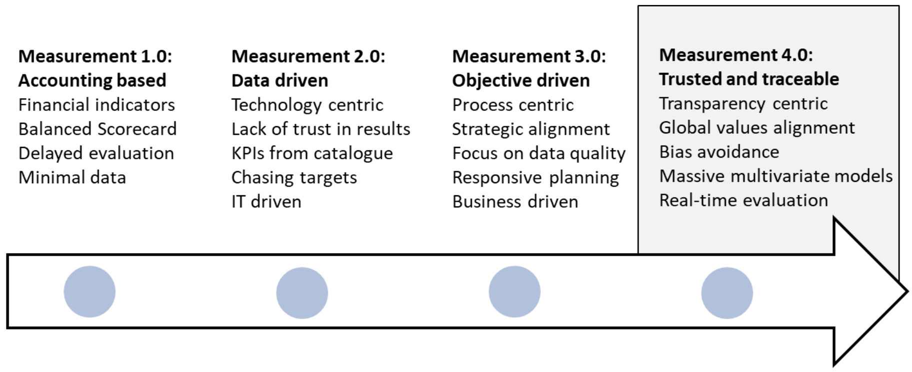


*Figure 2 Evolution of performance measurement*
*Source: author's adaptation from (Lance Jacob, 2021)*

According to the literature, performance measurement is valuable when it corresponds to the organization's environment. The ability to apply performance measurement effectively depends on the organization's ability to apply theoretical methods into practices, incorporate information into the decision-making process, and improve processes according to changing external conditions and internal potential (Fukushima & Pierce, 2011; Mathur et al., 2011; Kloviene & Valanciene, 2013).

The PI is a management tool that allows multiple sets of data to be compiled into an overall measure. Key performance indicators (KPIs) provide information to stakeholders about how well the services are being provided. Performance indicators should reflect not only the concerns of the system owner or operator, but also the satisfaction of the users. Combining data into indicators is necessary to simultaneously present information from several related areas and data sources. This process provides a statistical measure that describes the change of performance over time (Oswald et al., 2011).

The terms "performance measurement," "monitoring," and "management" are often defined and interpreted differently. Figure 3 shows a performance-measurement system used for performance management, monitoring, evaluation, and ICT operations management. In this study, performance monitoring is understood as a process, based on continuous performance measurement, industry standards, and technology advancements, that will bring improvements in behavior, motivation, and other processes.

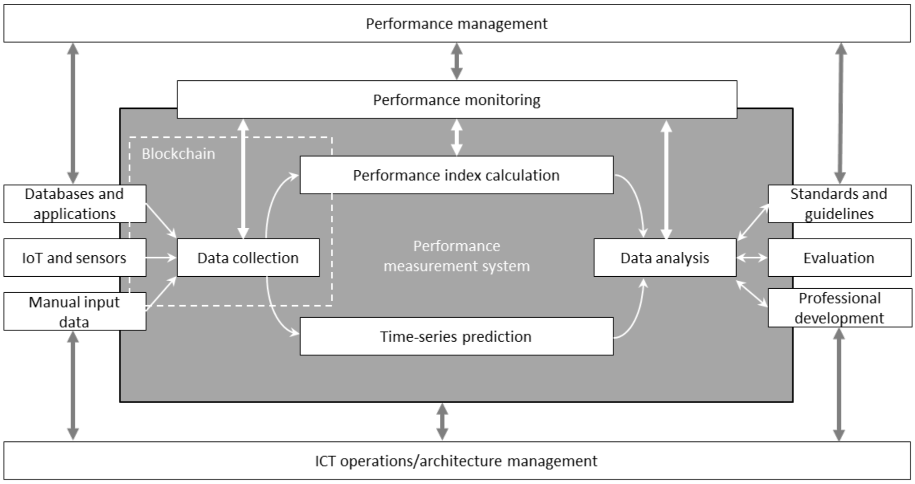


*Figure 3 Performance measurement, monitoring, and management*
*Source: author's adaptation from (Hagerty & Hofman, 2006)*

Performance measurement is the use of statistical evidence to determine progress toward specific defined social or organizational objectives (I). Organizations can choose how they implement performance measurement. Some larger organizations have implemented performance measurement differently for separate organizational units to evaluate financial, production, and service-quality dimensions (Verhaelen et al., 2021). A performance-measurement system must support defining and optimally clustering PIs across appropriate dimensions for each organizational unit and user group. In this work, performance measurement is seen as the fourth-generation concept, according to the description shown on Figure 2, broader than the traditional accounting-based approach.

## 1.4 Time-series prediction

In dealing with human or sensor measurements, some measurements may disappear due to human error, faults in the communication network, problems in the data collection system, or the defective state of the sensor itself. A more serious issue might be the collection of false measurements. Missing or faulty data can be avoided by creating a measurement system with a more robust and resilient design. Often the economic cost of a robust system is not feasible, however, and missing or incorrect data must be handled. Most large-scale sensor networks (e.g., smart meter networks, road sensors, container trackers), where many sensors are deployed across the network infrastructure, share the property of not being designed to be robust and resilient.

Although algorithms and machine learning techniques should be designed to eliminate bias, they are created by humans and are thus susceptible to algorithmic bias (Baer, 2019). The input data validation and missing values prediction are key for correct verdicts and conclusions (Main & Chen, 2019). One example of the Internet of Things (IoT) and sensor deployment is electricity or water smart meter networks. The best practice architecture for such systems is split into two parts: data collection and data management. Data management implements the VEE (validation, estimation, and manual entry) pattern. The validation function checks the anomalies in the time-series data using simple or complex new algorithms. The estimation function interpolates missing values to fill the gaps and predicts future values. Manual entry provides the ability to insert and adjust the values. In this way, the time series are kept meaningful and provide an adequate base for decision-making.

It is important to distinguish the impact of erroneous or missing data on operational decisions based on historical time-series data and preventive or predictive actions based on time-series data that are estimated (or extrapolated) from historical time-series data. While missing or incorrect values in historical data increase the uncertainty of the decisions linearly, the estimation error might be logarithmical or even polynomial. The error in both categories must be reduced by filling the gaps (interpolating) of missing or erroneous data and predicting what is imminent by using historical time series and extrapolating into the future.

Predictive modeling is the practice of applying known measurements to generate, process, and validate a model to forecast future outcomes (Scheinost et al., 2019). By analyzing historical time series and events, one can use predictive modeling to increase the probability of forecasting events and the behavior of single or aggregated PIs.

The performance of a system is often uncertain because the observations of the system's features are a) partial, b) noisy, or c) insignificant features are observed given the exact time moment. When using deterministic models, the uncertainty of the system's state is not apparent, and so applying deterministic models is more likely to give a false diagnosis (II). In addition to missing data, anomalies in time-series arrays my occur. It is as important to detect erroneous data as it is to detect missing data. Figure 4 portrays the time-series concepts, such as anomaly, missing data, and prediction.

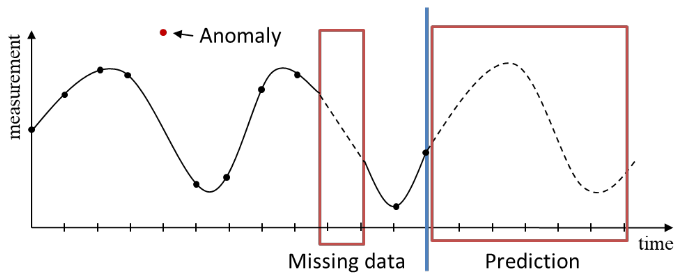


*Figure 4 Time-series terminology: anomaly, missing data, and prediction*

Work on time-series prediction models has been ongoing since the 1940s. Many variations of different methods have been published that are superior to one another in different respects. Many papers have proposed new machine learning algorithms, suggesting methodological advances and improvements in accuracy. Limited objective evidence is available, however, regarding their performance relative to a standard forecasting tool (Makridakis et al., 2018). There are many ways to cluster and systemize the different methods and their benefits and risks. This task will not be attempted in this work, however, as it is more suitable for statisticians. The studies of Little & Rubin (2002), Koller & Friedman (2009) and Goodfellow et al. (2016) provide many insights into what to do when some of the data in time-series are missing. This thesis examines three major groups of time-series prediction models:

- Classical linear methods; for example, autoregression and moving average combinations and variances for single or multiple imputation models, exponential smoothing variations (Little & Rubin, 2002).

- Deep learning methods; for example, recurrent neural networks, multi-layer perceptron, long short-term memory (Goodfellow et al., 2016; Chen et al., 2021; Popa et al., 2021).
- Graphical probabilistic methods; for example, DBN with maximum likelihood, maximum *a posteriori*, or Markov chain Monte Carlo estimates (Koller & Friedman, 2009; Särkkä, 2013; Rabbi et al., 2020).

Classical linear methods focused on linear relationships are mature and perform well on an extensive range of challenges, assuming that the data are well prepared and the method is suitably configured. The downside of using classical methods in the application proposed in this work is that it would be necessary to understand the aggregated standard error impact on the estimates, making the application difficult to use for decision-making.

The same criticism is valid for deep learning methods. Even with a perfect estimation result, understanding the reliability of the prediction is equally important to performance measurement-based decision making. In addition to point forecasts, deep learning methods must also be capable of specifying the uncertainty around them or providing confidence intervals. At present, the issue of uncertainty has not been included in the research agenda of the deep learning field, leaving a void that must be filled, as estimating the uncertainty in future predictions is as important as the forecasts themselves. To overcome this issue, many researchers have proposed simulating the intervals by iteratively generating multiple future sample paths. Even in that case, however, the forecast distribution of the methods is empirically, not analytically, derived, raising doubts about its quality (Makridakis et al., 2018).

Another aspect, relevant to the DBN approach, is the ability to include expert knowledge recorded into domain performance models in the form of a bi-directional dependency graph (I). In this approach, it is not necessary to create large training datasets, needed for deep learning methods, before seeing meaningful results. The DBN inference algorithms can be used to execute queries over the belief network to predict the state of the variables or detect anomalies (Koller & Friedman, 2009). Knowledge-based model construction is the most efficient way to achieve data-supported business decisions in the absence of large sets of historical data.

It is often not practical to build robust large-scale sensor-data collection systems; however, informed data-based business decisions must be made to provide best value to society while managing or regulating network industries. Missing or erroneous data without proper estimation of sample data variabilitymay cause biased decisions (Wainer, 2007). There are many methods available to predict missing data. It is important to consider the domain expert knowledge when building the prediction models, and the chosen algorithms must be capable of providing confidence likelihoods or intervals around the predicted point values. For this thesis, the DBN was chosen as an interesting candidate for performance-indicator predictions.

## 1.5 Blockchain

Blockchains are immutable digital ledger systems (Yaga et al., 2018). They evolved from distributed hash chains. In this context, “distributed” means that there is no central authority to control the manipulation of data. If the community that hosts the network nodes grows, the likelihood diminishes that one party gains control over the data stored across all nodes. This mechanism enables the users to record transactions in a public ledger that is visible, immutable, and trusted by all parties.

In 2008, the blockchain idea was combined in an innovative way with several other technologies and computing concepts to enable the creation of modern cryptocurrencies: electronic money protected through cryptographic mechanisms instead of a central repository. The first such blockchain-based approach was Bitcoin (Nakamoto, 2009). Electronic money made the blockchain ecosystems popular and, to some extent, are believed to solve more problems than they were built to solve.

The concept of electronic money introduced into the blockchain architecture a harmonized identity-management approach called wallets. A wallet is a hardware device or piece of software that can, in conjunction with cryptographic protocols, be used to securely identify the transaction parties and make transactions using assets associated with the wallet identifier. Attempts have been made to connect wallets to authorized-user identity verification and signature services so that users are not anonymous, but the user's identity associates to their blockchain wallet to allow asset transfers to take place only with legally valid identity-based signatures of the approver and the user (Tsõganov, 2019).

The cryptographic keys associated with wallets are used to sign transactions. The ledger records the transaction publicly, allowing all parties on the network to verify and validate the transaction. The nodes must agree that the transaction is valid. In place of a central authority, blockchain uses a consensus mechanism to reconcile discrepancies between nodes in a distributed application (Agbo et al., 2019). The parties keep a full record of all transactions in their blockchain network nodes to make it resilient to attempts to forge transactions.

Although blockchain has only recently become a popular technology, Estonia has been testing the technology since 2008. Since 2012, blockchain has been in use in Estonia's data registries, including the national health, judicial, legislative, security and commercial code systems, and there are plans to extend its use to spheres such as personal medicine, cybersecurity, and data embassies (EAS, 2020).

While the first-generation blockchains guaranteed immutable event sequences (Figure 5), and the second-generation added distributed trust architecture, the third generation introduced the ability to store executable trusted and immutable program code in the same chain. This technology is called *smart contract* (or in some cases *chain code*). It enables automation to be built around the immutable distributed transaction management system. Although not represented in every blockchain, smart contracts are the most interesting add-on to the ecosystem, allowing digitalization and accounting of fungible and non-fungible real-world assets and transactions using those assets. At the same time, the distributed ledger keeps a log of all the exchanges in a secure and immutable way (Tijan et al., 2019).

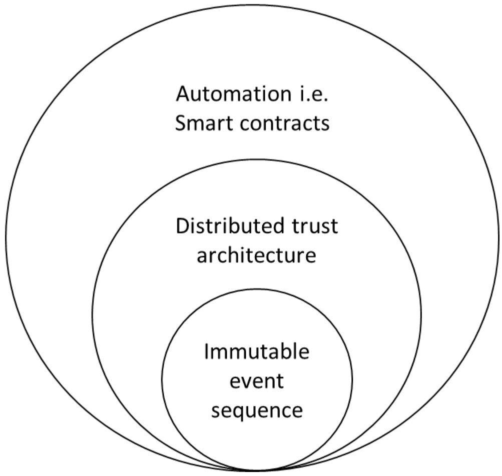


*Figure 5 Evolution of blockchain features*

As a side note, "immutability" in this context means that blockchains are tamper-resistant and tamper-evident. They cannot be considered completely immutable, however, because there are situations in which the blockchain can be modified (Yaga et al., 2018); for example, in smaller networks and private networks where the network governance is not properly implemented (Sayeed & Marco-Gisbert, 2019). Attacks may be successful when a transaction is not yet committed or is one of the last committed blocks to the chain. Moreover, it is important to mention that easiest form of attack is to tamper with the edges of the blockchain network. Oracles – agents that fetch information from the external world – can be compromised when special care is not taken to guarantee the trust of the process (Lo et al., 2020). A blockchain network is only as strong as the aggregate of all the existing nodes participating in the network. If all the nodes share similar hardware, software, geographic location, and messaging scheme, then the risk of undiscovered security vulnerabilities is greater than in more diverse networks (Yaga et al., 2018).

This thesis does not provide in-depth descriptions and comparisons of blockchain technology. Numerous research papers have focused on blockchain variations, conceptual descriptions, and technical details (Figure 6). Systematic technology overviews can be found in Yaga et al. (2018), Agbo et al. (2019) and Tsõganov (2019). The present work attempts to answer the following question: Where the blockchain might be useful in performance measurement for network industries, what are the important properties to keep in mind and which network is most suitable for such an application?

The key feature used to categorize blockchain networks is permissions; that is, whether the network is permissioned or permission-less. This feature defines who maintains control of the blockchain nodes. If anyone can publish a new block in the chain, the blockchain is permission-less; if only particular users can publish blocks, it is permissioned. In simple terms, a permissioned blockchain network is like a corporate intranet that is controlled, whereas a permission-less blockchain network is like the public internet, where anyone can participate (Yaga et al., 2018). Permissioned blockchain networks are usually governed by consortiums of individuals or organizations.

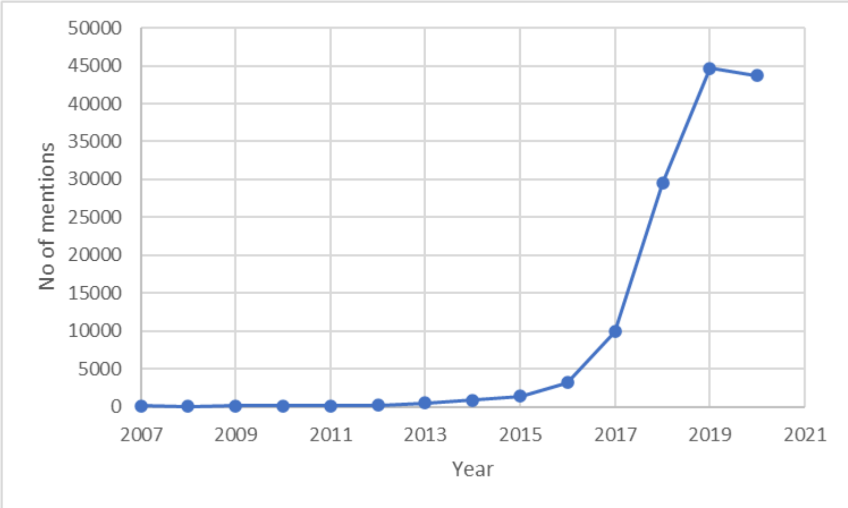


*Figure 6 Occurrences of the word "Blockchain" in scientific research papers (2007-2020)*
*Source: author, based on Google Scholar statistics*

The other important features that must be considered during system design and the technology-feasibility check are decentralization, data security and privacy, data ownership, availability and robustness, transparency and trust, and data verifiability (Agbo et al., 2019). For this thesis, the most important properties are data integrity, the traceability of calculations, and auditability.

Blockchain technology takes existing, proven concepts and merges them into a single ecosystem (Andoni et al., 2019). When applied with care and knowledge, blockchains can make it cost-efficient to solve large problems that it was previously not economically feasible to solve (Du et al., 2020). In most types of deployments, including the application in this work, only permission-less public blockchains with reasonable network sizes (or private chains with combinations of such networks) are serious candidates for implementation. Such networks are the only way to guarantee immutability, security, availability, and verifiability, leading to transparency and trust.

## 1.6 Research questions

The following initial conclusions can be drawn from this chapter. Performance should not only be measurable, but also fully traceable and auditable, particularly for network industries. Missing or erroneous data may cause biased decisions. Many methods are available to predict missing data. It is important to consider the domain expert knowledge when building the prediction models, and the chosen algorithms must be capable of providing confidence likelihoods or intervals around the predicted point values. When applied with care and knowledge, blockchains can bring trust, traceability, and cost-efficiency into the solutions for large problems that were previously not economically feasible to solve.

The following research questions were formulated:

1. How can a harmonized architecture for the performance measurement of network industries be created?

2. What methods should be used to fill the gaps in data and predict the near-future state of the system with probability estimates?
3. How can the traceability and trust of the measurement system be guaranteed?

Chapter 2 describes the research methodology used to answer these research questions.

# 2 Research design

This chapter describes the methodology used in this research. It is divided into five main parts. Section 2.1 outlines the research strategy and explains the high-level methods to accomplish each task. Sections 2.2 to 2.4 cover the detailed work methods. Section 2.5 explains how the case studies were carried out.

## 2.1 Research strategy

This section outlines the research procedure. The applied inductive research aims to contribute with concepts, techniques, and architecture for harmonized validated across network industries performance measurement. The methods for collecting and analyzing data depend on the publication. The research uses mixed methods such as experiments and observations, literature review, case studies, and a proof-of-concept implementation to test the proposed architecture in a real-life setting. The research question, tasks, and publication mapping are shown in Table 1.

*Table 1 Research question mapping to task, chapter, and publication*

<table>
<tr><td colspan="4">Problem: The current performance-measurement methods used in network industries lack temporo-spatial transparency and traceability. Measurement architectures cannot cope with large amounts of spatial and sensor data. It is difficult to gauge the trustworthiness of the calculated performance indicators and future predictions. The possibility of simplifying and harmonizing performance measurement across network industries has not been extensively studied.</td></tr>
<tr><td colspan="4">Hypothesis: It is possible to create a system for performance measurement in network industries that can provide transparency and traceability of performance indicators across location and time.</td></tr>
<tr><td colspan="4">Objective: To examine the similarities of performance-measurement methodologies in different network industries with the aim of proposing a harmonized trusted system for performance measurement across industries, enabling optimized planning and operation of the networks using large amounts of sensor data.</td></tr>
<tr><th>Research question</th><th>Research task</th><th>Section</th><th>Publication</th></tr>
<tr><td rowspan="3">How can a harmonized architecture for the performance measurement of network industries be created?</td><td>Investigate similarities in performance-measurement methodologies for network industries and evaluate possibility of harmonizing methodologies</td><td>2.2, 3.1</td><td>I, VIII</td></tr>
<tr><td>Propose performance-measurement system architecture for network industries</td><td>3.2–3.4</td><td>I, VIII</td></tr>
<tr><td>Conduct case studies on selected industries to test proposed methodology and system architecture</td><td>2.5, 3.1</td><td>I, III - VIII</td></tr>
</table>

*Table 1 (cont.)*

| Research question | Research task | Section | Publication |
|---|---|---|---|
| What methods to use to fill in the gaps in data and predict near future state of the system with probability estimates on? | Evaluate DBN model suitability for predictions of performance indicators in network industries. | 2.3, 3.2 | II |
| How can the traceability and trust of the measurement system be guaranteed? | Propose solution for validated performance-measurement system | 2.4, 3.4 | IV |

*Source: author*

For concept and system modeling, the Unified Modelling Language (UML) was used. UML is a graphical language for visualizing, specifying, constructing, and documenting the artifacts of a software-intensive system. It was adopted as a standard by the Object Management Group and serves as the standard language for defining software architectures (Booch, 1999). In this work, it was used to capture complex relations in functionality, domain, and components of the performance-measurement architecture.

This research was inspired by the previous work carried out by the Tallinn University of Technology research group on performance measurement for road networks (Kaare, 2013; V-VIII) and on extensive TM Forum work on telecommunication operations support systems information framework modelling (TM Forum, 2015), especially the performance measurement parts of that work.

The structure of the research is illustrated in Figure 7. During the first phase of the study, the high-level purpose of the research was defined. This was followed by the literature review, introduction of the theory, and definition of concepts. The research gaps were identified, research questions and objectives mapped out, and tasks defined. Gap analysis is a process that compares the state-of-the-art practice with the desired state. The method provides a way to identify suboptimal or missing capabilities, practices, and technologies and then recommend steps that will help to meet the research goals.

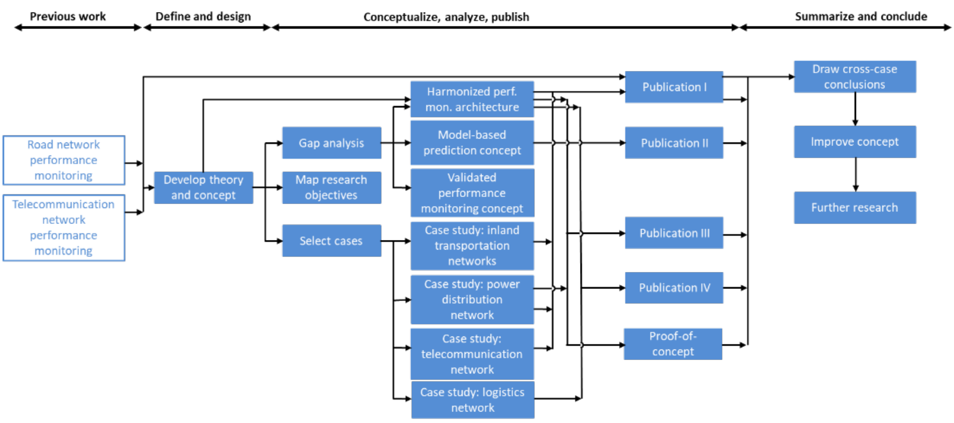


*Figure 7 Structure of the research*

To validate the most critical aspects of the architecture, a multiple case study was conducted. According to (Yin, 2014), a case study should be considered when: (a) the focus of the study is to answer "how" and "why" questions; (b) the researcher cannot manipulate the behavior of those involved in the study; (c) the researcher wants to cover contextual conditions because they believe they are relevant to the phenomenon under study; or (d) the boundaries are not clear between the phenomenon and context. A multiple case study enables the researcher to perform analysis within each setting and across settings (Koulikoff-Souviron & Harrison, 2005). Unlike in a holistic case study with embedded units, which allows the researcher to understand only one unique case, in a multiple case study, the researcher examines several cases to understand their similarities and differences (Baxter & Jack, 2008). The results of multiple case studies tend to be more convincing and more robust than those of a single case study. This thesis investigated and drew conclusions from four high-level and two in-depth cases of network industries. A proof-of-concept was built for performance measurement in an electricity distribution network.

The thesis is based on four publications (I–IV) attached to this work. The findings, conclusions, and peer-review feedback were considered, and the concept was iteratively improved after receiving the feedback for each publication. Finally, conclusions were made, and further research topics were documented.

## 2.2 Harmonized performance measurement

Network industries should harmonize their terminology, requirements, and methods for monitoring and reporting performance to increase their transparency, productivity, and efficiency and reduce the total societal cost of maintaining and modernizing the networks. The process by which such a system was developed for this study is described below. It is important to state, however, that harmonization does not mean that the performance-indicator formulas should be identical across industries.

The first step in the process was the identification of the various indicators used in by different companies in network industries and across sectors. A desk review was conducted to consolidate the information about the performance-indicator systems in different network industries, including requirements, monitoring, and evaluation of indicators. The results were collected in similar, systematic ways. Not all network industries were covered by the case studies. The choice of industries was based on two factors: (1) the overall contribution of the industry to future European economic or sustainability goals and (2) the availability or accessibility of data.

The next step was to model the indicators in a single framework. Based on the literature, Figure 8 shows a visualization of the hierarchy of PIs. The core indicators were combined into a generic performance indicator (GPI), a combined performance indicator (CPI), a KPI, a PI, and technical parameter (TP) levels. Moreover, the CPI groups were identified and clustered. Groundwork was conducted to understand the common characteristics and make sure that it was possible to create a common indicator system. Similarities between cases were identified but systemizing the findings and proposing a common indicator system is beyond the scope of this thesis.

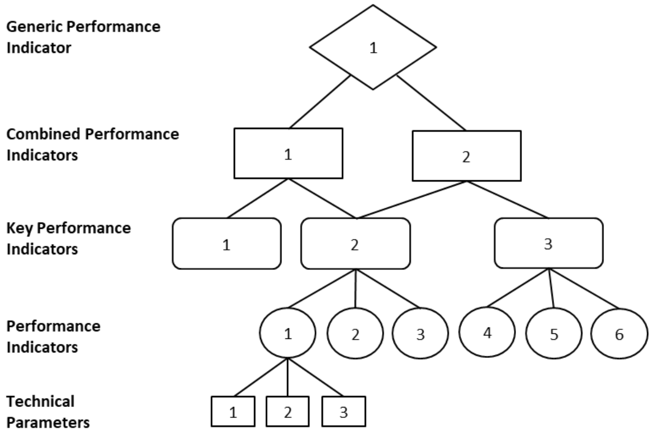


*Figure 8 Hierarchical structure of the performance indicators based on the literature*
*Source: author's adaptation from (Kaare, 2013)*

Figure 8 proposes a general conceptual model for PIs. It can be used to assess the performance of network nodes and edges and their performance trends over time. The following mathematical formulas show the layer dependencies:

$$\mathrm{PI_j} = f_{\mathrm{aggregate}}(f_{\mathrm{weight}}(f_{\mathrm{scale}}([\mathrm{TP_{1\ldots n}}])), \quad (1)$$

$$CPI_k = max[PI_{1\ldots m}], \quad (2)$$

$$GPI = max[CPI_{1\ldots p}], \quad (3)$$

TPs are measurable or observable environmental characteristics whose values vary over time. A PI defines the measurement of a piece of useful information expressed as a percentage, rate, or other metric monitored at regular intervals. Several scaling, weighting, and aggregation methods may be applied based on the nature of the data. The maximum function max() is proposed by author to combine and propagate the importance of the value through the indicator hierarchy. Theoretically, other functions could be used instead of max(); however, none of the indicators built for the cases in this study required other functions (I).

Data for modeling a harmonized performance-measurement system was collected. Use-cases were captured and modeled to understand the desired behavior of the system. Domain modeling was conducted to develop a logical data model for capturing the indicator data. The full system was decomposed into logical components, and a reference architecture was proposed. The architecture was proven in two case studies. The findings were submitted to the next iteration of the architecture development.

Finally, a proof-of-concept experiment was conducted to test the architecture in a live electricity distribution network. The main indicators were calculated for the network nodes the proposed performance-measurement system. There was no attempt to consolidate them into CPIs and a GPI. Modeling and implementing a GPI for performance measurement of an electricity distribution system is possible, but it requires a significant amount of work that is beyond the scope of this research.

## 2.3 Dynamic Bayesian network for performance prediction

This section describes the creation of a prediction model that can provide answers to queries when uncertainty is present in a dataset of performance measurements. A short introduction to DBNs is provided, followed by an explanation of building performance graph structure and prediction (i.e., inference) algorithm choice.

Bayesian networks correspond to a set of variables in the shape of nodes on a directed acyclic graph, mapping the conditional independencies of these variables. The graph used in this work is the performance graph from section 1.3. A DBN is defined as a repeating conventional network in which a time step to another is added to the dependency graph. Each network includes several random variables representing observations and hidden states of the process (Koller & Friedman, 2009).

DBN inferences are typically used to calculate the conditional probability of a variable at a given moment of time, provided that all the observations of the connected variables at all known moments of time are available. The following tasks can be performed with a DBN:

- Filtering is used to estimate the belief state at a given moment of time, given all the observations until this moment. It is a special case of prediction. Filtering can be used, for example, to determine the probability of a PI exceeding a given threshold.
- The decoding function is to determine the most likely sequence of hidden states, given the observations up to a given moment of time. Decoding can be used to validate the measurement data and detect anomalies.
- Prediction involves estimating a future observation or state, given the observations up to the current time. Prediction is used to determine any future state of the PI graph, taking into consideration the evidence gathered up until now.
- Smoothing is used to estimate a past state, given the observations up to the current time. Smoothing can be used to fill in the gaps of PI time-series (Ghanmi et al., 2011).

To define a DBN, its topology (graphical network) and the conditional probability distribution must be described. Finding out a topology is more difficult than learning its parameters (Särkkä, 2013). For this thesis, the topology was based on industry best practice or domain experts. For the conditional probability distribution, the following parameters need to be defined: the transition probability between states and the conditional probability of hidden states, given observational data and the probability of the initial state. These two parameters must be determined for each time interval of interest. Those probabilities can easily be determined by carrying out exploratory analysis of the initial measurement dataset.

*Table 2 Determining DBN prediction method*

| **Structure** | **Observability** | **Method** |
|---|---|---|
| Known | Full | Simple statistics |
| Known | Partial | EM or gradient ascent |
| Unknown | Full | Search through model space |
| Unknown | Partial | Structural EM |

*Source: (Ghanmi et al., 2011)*

There are several inference algorithms for DBNs. Thy can be divided into two broad classes: exact inference (e.g., forward-backward algorithm) and approximate inference (e.g., expectation maximization and maximum likelihood algorithms). Table 2 summarizes four options for inference algorithms. In this thesis, the expectation maximization (EM) or gradient ascent algorithms were tested to find the best functioning algorithm.

Inferences in DBNs can, in principle, be made by unrolling the graph and using standard Bayesian network inference methods. The main source of complexity is that the graph may be large and densely connected, requiring careful choice and optimization of algorithms. The final choice and optimization of algorithms is not part of this thesis.

## 2.4 Traceability and trust in performance measurement

Blockchains can introduce efficiency into solutions for problems that it was not previously feasible to solve. In this thesis, transaction throughput and cost modeling was performed for the permission-less Ethereum network to understand the possibility of using a public network for the performance measurement of networked industries. The case study was implemented to verify the method using a subset of SmartLog – Smart Logistics and Freight Villages Initiative (Kõrbe Kaare et al., 2020) project data and as an illustrative example of the challenges that are faced while trying to preserve data immutability in freight monitoring.

The blockchain technology landscape appears to be vast. On closer inspection, however, only a few chains meet the criteria defined in section 1.5 (guaranteed data integrity, traceability of calculations, public auditability). The Ethereum network and Hyperledger technology with an appropriate setup have been considered as candidates for the SmartLog project. Ethereum was analyzed as a baseline for public blockchain networks and Hyperledger as a private network technology.

Ethereum smart contract functionality is powerful and makes it a reasonable platform for various kinds of applications. Its permission-less mode of operation and its total transparency, however, comes at the cost of performance scalability, privacy, use (Xu et al., 2017). Hyperledger solves performance scalability and privacy issues by its permissioned mode of operation and by using a byzantine fault tolerance algorithm and fine-grained access control (Valenta & Sandner, 2017). Publication (IV) describes several new developments that have the potential to solve issues with current blockchains. It also contains a comparison matrix of their basic features.

In addition to blockchain network features and setup, the cost of using the network needs to be explored. Transaction throughput $\tau$ per chosen period (4) shows how many transactions are needed to performance measurement data into Ethereum blockchain.

$$\tau = \chi * \sigma * \pi \tag{4}$$

where $\chi$ is shipment units per route per period (e.g., per year or day); $\sigma$ is the number of stops on the route; and $\pi$ is the number of TPs (e.g., expected delivery time, delivery time).

The transaction cost of a single write operation $\omega$ in the Ethereum network can be modeled as follows:

$$\omega = \gamma * \theta * 10^{-9} * \varepsilon \tag{5}$$

where $\gamma$ is gas used per write operation; $\theta$ is gas price in Ethereum; $\varepsilon$ is the Ethereum price in the selected fiat currency.

The overall blockchain cost $\xi$ is calculated as follows:

$$\xi = \tau * \omega \quad (6)$$

In Hyperledger, the write operations have no transaction cost, meaning that the direct overall blockchain transaction cost is relative to the investment in infrastructure setup and maintenance.

Properties to consider when choosing a blockchain technology include whether it is centralized or decentralized, how the data security and privacy are handled, how data ownership is managed, what the availability and robustness promise is, how transparent and trustworthy it is, and how well the data can be verified. Other aspects include the transaction write cost, public auditability, data integrity, and traceability of calculations. For the purposes of this thesis, only Ethereum and Hyperledger remained as candidates.

## 2.5 Case studies

This section describes the case studies used in this thesis. Electricity and transportation sectors are the largest sources of greenhouse gas emissions. For this study, power distribution grids and logistics networks were selected as examples of how these sectors could become more efficient and better managed. In the case study of the electricity distribution network, the thesis investigates the practical modeling and testing of one of the important reliability indicators: System Average Interruption Duration Index (SAIDI). In the case study of the logistics network, the thesis explores real-life blockchain use in cargo delivery.

### 2.5.1 Reliability of electricity distribution network

Vast numbers of smart meters are deployed around the globe to solve the issue of energy liberalization. The functioning of a free electrical energy market requires measurement of production and consumption at sub-hour (30 min to 5 min) intervals. Smart meters are deployed to measure the bidirectional energy flows so that the prosumers can participate on the energy market. Smart meters can be used every day by grid operations teams to prioritize the tasks of field workers and by grid planners to understand the most influential investments to increase the value to society and decrease the socioeconomic cost.

This thesis describes a method of using regular residential smart meter data to calculate the PIs of a power network so that its reliability can be measured (using SAIDI). The reference architecture was verified by calculating and visualizing the metrics on any level of the electricity distribution grid topology. The results were compared to manual performance calculations.

Studies by the Council of European Energy Regulators (CEER, 2015) and the Institute of Electrical and Electronics Engineers (Agüero & Xu, 2014) show that the most popular sustained-interruption indicator among European and U.S utilities is SAIDI followed by the System Average Interruption Frequency Index (SAIFI), the Customer Average Interruption Duration Index and the Average Service Availability Index. SAIDI expresses how often the average customer experiences an interruption over a predefined period (Figure 9). This research uses SAIDI indicator calculation to validate performance measurement system architecture. The method can be used to calculate all IEEE 1366 (2012) reliability indicators or newer indicators such as customer interruption cost per kWh in a temporo-spatially disaggregated way.

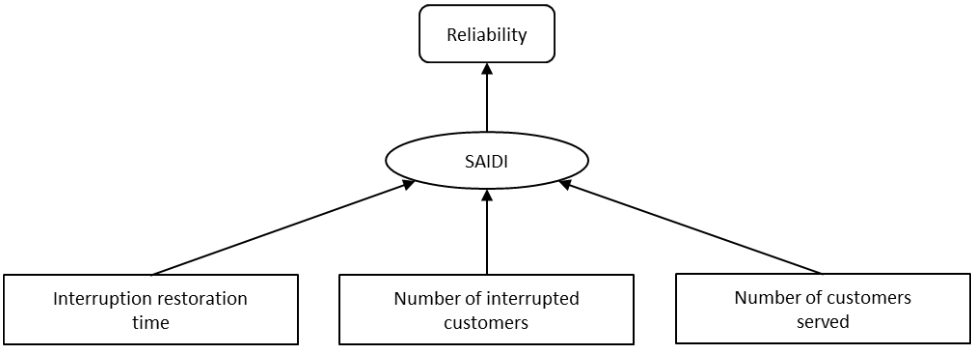


*Figure 9 The electricity network performance indicator SAIDI*

Today, smart meters are the closest measurement devices to the end customers. The functionalities offered by such meters vary, but all state-of-the-art meters have a similar base set of functions:

- energy measurement,
- load profiles,
- time-of-use tariffs,
- voltage level bypass,
- phase asymmetry,
- phase loss,
- interruption events.

The case study involved a large homogeneous meter network covering approximately 60% of the total low-voltage power grid usage (Table 3). The meters are distributed evenly across the power distribution grid. The smart meter network of the selected distribution network operator has reached 100% coverage. Due to the nature of the country and the grid, most (62%) of the metering points are situated in rural areas behind long feeder lines.

*Table 3 Data overview*

| Parameter | Value (Millions) |
|---|---|
| Total metering point count | 0.70 |
| Reporting metering point count | 0.42 |
| Reporting metering points in urban areas | 0.26 |
| Meter event records in measurement period | 200.94 |

*Source: author (III)*

The meter data collection system used in this study captures meter events according to the IEC 61968-9 (2013) international standard. The measurement dataset contained raw information about the first 10 months of the selected calendar year. The total number of meter events during the period exceeded 200 million. The meters were configured to send out events according to the European standard EN 50160 (Markiewicz & Klajn, 2004). Time was synchronized between the meter data collection system and field equipment over the network time protocol. Time synchronization malfunctions were monitored and reported.

Meter events related to power quality were reported in multiple ways. Typically, a problem's start and end are registered as separate records (Table 4). Depending on the meter and communication setup, events may be reported repeatedly until the problem (e.g., missing voltage) is solved. Normalization of the event data was performed to filter out all meter events related to interruptions from the full dataset and find the correct start and end times. The interruption event is stored as one record and enriched with information about the low-voltage grid topology (i.e., substation, transformer, feeder line, and metering point). In this context, "interruption" can be defined as a data record containing start and end times, phase, and location where the loss of service occurred.

*Table 4 IEC 61968-9 power quality event types*

| EndDeviceEventType | Description |
|---|---|
| 3.26.0.85 | Power down |
| 3.26.126.85 | Missing voltage L1 |
| 3.26.134.85 | Missing voltage L2 |
| 3.26.135.85 | Missing voltage L3 |
| 3.26.0.216 | Power up |
| 3.26.131.37 | Voltage L1 resume |
| 3.26.132.37 | Voltage L2 resume |
| 3.26.133.37 | Voltage L3 resume |

*Source: author (III)*

For validation purposes, the calculated indicators were compared against the previous calendar year's public SAIDI values of the same grid operator. The SAIDI values were reduced to the meter event data timescale. Linear SAIDI across the observation time and geography was assumed. Major event days were included in the calculation. In addition to the desk study, an experimental proof-of-concept system was implemented following the conceptual architecture of the performance measurement in the networked industries.

### 2.5.2 Blockchain feasibility for Tallinn–Helsinki cargo delivery

Most of the time lost in delivering cargo is in waiting at warehouses or logistics nodes. The bureaucracy concerning procedures, limited digitalization, and the amount of paperwork required at these nodes add to the delays and to the cost of services. The number of manual procedures along the route allows for mistakes, delays, and questions regarding validity (Fulzele & Shankar, 2021).

The SmartLog project developed a blockchain technology-based solution to solve these shortcomings for logistics and supply chain companies (Kõrbe Kaare et al., 2020). Blockchain is a technical element in the creation of the digital supply chain. Blockchain technology could enable the change in society by introducing disintermediated digital trusted data exchange. This technology is regarded as a potential means of enhancing the information flow among different actors in supply chain and guaranteeing security and trust. Blockchain technology has a dual effect of removing the need for actively intermediated data-synchronization and concurrency control.

Companies from Sweden, Finland, Estonia, and Latvia were involved in the project along two TEN-T corridors: the North Sea–Baltic corridor (Figure 10) and the Scandinavian–Mediterranean corridor. In total, 648 companies were contacted, and detailed analyses were conducted in 151 companies operating along these two corridors. The aim of these analyses was to gain input to the software development, understand and map the companies' processes, acquire an understanding of the maturity level of the hardware and software, and gauge their susceptibility to the new technology (Kabashkins & Gromovs, 2017). Detailed process maps were developed, and simulations using measurement data were created for 48 companies. Finally, the developed software was connected to the ICT systems of 12 companies, and real-time data were gathered and analyzed. The project included all land transport (road, rail, sea) and excluded air transport.

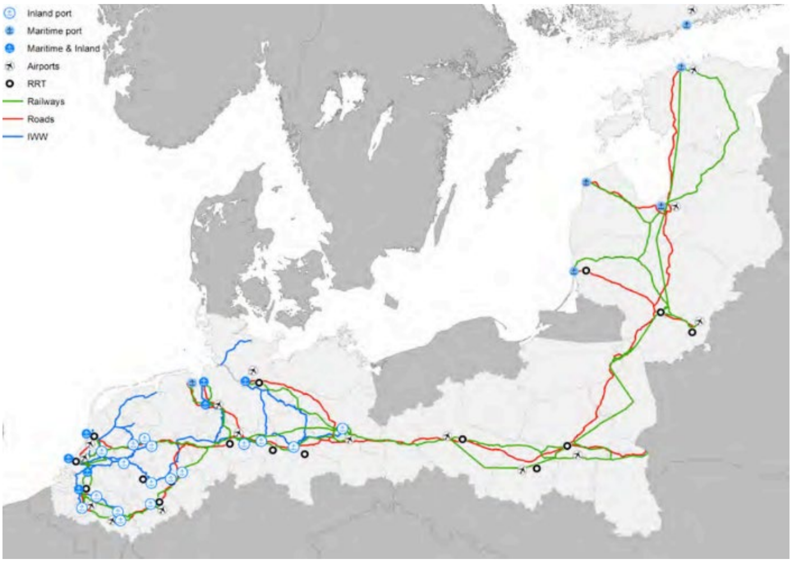


*Figure 10 TEN-T North Sea–Baltic Core Network Corridor*
*Source: (EC, 2014)*

The initial design of this research assumed that full supply-chain data could be collected and analyzed with the approval and participation of the owners of the goods. A goods owner – as the owner and receiver of the logistics data about the transport of their goods – can also approve data access for the parties involved. However, due to technical limitations, the data being scattered, and the lack of structured digital form in most of the data, an unexpected outcome resulted: the owner of the data was not always the controller of the data.

The SmartLog project aims to introduce blockchain technology into the operational data transfer in logistics businesses, not as a commercial, proprietary application suite, but rather as an industry-wide open solution that every interested party can join and from which every involved party can directly benefit (Kõrbe Kaare et al., 2020).

The metrics needed by the project are the measurements regarding the end-to-end transit times of cargo along the two TEN-T core network corridors. The project aim was to reduce cargo transit times on those corridors, according to the EU policy objectives.

# 3 Traceable temporo-spatial performance measurement concept

This chapter presents the results of the work. It is divided into six sections. First, the performance-measurement best practices across industries are summarized using the same notation to highlight similarities and differences, with the aim of empirically determining the possibility of cross-industry harmonization. The second section covers important aspects of the architecture of the ICT implementation, such as the logical information model and system components. The third section explains how the chosen performance-prediction model works. In the fourth section, the use of blockchain in performance measurement is illustrated. The fifth section describes the proof-of-concept, which is intended to show the applicability of the architecture to real life. Finally, suggestions are made for further research.

## 3.1 Harmonization of performance-indicator systems

This section summarizes the performance-measurement best practices in road, railway, power distribution, and telecommunication networks. The similarities and patterns are highlighted and synthesized.

The road industry defines PIs for different types of pavements and highway categories. Most common practices are described in the European Cooperation in Science and Technology (COST) report COST354 (Litzka, 2008) and the European Vehicle Infrastructure Transportation Alliance (EVITA) report (Lurdes Antunes, 2011). In the past, measuring the performance of roads and transportation has taken a great deal of effort to manually collect data. An increasing number of sensors are becoming available, however, to automate large-scale data collection (speed detectors, weight-in-motion sensors, traffic detectors, automatic vehicle identification sensors, and connected environmental sensors).

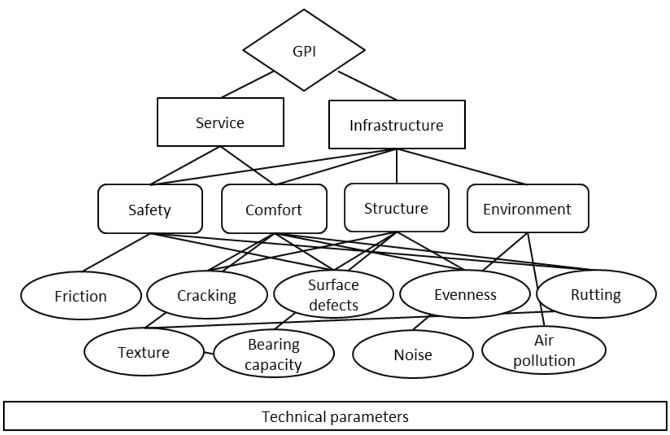


*Figure 11 Performance indicators in road industry based on COST354 and EVITA*

Road TPs are aggregated to first-level PIs that describe the characteristics (e.g., friction, cracking, rutting) of the road pavement. The next step is the grouping of single PIs into KPIs: safety and comfort performance (demands made on road by track users), structural performance (structural demands to be met by the road pavement), and environmental performance (demands made on road from an environmental perspective) (I). The KPIs are then transformed into CPIs, such as service and infrastructure performance. Finally, a GPI can be defined based on the CPIs to indicate the general condition of the road and enable the comparison of different road sections (Figure 11).

PIs for railway infrastructure are built in a similar way. Figure 12 shows an example of a GPI for a railway based on work by the railway infrastructure management working group of the PRIME – Platform of Rail Infrastructure Managers in Europe (Flemming et al., 2019) and another work (Stenström et al., 2012). The KPIs are safety, punctuality, reliability, capacity, condition, and environment. There is a similarity in road and rail PIs on the KPI level. However, the industry practice is to measure and compose different PIs. The service and infrastructure CPI could be combined into a GPI, similarly to the practice in the road industry.

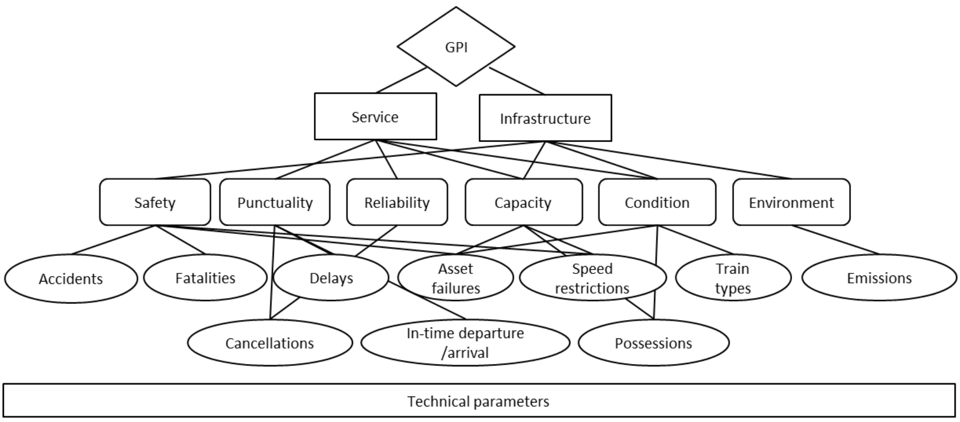


*Figure 12 Railway performance indicators based on PRIME*

According to Queiroz & Mendonça (2012), Ausgrid (2012), Gosbell (2002) and Meldorf et al. (2007) attempts were made to create overall indicators for the evaluation of the quality of supply and reliability of power distribution networks. Emerging smart grid developments are putting emphasis on understanding the performance of the power network not only from power quality and grid reliability perspectives, but also as a whole. However, the indicator systems in the power distribution network are not yet as comprehensive as they are for road networks. Their development remains a topic for further research (I).

There has been significant research focusing on voltage quality. Standardization bodies have proposed several indicators (Markiewicz & Klajn, 2004; IEEE 1366, 2012; EPRI, 1999). At the time of this research, however, the commercial quality, quality of service, safety of operations, and the socio-environmental impacts of power distribution network operations have not been researched systematically. In addition, shifting global focus to environmental, sustainability, and governance topics, or the triple bottom line, will bring the socio-environmental issues into focus in the nearest future.

Power production environmental indicators are well defined and measured in contrast to power distribution environmental impact indicators. The transmission and distribution losses, maintenance activities, and construction can have a negative impact on forests, wetlands, and other natural areas and should be measured (Figure 13).

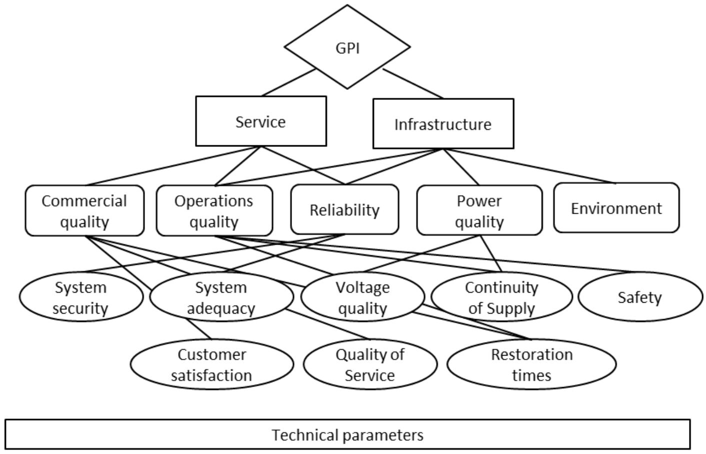


*Figure 13 Performance indicators in power distribution industry*

The proposed method guarantees higher visibility and offers the possibility to narrow the focus from the overall system-level PI to a specific area or object. The deviation from the target and root cause of deviation, can be easily found through visualization. A similar method applies to other power-quality metrics. The method will have an effect on issue classification, localization, and restoration times, and it supports long-term grid investment planning.

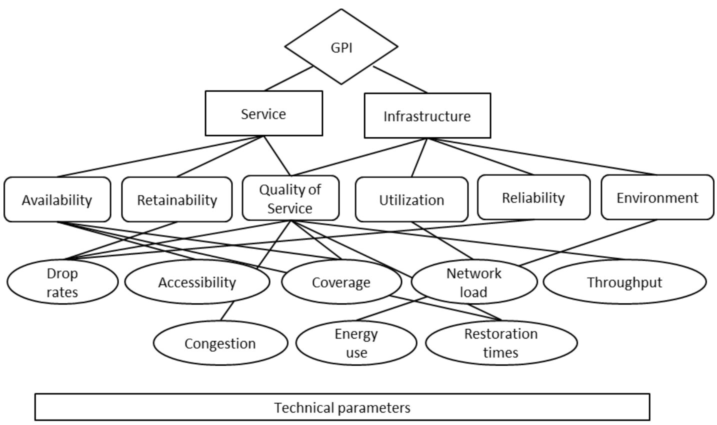


*Figure 14 Performance indicators in telecommunications*

Telecommunications is related to most of other business sectors. Telecommunication sector is regulated, but the competition is normally intense among different service providers. Performance measurement in telecommunications focuses on two major groups of non-financial indicators: operational efficiency and overall customer satisfaction and experience. The focus in performance measurement is clearly on the customer, and efficient service delivery is the main requirement (Figure 14) (I).

The increasing complexity of supply chains, whose structure is changing from a linear to a network form, creates the need to track a growing amount of information (Figure 15), allowing the performance measurement of the entire supply chain. Developing performance measurement indicators for the supply chain requires the appropriate selection of indicators. Performance should be measured in a particular context, and the analyzed dimensions of the indicators resulting from the purpose and focus should be determined (Leończuk, 2016).

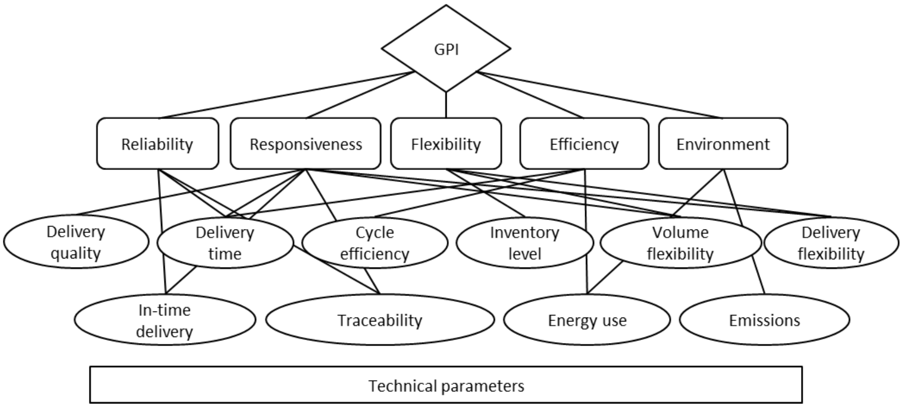


*Figure 15 Supply chain performance indicators*

In the literature, the performance measurement of the supply chain is approached in several ways. The performance indicators are split within strategic, tactical, and operational management decision levels. Another approach is to divide the indicators into financial and non-financial dimensions. There are also methodologies using the already well-established paradigms and models as a baseline and selecting perspectives according to the BSC, and SCOR – the supply chain operations reference model (Kaplan & Norton, 1996; SCOR, 2012).

The examples of PIs in network industries (what is measured, how the measurements are grouped and presented) reveal similarities and patterns. The indicators are developed similarly and share the same principles. Despite clear similarities, however, the focus of the indicators differs among industries. The focus reflects the main issues that are currently topical, omitting other aspects that deserve equal management attention. In the long run, the control and steering decisions that are based on the subset of visible information are not efficient or optimal (I).

To systematize the numerous parameters affecting performance and to maintain conciseness, understanding, and clarity, it is important to find new ways to combine parameters systematically across network industries into one GPI and standardize the approach to CPIs (I). It is possible to harmonize performance-measurement principles (Figure 16). Such systemized approach enables harmonized visualization, comparison, and management of performance across network industries within a general ICT framework.

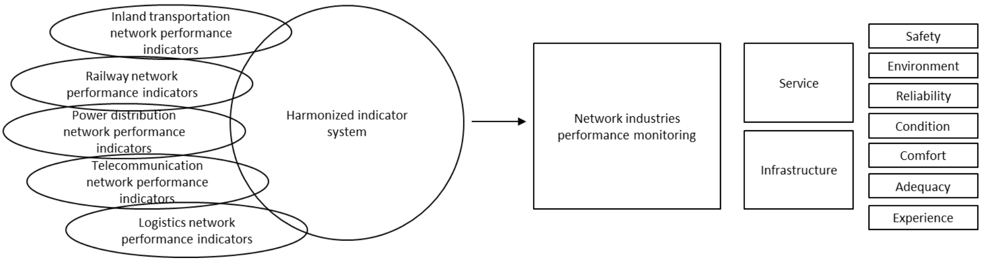


*Figure 16 Harmonized indicator system*

## 3.2 Building dynamic Bayesian network from expert knowledge

Performance models encapsulate industry-wide knowledge and relations. The method chosen and applied in this work integrates accuracy estimation and transparency of reasoning into the values prediction.

Prediction in DBNs starts with prior knowledge about the model structure: a set of edges and nodes in a belief network. PI graphs are common and structured in such a way to represent the expert knowledge concerning dependencies between measurable TPs and PIs. By combining such graphs with time-series data, we built an initial dependency graph of PIs and CPIs to use for missing data estimation, part of which is shown in Figure 17. The exact inference in DBNs to estimate continues timeseries values is difficult if not possible to achieve. The method can be applied to estimate discrete PI values, as PIs are usually discrete by nature and the quantization algorithms have been proposed in the standards. This allows simplifying the model and looking at it as linear Gaussian state-space model (II).

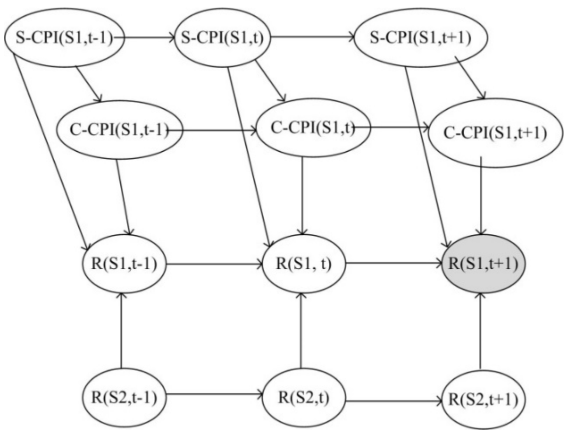


*Figure 17 Part of initial dependency graph*

In the example of performance measurement for road networks (Figure 17) R represents the rutting indicator, C-CPI is the comfort indicator, and S-CPI is the safety indicator. S1 and S2 are similar road sections. In a similar way, all the dependencies are captured on a graph to build initial models. Some of the currently missing values were derived from other measurements and similar historical cases. Some can be approximated and used in the performance calculations, indication to the end user the probability of correctness.

In this way, a model can be built in each network industry with a common performance-measurement standard. This initial model gives a prior probability distribution over the model structure. Enriching it with data will lead to posterior probability of the parameters (II).

If E = {e} is the collection of evidence containing observations about S-CPI, C-CPI, R, S1, and S2 over {1:t}, then we can use (7) to solve the first-step prediction problem for time slice t+1:

$$P(R_{t+1;S1} \mid e_{1:t}) = \sum_{R_t} P(R_{t+1} \mid X_t) P(X_t \mid e_{1:t}) \tag{7}$$

One way to handle the estimation issue in this type of network is with the EM algorithm. This algorithm uses iterative update steps, each time regulating the parameters so that they maximize the expected logarithmic likelihood, where the expectation is taken with respect to the previous values of the parameters. This algorithm is guaranteed to converge to a locally optimal solution whenever the missing or hidden data are missing at random (i.e., without there being any dependence of the missing data pattern on the values the variables would have had, had they been observed) (II).

An initial model for performance prediction can be constructed that captures industry knowledge and carries along the correctness probability indication. Such a method, based on industry knowledge in graph format, can give predictions immediately after deployment and explain how the model reached the prediction. There are methods to re-learn the edges of such a dependency graph over time when data are collected, leading to a self-adjusting model. In this case, being able to see the relations, understand the accuracy of the prediction, and narrow the focus to a single PI or TP are an advantage over more advanced neural network-based deep-learning models.

## 3.3 Traceable data and calculations with blockchain

When choosing blockchain technology the following properties need to be examined: whether it is centralized or decentralized, how the data security and privacy are handled, how large the network is (to avoid the 51% attack) (Sayeed & Marco-Gisbert, 2019), how data ownership is managed, what the availability and robustness promise is, how transparent and trustworthy it is, how well the data can be verified, and what the transaction write cost is. In this work, given all the requirements, only a few technologies remained as candidates: Ethereum (permission-less) and Hyperledger (permissioned) (IV).

Data manipulation is often highlighted as a serious threat to data and calculations integrity. Malicious actors can use tampered data or formulas to their advantage. Data users of various application domains need to be guaranteed that the data they are consuming are accurate and have not been tampered with (Zikratov et al., 2017). Blockchain technology in the system architecture gives the necessary proof of integrity.

Storing full datasets in a public blockchain is not feasible for performance measurement. Using Ethereum, the cost of writing data into the chain is unreasonable. Another constraint is the low limit of data that can be written in one transaction. The limit can be calculated with the help of the Ethereum Yellow Paper (Wood, 2014). The limit is not a fixed number; it varies and is currently around 30 kB. The overall cost of a single transaction can be calculated using formulas (4)–(6).

In the SmartLog project, using the Tallinn–Helsinki cargo delivery route, the yearly cost of tracking all pallets was calculated to be around 2–3 million euros (Table 5). This shows that the public blockchain application is not economically feasible (IV). Using a hybrid blockchain architecture, the yearly cost would be around only 1,000 euros, making this a viable solution for the performance measurement of network industries.

*Table 5 Helsinki–Tallinn route cargo tracking cost (Ethereum vs. hybrid solution)*

| Route | Parameters | | Trucks | | Pallets | |
|---|---|---|---|---|---|---|
| | Shipments (year) | TPs | Ethereum cost (year) | Hybrid cost (year) | Ethereum cost (year) | Hybrid cost (year) |
| Helsinki–Tallinn | 170,000 | 4 | 81,600 | 1,051 | 2,692,800 | 1,051 |
| Tallinn–Helsinki | 156,000 | 4 | 74,880 | 1,051 | 2,471,040 | 1,051 |

*Source: author (IV)*

End-to-end transit time and deviations from the expected transit time were taken as the most important PIs for cargo transit in the SmartLog project. By testing on a simplified case in which those indicators were decomposed into TPs, we established four parameters that need to be written into the blockchain: scheduled pick-up time, real pick-up time, scheduled delivery time, and real delivery time. A shipment along these corridors needs 4–32 parameters written in the blockchain, depending on the complexity of the transport. Those parameters allow us to calculate several indicators for transport timeliness and transit time and allow greater optimization along the supply chain.

In the case of the Hyperledger private blockchain, the transaction cost, length, and throughput are not constraints (Lincoln, 2019). Nevertheless, attention must be paid to organizational setup and security measures around the administration of the network if a publicly auditable secure system is required (Davenport et al., 2018; Dabholkar & Saraswat, 2019). This requirement makes the solution mentioned above infeasible.

To validate the integrity of the data or formulas and overcome the issues, the blockchain based hash validation method was used. The method assumes that the actual data are stored separately from the public blockchain, and it allows a data identifier and a hash of these data to be submitted to the public blockchain. The actual data can be validated against the hash on the blockchain at any time (Kalis & Belloum, 2018). The audit logs are hashed to capture the actions of participants so that auditors can check compliance with policies. Thus, the blockchain is used to create a tamper-proof trail of any data manipulation on the system (Sutton & Samavi, 2017). This hybrid approach allows the cost of using the blockchain to be controlled while offering the same integrity guarantees (Table 5) as using public blockchain.

If Hyperledger is used as the blockchain technology, the formulas and calculations can be stored in chain code. The solution for the Ethereum blockchain is not to use the built-in smart contracts for PIS, formulas, and calculations, but to use the method to write the hash of the execution and change log periodically into the Ethereum blockchain. The execution and change log must contain all the manipulations of the calculation logic and the input data, calculation code reference, and output value(s).

It is feasible to use blockchain to ensure the traceability and immutability of the base dataset and PI formulas when certain hybrid architectural solutions are used. Using a public blockchain-based method guarantees the trustworthiness of the calculated PIs and transparency for decision-making.

## 3.4 Traceable temporo-spatial performance-measurement system

This section proposes a reference architecture for a system that can process the data from a vast number of sensors, combine them with various other data sources, and calculate traceable and trusted PIs for any networked industry across space and time. Considering the findings in sections 3.1–3.3, a system is designed that can process the data from a vast number of sensors, combine them with various other data sources, and calculate performance in any networked industry across space and time.

Unlocking additional value from the existing data and combining them with new data sources (e.g., sensors, smart meters, IoT) will have a transformative impact on the management of network industries. More efficient, and therefore less expensive, data communication, storage, and presentation and better data processing mechanisms will allow soon allow the quicker handling of a greater variety and volume of data, which will lead to accurate and actionable insights (I).

Author developed the ICT architecture reference model to provide a high-level summary of the functional components of the performance-measuring platform to enable processing of the TPs, combining them into clear logical PI hierarchies, and visualizing them to the end-user. The layered diagram in Figure 18 presents an overview of the performance-evaluation system and specific functional layers of the platform. The model is divided into five component layers, each with a clear responsibility borderline (I).

The first layer contains components for manual entry and raw data input from sensors and databases or applications. It contains a wired or wireless data-communication component and a data-ingestion component that can implement request-response and publish-subscribe integration patterns (Hohpe & Woolf, 2004). It directs data towards the processing engine and data repository. The blockchain component data checksums for integrity checks are taken as near as possible to the data source (if not inside the data source) to eliminate the risk of data manipulation (section 3.3). The data volume and arrival rate play a major role in selecting the communication technology. The main role of the layer is to manage the volume, velocity, and variety of the data coming to the system. The layer's components must be scalable to adapt to changing arrival volume and speed.

The responsibility of the data-handling layer is to ensure data completeness, conformity, consistency, and timeliness. The data-processing component ensures that the missing values are highlighted and known, prediction algorithms are executed to fill the gaps and predict future trends, anomalies are detected, and the data are valid. Data validation is an additional responsibility of the data-processing component. The data-management component transforms the data format according to a common data model, correlates events, and performs data enrichment. It is also responsible for managing data-retention rules. The components of this layer require access to and use the functionalities of the data-repository component. When missing values are filled in or any form of data correction is applied, the entry must be written to the blockchain for integrity checks.

The indicator calculation layer calculates historical, real-time, or future PI hierarchies. The queries component is responsible for performing batch queries over the (large) historical dataset to implement scenarios that do not require real-time processing. The event-processing component controls the processing of streaming real-time data using time window queries and triggers. The data-aggregation component uses the queries component and the event-processing component to calculate PIs. The aggregation formulas and queries or their hash values are stored in the blockchain.

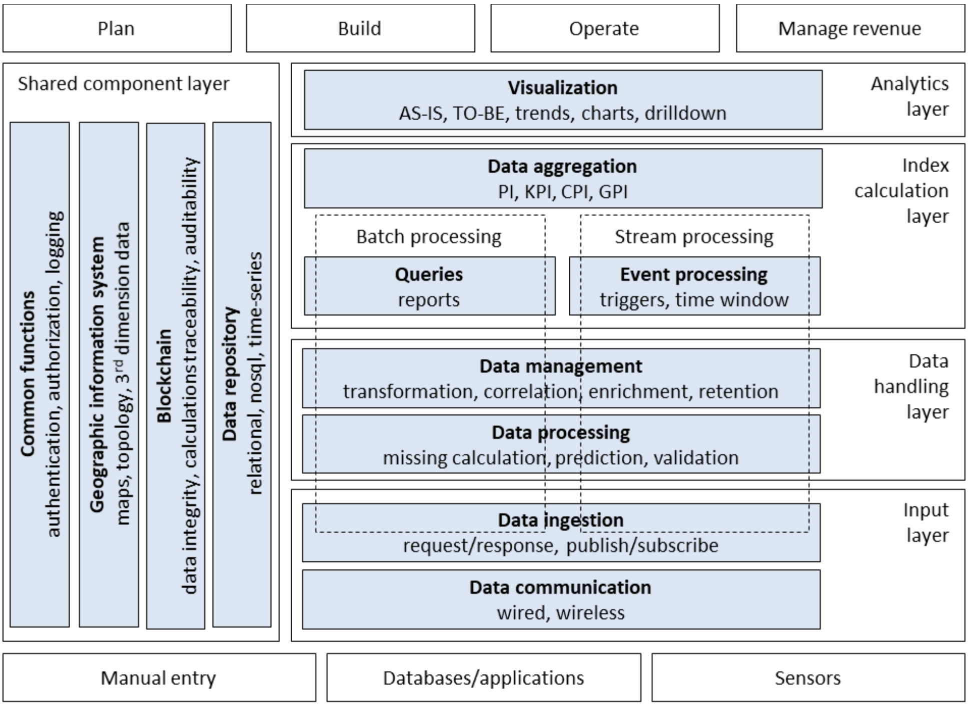


*Figure 18 Components of the performance-measurement system*
*Source: author (I)*

The responsibility of the analytics layer is to make the PIs understandable to the end-users. The situational awareness, future predictions, trend analytics, charts, and temporo-spatial narrowing capabilities are supported by the visualization component.

The shared component layer contains components that are used by other components across the architectural layers. Common functions include the authentication of users, access control, and the central logging and monitoring of the platform. The geographic information system component contains maps, topology information, and the third dimension (z-coordinate) data that are important in many use-cases. The blockchain component's main responsibility is to guarantee data integrity, calculations traceability to individual TPS, and full auditability of the indicator calculation process (section 3.3). The data-repository component needs to support multiple storage technologies. The key to such a solution is proper time-series storage functionality, with support for data sharing and large queries. More traditional relational database and NoSQL (document, graph, sematic) database functionality support is required in certain use-cases.

## 3.5 Proof-of-concept

To demonstrate the feasibility of the proposed performance-measurement architecture in a real live setting, a proof-of-concept was implemented on a major electricity distribution network in the Baltics using a live dataset. The platform architecture was used to visualize the grid and calculate PIs based on smart meter event data. The proof-of-concept use-cases are presented on Figure 19.

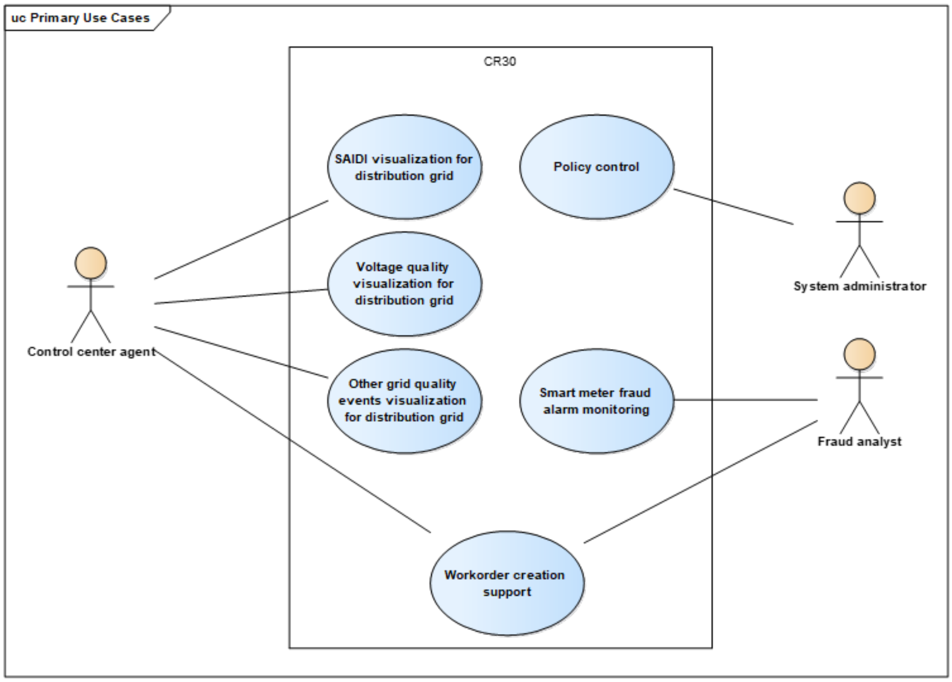


*Figure 19 Proof-of-concept use-cases*

The smart meter event data and the topological information of the distribution network were used to calculate the selected indicators in time and for all network topology levels. Time selection included year, quarter, month, week, and day selectors. The topology levels were country, region, city, substation, feeder line, and metering point.

SAIDI and other grid performance indicators were calculated from the meter data. Geographical and list type visualizations (Figure 20) were used to provide easy to understand graphic representation of objects and their relations. The objects were sorted based on deviations from performance indicator targets. User interface provided the ability to focus on specific elements of the grid to locate problematic grid sections. SAIDI variation over time was monitored.

Calculation and visualization of voltage quality at the metering point, feeder line, transformer, substation, and higher levels was implemented. The voltage quality variations on all phases were presented. That enabled to detect several types of installation and operational issues.

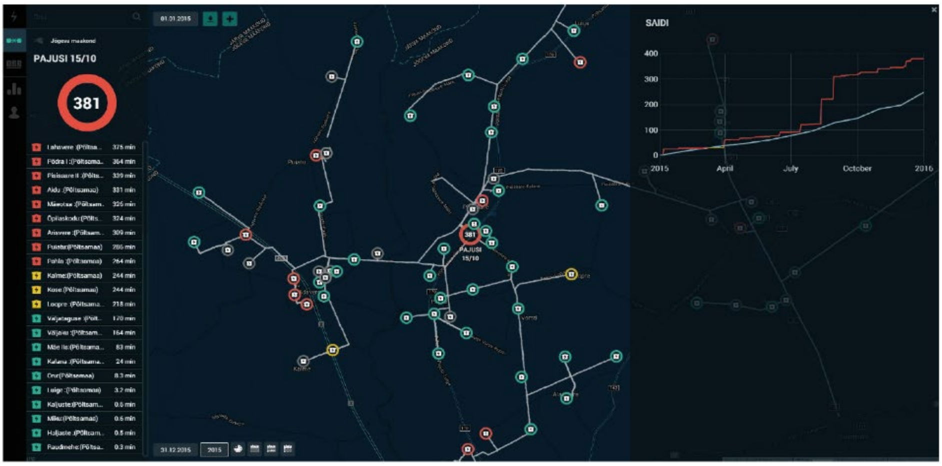


*Figure 20 Screenshot of proof-of-concept*

In addition, fraud indicator visualization based on events in combination with consumption data was implemented. The data from control meters in substations was combined with residential meter data to detect the possible high-loss metering points. Work order creation, task formation and prioritization and field work status visualization with performance tracking was carried out.

The case study and experiment demonstrate that the proposed architectural solution is feasible. The performance models can be configured and adapted for such a use-case. The support for long-term planning decisions and short-term operational decisions can be achieved using a single sensor dataset that is aggregated through different PIs in space and time, providing valuable insights for decision-making and even decision automation. The system is suitable for other networked industries with some minor changes to the integrated data sources, the migrated topological information, and the definition of the performance-calculation models.

## 3.6 Further research

This work has proposed the unification and combination of various aspects of different indicators into a common PI for network industries. A harmonized framework, however, remains a topic for further research.

Indicator systems in power distribution networks are not yet as comprehensive as those for road networks. Their development remains a topic for further research. Much effort has been put into voltage quality research. Standardization bodies have authorized several indicators. Researchers, however, have still to investigate the commercial quality, quality of service, safety of operations, and socio-environmental impacts of power distribution network (or any other network) operations.

The architecture and method for performance measurement proposed in this work is universal. In addition to network industries, it can be used in several other domains such as environmental monitoring. Much of the potential lies in applying the same principles to sustainability monitoring. The circular economy cannot be implemented without such a monitoring system. The application of this architecture in other industries (e.g., for COVID spread tracking, decision support and measures impact tracking), however, has still to be explored.

The financial indicators and their connection with the technical indicators have been left out of this thesis. Combining financial indicators and sustainability targets will enable measuring moving towards more sustainable enterprises. Performance-based taxation models and value distribution models, among others, can only be implemented with proper performance measurement.

# Conclusion

This thesis presents transparent and traceable performance-measurement system concept for network industries. The proposed architecture can cope with large amounts of spatial and sensor data. The method to gauge the trustworthiness of the calculated performance indicators and future predictions is suggested. The performance of all the examined industries can be analyzed and visualized using the proposed performance-measurement architecture. The unified conceptual model of performance measurement system to understand and compare performance inside and across network industries is suggested.

Author proposed the unification and combination of various aspects of different indicators into a common PI framework for network industries. For road networks, comprehensive systems of indicators are available. Indicators for power distribution systems mostly focus on voltage quality and do not provide end-to-end support for decision-makers. Telecommunications indicators focus on operational efficiency and customer experience. Railway indicators are similar to road network indicators.

Likelihood-based methods for missing data calculation can consider different parameters and the time aspect in a single model, enabling more trustworthy estimates than traditional methods. DBNs can be created from expert knowledge (in the form of standards and best practices), network element similarities, and historical changes in time series. This allows the filling of critical gaps in performance-measurement data together with estimation value likelihoods. It also makes missing data, estimations, and their trustworthiness visible to the decision-makers. The decisions and historical analysis can be carried out on partial datasets. Network industries can benefit from the visibility and traceability of their performance data.

Public blockchain networks (e.g., the Ethereum network) are not currently well suited to large-scale performance measurement system implementations, mainly due to the high transaction cost. Transaction throughput will become a bottleneck when a larger amount of data is collected. The currently available private blockchains (e.g., Hyperledger) are suitable for small-scale implementations, from a throughput and cost perspective, but they lack public visibility for all the market participants. This thesis presents a method how to combine the best characteristics of public and private blockchain to guarantee the end-to-end traceability of performance measurement.

The proposed performance measurement system concept guarantees greater visibility and offers the possibility to analyze overall system level PI and to narrow the focus to a specific area or object that is causing deviation from the target. The method will have an effect on issue classification, localization, and service restoration times, and it supports long-term planning.

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# Abstract

## Traceable temporo-spatial performance measurement concept for network industries

A well-designed and trustworthy performance-measurement system for network industries gives the regulating bodies vital information and feedback about the impact of their decisions. Such performance-measurement systems, as the source of information to governments and regulators, have a wide impact. The current performance-measurement methods used in network industries lack temporo-spatial transparency and traceability. Measurement architectures cannot cope with large amounts of spatial and sensor data. It is difficult to gauge the trustworthiness of the calculated performance indicators and future predictions. The possibility of simplifying and harmonizing performance measurement across network industries has not been extensively studied.

The objective of this thesis was to examine the similarities of performance-measurement methodologies in different network industries with the aim of proposing a harmonized trusted system for performance measurement across industries, enabling optimized planning and operation of the networks using large amounts of sensor data. Author set the hypothesis, it is possible to create a system for performance measurement in network industries that can provide transparency and traceability of performance indicators across location and time. The following research questions were set: (1) how a harmonized architecture for the performance measurement of network industries can be created; (2) what methods to use to fill in the gaps in data and predict near future state of the system with probability estimates on; (3) how the traceability and trust of the measurement system can be guaranteed.

During the first phase of the study, the high-level theoretical framework of the research was defined. This was followed by a literature review, theory, and concept definition. The gaps in the literature were identified, research questions and objectives mapped out, and tasks defined. To validate the most critical aspects of the architecture, cases were selected, and a multiple-case study was conducted. Four high-level cases and two in-depth network industries were investigated. A proof-of-concept was built for the electricity distribution network. The work was disseminated via four publications. The cross-case findings and peer-review feedback was considered, and the concept was iteratively improved after receiving feedback for the individual publications.

As a result, traceable temporo-spatial performance measurement concept for network industries was developed. The novelty of the thesis is: (1) Unifying and combining network industries performance indicators into a common framework was verified and presented; (2) Reference architecture for performance measurement based on sensor and spatial data was suggested; (3) An approach was proposed to predict missing values in time series and detect anomalies using Dynamic Bayesian Networks; (4) A solution for traceable performance measurement data and calculations based on blockchain was recommended.

# Lühikokkuvõte

## Tõestatav ja ajas ning ruumis jälgitav tulemuslikkuse mõõtmise kontseptsioon võrguettevõtetele

Doktoritöö käsitab võrguettevõtete tulemuslikkuse (tõhususe ja mõjususe) mõõtmist, mis on eelduseks ettevõtte tulemuslikkuse juhtimisel. Võrguettevõteteks loetakse tänapäeval ettevõtteid, mille peamisteks tunnusteks on mastaabiefekt (eelkõige võrgusääst) ja võrgustumine, tihti koos loomuliku monopoli tunnustele vastava infrastruktuuriga. Käesolevas töös on võrguettevõtted piiritletud lähtuvalt nende tähtsusest rahvamajandusele ja andmete olemasolust maanteede, elektrienergia ülekande, logistika ja telekommunikatsiooniga.

Kuigi selliste ettevõtete tulemuslikkuse mõõtmine on viimastel aastatel teinud läbi kiire arengu finantsarvestuse põhisest tulemuslikkuse mõõtmisest tulemuslikkuse mõõtmiseni reaalajas, on võrguettevõtete peamisteks probleemideks selles valdkonnas vähene tõestatavus ning ajaline ja ruumiline jälgitavus. Autor püstitas hüpoteesi, et on võimalik välja töötada sektoriülene tulemuslikkuse mõõtmise kontseptsioon, mille elluviimine tagab tulemusnäitajate tõestatavuse ja jälgitavuse nii ajas kui ruumis.

Doktoritöö eesmärgiks oli välja selgitada sarnasused erinevate võrguettevõtete tulemuslikkuse mõõtmise praktikates sensorandmetel põhineva harmoniseeritud sektoriülese tulemuslikkuse mõõtmise kontseptsiooni väljatöötamiseks. Doktoritöö koosneb autori juhtival osalusel publitseeritud neljast teadusartiklist, mis on osa aastatel 2012-2018 avaldatud pikemast artiklite seeriast.

Nimetatud artiklid võtavad kokku autori kombineeritud uurimisstrateegia, millega leiti vastused autori uurimisküsimustele: (1) kuidas on võimalik välja töötada sektoriülese tulemuslikkuse mõõtmise süsteemi arhitektuur; (2) milliste meetoditega on võimalik tagada tulemusnäitajate aegridade täielikkus ning kuidas kasutada saadud tulemusi prognoosimisel; (3) kuidas on võimalik tagada tulemuslikkuse mõõtmise süsteemi tõestatavus ning ajaline ja ruumiline jälgitavus.

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Doktoritöö uudsus väljendub järgnevas: (1) ühtlustati tulemusnäitajad ja esitati harmoniseeritud tulemuslikkuse võtmenäitajad; (2) töötati välja automaatselt kogutavatel sensor- ning geoandmetel põhinev võrguettevõtete tulemuslikkuse mõõtmise süsteem; (3) pakuti välja dünaamilistel Bayesi võrkudel põhinev meetod puuduolevate andmete tuletamiseks ning lähteandmete anomaaliate tuvastamiseks; (4) leiti lahendus süsteemiüleste andmete ning arvutuste jälgitavuse tagamiseks plokiahelat kasutades.

# Appendix

**Publication I**

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PRODUCTION
MANAGEMENT

# A concept for performance measurement and evaluation in network industries

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**Abstract.** The structure and functioning of network industries have a great effect on the well-being of society, being also prerequisites for economic growth and productivity. Social goals, industry trends, ownership structures, and the economic environment play an important role in the development of such networks. Most network industries enjoy a dominant position on the market. Their performance is steered by national regulatory authorities via price control and quality requirements. For this the regulatory authorities need besides financial indicators feedback on the technical performance of the provided services. The vast development in sensing, data transmission, and collection technologies, as well as in analytical methods, has made it possible and feasible to acquire the needed feedback. Such comprehensive data enable to construct a performance measurement system to regulate, develop, and administer the networks. This paper explores the possibility of developing an overall technical performance index and presents a relevant concept. The suggested overall index would be an additional regulatory tool to evaluate the performance of network industries and their compliance with consumers' requirements. The aim of the proposed concept is to establish empirically verifiable feedback between a given state of technology, state of institutional governance, and the performance of network industries.

**Key words:** industrial engineering, network industries, performance indicators, system architecture.

## 1. INTRODUCTION

The economic growth and competitiveness of countries or regions rely on the development level and functioning of network industries. People, businesses, and public services depend on infrastructure networks to function efficiently. These networks comprise of roadways, railways, waterways, pipelines, electricity lines, postal services, and telecommunications to transport goods, obtain and transfer information, gain access, provide services, etc. [1].

Network industries can be defined as entities where the institution or its product consists of many interconnected nodes and where the connections among the nodes define the character of commerce in the industry [2]. A node in this context can be an institution, a unit of an institution, or its product.

The products and services provided by network industries represent a sizeable input for every country's economy accounting for a large part of their gross domestic product (GDP) [3]. On the other hand, the majority of the services provided by network industries are services of general interest. Governments intervene in markets to promote general economic fairness and maximize social welfare. Government intervention through regulation can directly address inefficient markets and cartels as well as other types of organizations that can wield monopolistic power, raising entry costs and limiting the development of infrastructure. Without regulation, businesses can produce negative externalities without any consequences. This all leads to diminished resources, stifled innovation, and minimized trade and its corresponding benefits [4]. Therefore it is necessary to evaluate and measure the performance of the network industries to ensure that the current structural changes do not prevent those social and public policy objectives being attained [3].

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Interest has recently considerably grown in performance measurement. The topic of performance measurement has generated much coverage over two decades in many disciplines within the private and public sectors [5].

The main objectives of the research reported here are to

- explore the possibility of developing a generic performance index (GPI) to evaluate the performance of network industries across traditional borderlines;
- propose a high-level reference model of conceptual information and communication technology (ICT) architecture to allow timely data collection, prediction, and analysis in order to support GPI calculation across network industries.

Latest developments in the ICT sector, such as Big Data and analytics in conjunction with novel user interaction design patterns, pave the way to measure all important performance parameters, create radically better understanding of the problem domain, and translate that knowledge into management decisions.

## 2. BASICS OF PERFORMANCE MEASUREMENT

### 2.1. Definition

Performance measurement is the use of statistical evidence to determine progress toward specific defined social or organizational objectives (see Fig. 1). In this paper, performance is seen as a broader concept than in the traditional financial approach, quality of supply, or quality of service, embracing the requirements of consumers in relation to the service provided by network industries. Many comprehensive studies have been performed about enterprises, but not covering full industry verticals or going across verticals [2].

The National Performance Review of the U.S. Federal Highway Administration provides a complementary definition of performance measurement [8],

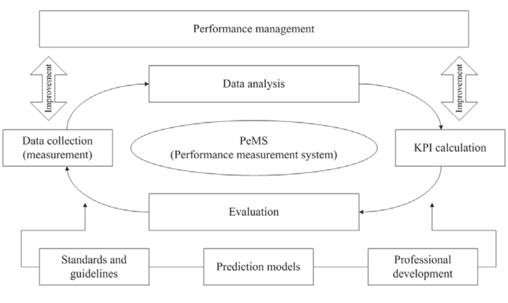


**Fig. 1.** Performance measurement system [6,7]. KPI – key performance index.

which is applicable in the context of network industries: 'A process of assessing progress toward achieving predetermined goals, including information on the efficiency with which resources are transformed into goods and services (outputs), the quality of those outputs (how well they are delivered to clients and the extent to which clients are satisfied) and outcomes (the results of a program activity compared to its intended purpose), and the effectiveness of government operations in terms of their specific contributions to program objectives.'

Every performance measurement system (PeMS) requires developing and reviewing at a number of different levels as the situation changes. The PeMS should include an effective mechanism for reviewing and revising targets and standards and should be used to challenge the strategic assumptions [9,10].

### 2.2. Performance indices

In this paper the authors propose hierarchical models of performance measurement where there is a synthesis of low-level measures into more aggregated indicators. The 'real-time' data collection gives new possibilities for performance monitoring and management since the services in network industries are 'consumed' at the same time they are 'produced' [3].

The performance index is a management tool that allows multiple sets of information to be compiled into an overall measure [11]. Key performance indices (KPIs) provide information to stakeholders about how well the services are being provided. Performance indices should also reflect the satisfaction of the users not only the concerns of the system owner or operator [8,12].

The procedure of combining data into indices is necessary to present simultaneous information from several related areas and data sources. This process provides a statistical measure that describes the change of performance over time.

Figure 2 proposes a general conceptual model ((1)–(3)) for performance indices. It can be exploited in network industries to evaluate performance of different network locations and elements and their performance trends over time.

$$\mathrm{PI_j} = f_{\mathrm{aggregate}}(f_{\mathrm{weight}}(f_{\mathrm{scale}}[\mathrm{TP}_{1\ldots n}])), \tag{1}$$

$$\mathrm{CPI_k} = \max[\mathrm{PI}_{1\ldots m}], \tag{2}$$

$$\mathrm{GPI} = \max[\mathrm{CPI}_{1\ldots p}], \tag{3}$$

where $\mathrm{PI_j}$ is first-level performance indicator, $\mathrm{TP_i}$ is observed technical parameter, $\mathrm{CPI_k}$ is combined performance indicator, and GPI is generic performance index.

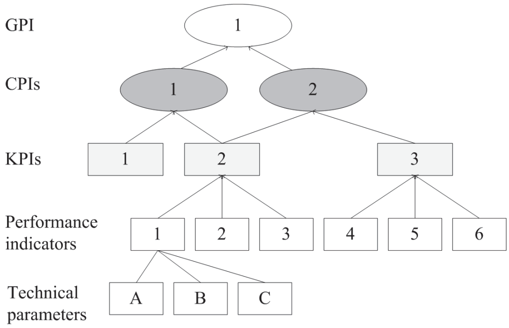


**Fig. 2.** Hierarchical structure of the performance indices in network industries [6,13–15]. GPI – generic performance index, CPI – combined performance indicator, KPI – key performance index.

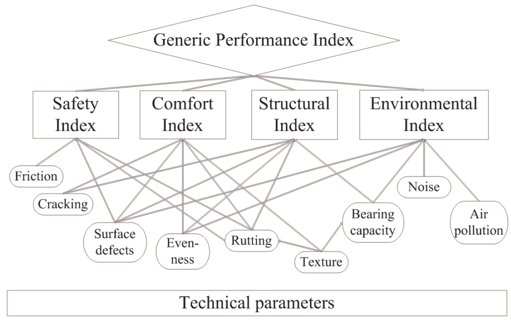


**Fig. 3.** Performance indices in the road industry as proposed by COST354 and EVITA [6,17,18].

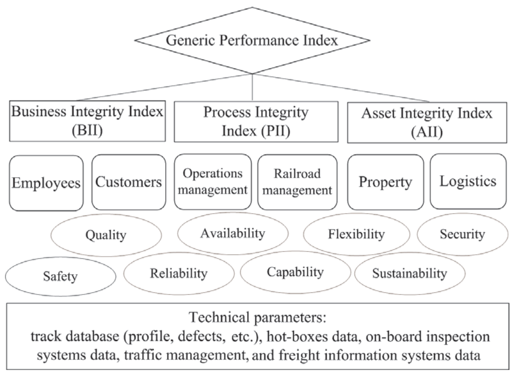


**Fig. 4.** Performance indices for rail infrastructure [19–24].

The TPs are measurable or observable environment characteristics, whose values vary over time. A PI defines the measurement of a piece of useful information about the performance of a programme or a work expressed as a percentage, index, rate or other comparable indicator that is monitored at regular intervals and is compared at least to one criterion. The use of PIs goes beyond simply evaluating the degree to which goals and objectives have been achieved [6,16].

Several scaling, weighting, and aggregation methods could be applied based on the nature of the data. The maximum function is proposed to combine and propagate the importance of the value through index hierarchy. Other combination techniques can be used.

## 3. EXAMPLES FROM NETWORK INDUSTRIES

### 3.1. Inland transportation networks

In the road industry, PIs are defined for different types of pavements and highway categories. On the first level several single PIs describing the characteristics of the road pavement are assessed [16]. The next step is the grouping of single PIs into KPIs and finally into representative CPIs as:

- functional performance indices (demands made on road pavements by road users);
- structural performance indices (structural demands to be met by the road pavement);
- environmental performance indices (demands made on road pavements from an environmental perspective).

Finally, based on the CPIs a GPI is defined for describing the overall condition of the road pavements (see Fig. 2 and Fig. 3). The GPI can be used for general optimization procedures [6].

A PeMS for railway infrastructure can be developed in a similar way. An example of how to model a respective GPI from railway and transportation CPIs and technical parameters is given in Fig. 4.

Inland transportation is a good example how performance can be measured as one comprehensive entity.

### 3.2. Power distribution networks

Attempts were made in [25–28] to create overall indices for the evaluation of the quality of supply and reliability of power distribution networks. Emerging Smart Grid developments are putting emphasis on understanding the performance of the power network not only from power quality and grid reliability aspects, but as a whole. However, the index systems in the power distribution are not yet as comprehensive as for road networks. Their development remains a topic for further research.

A lot of effort has been put into voltage quality research. Standardization bodies have implemented several indices [29–31]. However, the commercial quality, quality of service, safety of operations, and socio-environmental impacts of power distribution network operations have not been investigated thoroughly.

We made an attempt to combine different sources [25,28,32] of information into a single GPI (Fig. 5). This GPI can be visualized and hierarchically combined for substations (areas), feeder lines, phases, and metering points in the distribution network.

### 3.3. Telecommunication networks

No industry is related to so many other business sectors as telecommunications. The sector is regulated, but the competition is usually fierce among several service providers [33].

Measurement of the performance in telecommunications focuses on two major groups of non-financial indicators: operational efficiency and overall customer satisfaction and experience (see Fig. 6). This can be seen as the main difference from other network industries. The focus in performance measurement is clearly on the customer and efficient service delivery is the main requirement.

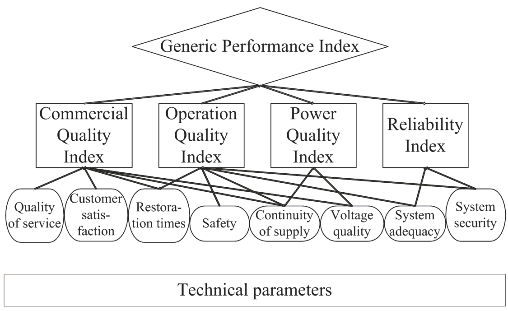


**Fig. 5.** Performance indices in the power distribution industry [18,25,28,32,34].

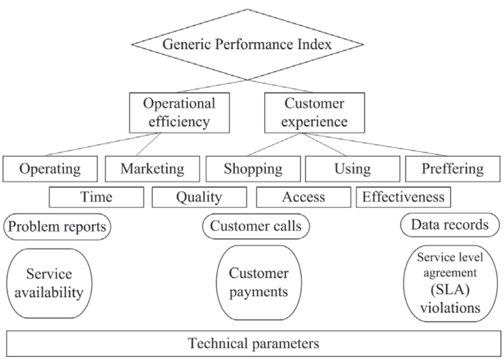


**Fig. 6.** Performance indices in telecommunications [33].

### 3.4. Synthesis

The examples of performance indices in network industries (what is measured, how the measurements are grouped and presented) reveal similarities and patterns. The indices are built up similarly and share the same principles.

Despite clear similarities, the focus of measured indices differs among industries. The focus reflects the main issues that are currently topical, omitting other aspects that deserve equal management attention. In the long run the control and steering decisions that are based on the subset of visible information are not effecient and optimal.

In order to systematize the numerous parameters affecting performance and to maintain conciseness, cognition, and clarity, it is important to find new ways to combine parameters systematically across network industries into one GPI and standardize the approach to CPIs (see Fig. 7). We see that here exist possibilities of harmonizing performance measurement principles. Such harmonization would allow of common visualization, comparison, and management of performance across network industries within a general ICT framework.

## 4. SYSTEM ARCHITECTURE

### 4.1. Data context

The process of unlocking additional value from the existing data and combining them with new data sources (e.g. sensors, Smart Meters, Internet of Things) will have a transformative impact on the management of network industries. More efficient, and therefore less expensive, data communication, storage, and presentation and better data processing mechanisms will allow of the handling of data of greater variety and volume with higher velocity in the near future, which will lead to adequate, accurate, and actionable insights [35,36].

We propose a reference model of system architecture developed to provide a high-quality overview of the functional components in a platform that enables processing the technical parameters and combining them into understandable indices as well as visualizing

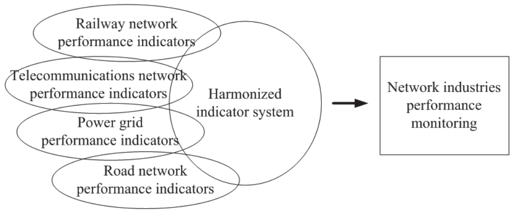


**Fig. 7.** Harmonized indicator system based on [24].

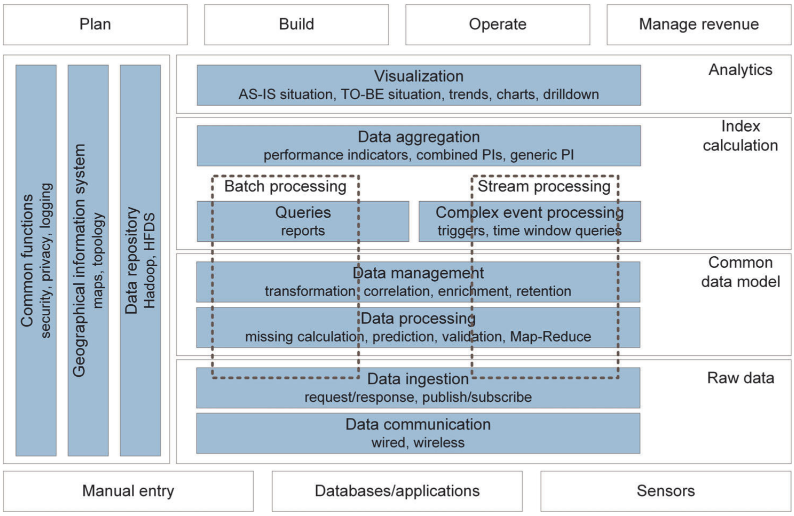


**Fig. 8.** Reference model of the system architecture of performance evaluation of network industries.

them for the end-user. By dividing layers of responsibilities between different functional components of the platform, we can get a clear view of the roles and responsibilities and lay the foundation for a common understanding.

The diagram in Fig. 8 presents an overview of the performance evaluation system and specific functional layers of the platform. The reference model is based on the work done at Tallinn University of Technology [6] and TM Forum [37].

### 4.2. Layers of the reference model

The purpose of the reference model is to provide a high-level overview of the functional components in the performance evaluation system. All layers have a clear responsibility borderline. Only a subset of functionality may be needed to satisfy the requirements of a particular performance evaluation scenario.

The data communication layer is responsible for transporting the data from data sources into the processing platform. The amount and creation speed of data will play the key role in choosing the communication technology.

The data ingestion layer is responsible for integrating various data sources and importing the technical parameters into the platform. The main task of this layer is to handle the volume, velocity, and variety of the data coming into the platform. Modules of this layer must be capable of scaling out in order to accommodate the data input bandwidth and speed.

The responsibility of the data processing layer is to ensure data quality. The validation of values is also done in the data processing layer. When data are missing, prediction algorithms can be applied to estimate the missing values [17].

The data management layer accommodates processes to perform format transformation towards a data model of uniform domain, correlation of events, and enrichment manipulation. Batch queries over the large historical dataset using the Map-Reduce [38] or a similar algorithm are to provide the functionality to implement scenarios that do not require real-time processing.

The Complex Event Processing (CEP) [39] layer on the other hand controls the processing of streaming data and the calculation of indices, doing it on on-going bases. As to large data, the two above-mentioned layers can be implemented by massively parallel-enabled data processors.

The data aggregation layer carries the responsibility of combining the results of CEP and queries into PIs and combined indices.

The visualization layer is often left out. However, it is the key to make the collected data easily understandable and meaningful to the end-users.

Common functions, Geographical Information System (GIS), and data repository are functions required to implement each of the layers.

## 5. CONCLUSIONS

Constant performance evaluation of network industries enables their more effective and efficient lifecycle management. Therefore, a lot of research on performance measurement and evaluation and even standardization efforts have been made.

For road networks systems of comprehensive indices are available. Indices of power distribution systems focus today mostly on the voltage quality side and do not provide real end-to-end support for decision-makers. Telecommunication indices focus on operational efficiency and customer experience. A railway GPI calculation system is presented only on an idea level.

Unifying and combining various aspects of different indices into a common performance index of network industries is proposed, but harmonized framework remains a topic for further research. The performance of all examined industries can be analysed and visualized using the proposed performance evaluation reference architecture.

The unified conceptual model of performance measurement as a system covering network industries as a whole should be used to understand and compare the performance inside and across network industries in a regulation realm to secure efficient and optimal investments into the structure and functioning of network industries.

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## Võrguettevõtete tulemuslikkuse mõõtmise ja hindamise kontseptsioon

Kristjan Kuhi, Kati Kõrbe Kaare ja Ott Koppel

Ettevõtteid, mida ennast või mille toodet võib vaadelda graafina, mis koosneb paljudest omavahel seotud sõlmedest, peetakse võrguettevõteteks. Sõlmed on graafi tippudeks ja servadeks on selle ettevõtte pakutav teenus või tegevus. Näiteks võib tuua elektri jaotus- ja ülekandevõrgu, telekommunikatsiooni- ning maismaainfrastruktuuri, posti-, vee- ja kanalisatsiooniettevõtteid. Tavaliselt on võrguettevõtetel turgu valitsev seisund ja nende tegevust jälgib turu-regulaator. Viimane mõjutab ettevõtete tegevust kvaliteedistandardite kaudu, millele peab pakutav teenus vastama, samas mõõdetakse tulemuslikkust reeglina finantsnäitajate abil. Autorite arvates on tehnoloogia areng teinud võimalikuks põhjaliku tagasiside saamise võrgu või selle osade efektiivsuse ja tehniliste näitajate kohta. Saadud andmeid süstematiseerides ja analüüsides on võimalik anda regulaatorile ning võrguettevõttele infot kvaliteetsete juhtimisotsuste tegemiseks. Käesolevas artiklis on selgitatud põhimõtteid, kuidas ehitada võrguettevõtete jaoks üles mõõdetavatel tehnilistel näitajatel põhinev üldine tulemuslikkuse mõõtmise süsteem, ja esitatud infotehnoloogilise süsteemi arhitektuur, mis võimaldab selliseid näitajaid koguda, töödelda, analüüsida ning võrrelda.

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# Using Probabilistic Models for Missing Data Prediction in Network Industries Performance Measurement Systems

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**Abstract**

The vast development of information and communication technologies has created new possibilities to acquire and analyze data to take performance measurement systems to next level. Most commonly performance measurement has been known as a financial management tool. Sophisticated new technologies have made it possible to collect continuous real-time data and enabled to start designing and implementing nonfinancial performance measurement systems. Most network industries are undertakings of dominant position and therefore subjects to strict supervision. For the authorities to fulfill their regulatory functions, precise monitoring and systemized feedback on the performance of network industries is essential. The problem lies in non-complete data in terms of missing, faulty or delayed values which might lead to incorrect management decisions. The objective of this paper is to explore the use of mathematical models for missing data prediction in performance measurement systems. Applying deterministic models hide the uncertainty of the value state therefore with higher likelihood false diagnoses occur. Authors propose probabilistic models because likelihood based methods for missing data calculation are able to take into account different parameters and time aspect in a single model to convey more trustworthy estimates in performance measurement systems than traditional methods.

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*Keywords:* industrial engineering; performance measurement; data collection; probabilistic graphical models

## 1. Introduction

Network industries can be defined as entities where the institution or its product consists of many interconnected

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nodes and where the connections among the nodes define the character of commerce in the industry [1]. A node in this context can be an institution, a unit of an institution or its product [2]. Examples of network industries are: transportation networks, postal services, electrical power networks, telecommunication networks etc.

When observed parameters of a system or a process are not delivered to processing entity (e.g. to performance measurement system, PeMS) in time, we consider the data missing. The problem of missing data afflicts a variety of application areas in network industries [3,4]. The datasets available to build models are often characterized by missing values, due to various causes such as sensor faults, problems of not reacting experiments, not recovering work situations, transferring data to digital systems [5].

PeMS are reliant on existence of data. Performance cannot be managed and controlled when the feedback cycle does not function properly or delivers faulty indications of the system state. In another hand missing data is everyday problem in statistics. Little and Rubin [6] explain that the mechanisms that lead to missing data are grouped into three distinct groups: missing completely at random (MCAR) – the absence of a data element is not associated with any other value in the data set, observed or missing; missing at random (MAR) – the absence of a values depend only on the observed values in the data set, not on the values that are missing; not missing at random (NMAR) – the absence of a value depends on the other missing values in the data set. In this paper we concentrate on the MCAR and MAR mechanisms where the absence of data does not have information value.

By applying this limitation, the methods for coping with missing values can be grouped into three main categories [6]: inference restricted to complete data (missing values are excluded), imputation-based approaches (missing values are filled in manually), and likelihood-based approaches (missing values are predicted).

The objective of this paper is to explore using mathematical models for missing data prediction in performance measurement systems. Constructing structured probabilistic models of the performance indicators (PIs) taking into consideration the surrounding indicator environment enables to find the indicator values with highest likelihood. It assists to fill gaps in data to improve the quality of the performance analysis and management decisions. In this paper authors present how to apply probabilistic graphical models to performance measurement in network industries that provides support for decision making in case of partial measurement data.

## 2. Hierarchical model for performance measurement

Performance measurement is the use of statistical evidence to determine progress toward specifically defined social or organizational objectives. Performance measurement describes also the feedback or information on activities with respect to meeting strategic objectives. They are used to measure and improve the efficiency and the quality of the production processes, and identify opportunities for progressive improvements in process performance. Most traditional measures overlook key non-financial PIs [7,8].

Performance is a term used in engineering, in economics and in many other areas. It can have a general meaning or a specific meaning. For the latter, and particularly for network industries, performance must be a measurable entity. Performance measurement techniques represent a key element of network industries asset management systems. Data collection for these systems is becoming feasible due to innovative technological advancements. This is essential for assessing the current and future state of specific fields and management efficiency in productivity, cost-effectiveness, environmental protection, preservation of investments and other functions.

According to literature contemporary PeMS should meet the following criteria: support strategic objectives; have an appropriate balance; have a limited number of performance measures; be easily accessible; consist of performance measures that have comprehensible specifications [9]. Other issues that should be considered selecting performance measures that can be used in evaluation includes forecast ability, clarity, usefulness, ability to diagnose problems, temporal effects and relevance [10,11].

Fig. 1 describes the conceptual model for PIs in the example of road industry. Technical parameter (TP) is measurable or observable environment characteristic. TP has value which varies over time. Uniform PIs permit an evaluation of the effects of different network design and maintenance strategies, but they can also be a basis for predicting network industries performance and for improving old and developing new prediction models. PIs are defined for different types of pavement structures and road categories. In a first step several single PIs describing the characteristic of the road pavement condition are assessed.

The next step is the grouping of these single PIs or indexes into representative combined performance indexes (CPIs) as:

- functional PIs (demands made on road pavements by road users);
- structural PIs (structural demands to be met by the road pavement);
- environmental PIs (demands made on road pavements from an environmental perspective) [10].

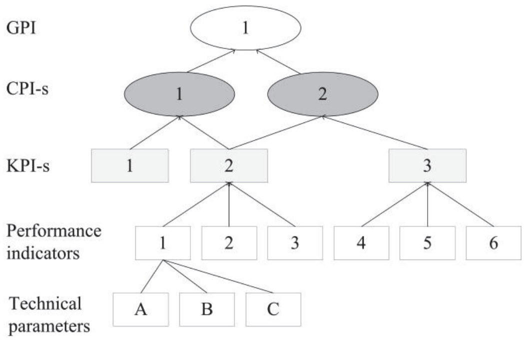

Fig. 1. Conceptual model for road PIs [12-15].

Finally, based on the CPIs a generic PI (GPI) is defined for describing the overall condition of the road network, which can be used for general optimization procedures [13]. For designing PeMS data should be collected about various structural PIs about the road network and about characteristics having an impact on the deterioration of the road. Consequently the performance index is a management tool that allows multiple sets of information to be compiled into an overall measure [16]. Similar trees or graphs are common in other network industries to understand the performance of the institution.

## 3. Method for missing data prediction

The performance of a system is often uncertain because the observations about the system features are partial, noisy or insignificant features are observed given the exact time moment. When using deterministic models, uncertainty of the system state is not visible, thus applying deterministic models are more likely to give false diagnosis [14].

Missing data can be approximated by multitude of different methods. Numerical analysis methods such as interpolation, extrapolation, time series modeling or likelihood based probabilistic modeling are the most common [6,7]. In this paper authors' explore Bayesian belief networks (BN) as a method that take into account expert knowledge, network element similarities and historical changes in times series in a single model, to calculate the probabilities of missing values.

A BN is a directed acyclic graph representing the joint probability distribution of all variables in a domain. The topology of the network conveys direct information about the dependency between the variables. In particular, it represents which variables are conditionally independent given another variable [7].

Given the knowledge represented as a BN, it can be used to reason about the consequences of specific input data, by what is called probabilistic reasoning. This consists of assigning a value to the input variables, and propagating their effect through the network to update the probability of the hypothesis variables. The updating of the certainty measures is consistent with probability theory, based on the application of Bayesian calculus and the dependencies represented in the network. Several algorithms have been proposed for this probability propagation. BNs can use historical data to acquire knowledge and assimilate domain experts' input [6-7,17].

Dynamic Bayesian Networks (DBN) is an attempt to add temporal dimension into the BN model [18]. Authors presume a time series dataset. Fig. 2 illustrates the probabilistic model. Variable $X=\{x_0, x_1, \ldots ,x_t\}$ represents the variable to be estimated, variable $Y=\{y_0, y_1, ... ,y_t\}$ represent piece of Bayesian network corresponding to all the related variables to X. $X_{t+1}$ represents the value of variable X at the time t+1, and $X_{t-1}$ represents the value of variable X at the time t-1.

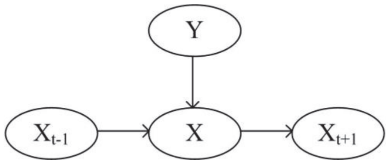


Fig. 2. Dynamic probabilistic model for data estimation [7].

In such system the joint probability factors out with the equation (1) [6].

$$P(X,Y) = P(x_0)\prod_{t=1}^{T-1} P(x_t \mid x_{t-1})\prod_{t=1}^{T-1} P(y_t \mid x_t) \quad (1)$$

If we divide $P(x_t|x_{t-1})$ and $P(y_t|x_t)$ to deterministic and stochastic components assuming linear deterministic part and Gaussian noise part then we can write it down like equations (2) and (3).

$$X_t = AX_{t-1} + w_t \quad (2)$$

$$Y_t = CX_t + v_t \quad (3)$$

Where A is the state transition array and C is the observation array, and $v_t$, $w_t$ are random noise vectors. This model represents a dynamic model which provides accurate information for estimating the variable in two senses: firstly, using related information identified by experts in the domain; secondly, using information of the previous and incoming values. This information includes the change rate of the variable according to the history of the signal.

DBNs represent the state of the system at different points in time, but do not represent time explicitly. As a consequence, it is very difficult to query a DBN for a distribution over the time at which a particular event takes place. Nodelman, Shelton and Koller [19] have presented an algorithm for approximate inference which takes advantage of the structure within the process over continuous time BN.

## 4. Applying DBN to performance measurement

Prediction in BN starts with some prior knowledge about the model structure: a set of edges and nodes in belief network. Performance index graphs are common and structured way to represent the expert knowledge concerning dependencies between measurable TPs and PIs (see e.g. [2]). Combining those graphs with time series data, we can build an initial dependency graph, which fragment is represented on Fig. 3, of PIs and CPIs to use for missing data estimation. The exact inference in DBNs to estimate continues values is difficult if not possible to achieve. The method can be applied to estimate discrete PI values since PIs are usually discrete by nature and the quantization algorithms has been proposed by the standards. This allows simplifying and looking the model as linear Gaussian state-space model.

If we take the example of road networks (see [14] for further details) performance monitoring, then R represents rutting PI, C-CPI is comfort index, S-CPI is safety index. $S_1$ and $S_2$ are similar road sections. In similar way all the dependencies are captured on a graph to build initial models. Some of the currently missing values can be derived from other measurements and similar historical cases. Some can be approximated and still used in the performance calculus giving indication to the end user of the probability of correctness [20]. In this way we can build a model in each network industries having performance measurement standard in place. This initial model gives us prior probability distribution over model structure. Enriching it with data will lead to posterior probability of the parameters.

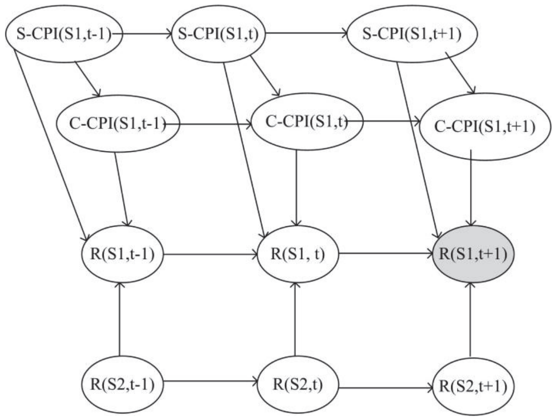


Fig. 3. Fragment of initial dependency graph.

If E={e} is the collection of evidence containing observations about S-CPI, C-CPI, R, $S_1$ and $S_2$ over {1:t} then we can build equation 4 to solve the first step prediction problem for time slice t+1.

$$P(R_{t+1;S1} \mid e_{1:t}) = \sum_{R_t} P(R_{t+1} \mid X_t) P(X_t \mid e_{1:t}) \tag{4}$$

A technique of handling estimation issue in this type of networks is the Expectation-Maximization (EM) algorithm. This algorithm makes use of iterative update steps, each time regulating the parameters so as they maximize the expected logarithmic-likelihood, where the expectation is taken with respect to the previous value of the parameters. This algorithm is guaranteed to converge to a locally optimal solution whenever the missing or hidden data are missing at random, i.e. without there being any dependence of the missing data pattern on the values the variables would have had, had they been observed [6].

## 5. Conclusions

Reliable and accurate predictions of performance can save significant amounts of public resources through better planning, maintenance, and rehabilitation activities. Non-complete data in terms of absent or defective values and deferred timing leads to incorrect decisions. The objective of this paper was to explore using mathematical models for missing data prediction in performance measurement systems

Authors propose an approach to compute missing data using probabilistic graphical models in combination with expert knowledge accumulated in performance measurement best practices to eliminate gaps in network industries performance data. Applying deterministic models hide the uncertainty of the value state therefore with higher likelihood false diagnoses occur. Using probabilistic models is suggested because likelihood based methods for missing data calculation are able to take into account different parameters and time aspect in a single model to convey more trustworthy estimates in PeMSs than traditional methods.

Main conclusions are the following:

- Likelihood based methods for missing data calculation are able to take into account different parameters and time aspect in a single model to convey more trustworthy estimates than traditional methods.

- DBN can easily be created from expert knowledge (in the form of standards and/or best practices), network element similarities and historical changes in times series and provide algorithm for approximate inference on PI level over continuous time.
- This allows filling critical gaps in performance monitoring data together with estimation value likelihood. It will enable making missing data, estimations and their trustworthiness visible to the decision makers.
- The decisions and historical drilldown do not depend on full datasets in each moment of time. Network industries can benefit from the visibility of their performance data.

The conclusions are in line with the previous research. Future research includes practical comparison on the effectiveness of such approach in comparison to unsupervised learning and other possible likelihood based estimation algorithms. Furthermore the research on excluded NMAR mechanism needs to be performed. Testing the model in real-life scenarios and practical optimization of the algorithm can be taken as further steps.

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**Publication III**

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# Calculating power distribution system reliability indexes from Smart Meter data

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***Abstract*—Electricity is an integral utility in modern society. Electricity networks carry power to various end users, and disruptions cause high socioeconomic cost. Electricity distribution network operators are ranked predominantly on system performance, economic performance and customer satisfaction. System reliability has an impact on all of the above mentioned indicators. High and medium voltage networks are covered with sensors allowing to calculate accurate reliability indexes. Low voltage (LV) grid sensor coverage is yet insufficient, but modern Smart Meters add functionality to gather necessary grid characteristics. Data from various meters can be combined to continuously generate indexes that depict state of the LV network. Calculated indexes enable to prioritize system faults and proactively correct shortcomings of the grid. This paper presents a method to calculate temporospatially disaggregated reliability indexes on all major levels of the LV network which on demand depicts detailed performance assessment of the grid.**

***Index Terms*—data analysis, meter reading, performance evaluation, power systems.**

## I. Introduction

In network industries performance management process can measure trends and track progress of infrastructure to meet demands of economy [1]. Performance index is a management tool that allows multiple sets of information to be compiled into an overall measure for stakeholders to monitor how well the services or products are being provided [2]. Performance indexes should also reflect the satisfaction of the users not only the concerns of the system owner or operator [3]. Data used to calculate indexes affects management, but also operational decisions, thus the selection of measurement parameters, time and location must be well chosen to obtain most relevant and accurate information about the observed object.

Customer interruption costs have more than doubled over the last 20 years [4]-[5], showing society's increased dependence on electricity and need for reliable power supply. Rapid growth of micro generation introduces quality issues in LV networks that are not visible beyond secondary substation [6]. In order to guarantee the effectiveness of planning and implementation of reliability improvement techniques, LV grid must be visible and traceable. The goal of this paper is to show the possibility to use existing Advanced Metering Infrastructure (AMI) and modern data analytics systems to enhance visibility of grid issues and calculate severity of problems like outages, supply quality issues etc. [7].

The loss of service to one or more customers connected to the distribution portion of the system is called interruption. It is the result of one or more component outages, depending on system configuration [9]. Single or multiple phase loss and voltage dips reaching below 90% Un (nominal voltage) for more than 5s is considered as customer service interruption in this paper.

Traditionally reliability indexes are followed up on system level. Pockets of poor reliability are hidden in system-wide average indexes. Reporting spatially disaggregated indexes is one possibility to overcome that issue [8]. Novel aspect examined in this paper is to compute temporospatially disaggregated reliability indexes on all major levels of LV grid (i.e. substation, transformer, feeder-line and metering point level) on pre-defined time intervals based on Smart Meter data to enable detailed performance assessment of the power distribution grid.

## II. Reliability Indexes

### A. Indexes

Various practices and techniques are used to measure the reliability of power distribution systems. The common measurements are interruption indexes (sustained, momentary) and load based indexes that are defined by the IEEE1366. Technical parameters that characterize reliability are: frequency, duration and the extent of the interruption [4]. Normally reliability indexes of distribution grid are calculated based on grid operation center MV fault classification results and customer complaints. The indexes covered by IEEE1366-2003 [9] are briefly summarized in Table I.

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TABLE I. SUMMARY OF IEEE1366-2003 INDEXES

| Index | Description |
|---|---|
| SAIFI | System average interruption frequency index |
| SAIDI | System average interruption duration index |
| CAIDI | Customer average interruption duration index |
| CTAIDI | Customer total average interruption duration index |
| CAIFI | Customer average interruption frequency index |
| ASAI | Average service availability index |
| CEMIn | Customers experiencing multiple interruptions |
| ASIFI | Average system interruption frequency index |
| ASIDI | Average system interruption duration index |
| MAIFI | Momentary average interruption frequency index |
| CEMSMIn | Customers experiencing multiple sustained interruption and momentary interruption events |

Reliability indexes cover just one fragment of more comprehensive index system to monitor performance of a distribution grid (Fig. 1). Emerging Smart Grid developments are putting emphasis on understanding the performance of the power network not only from power quality and grid reliability aspects, but as a whole. However, the index systems in the power distribution are not mature up till now [3].

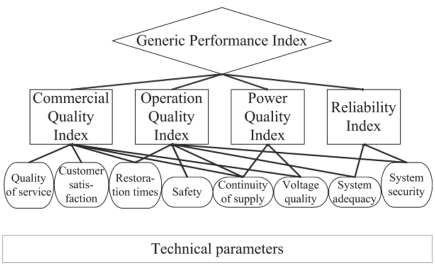


Figure 1. Performance index tree.

This paper is part of generic network industries performance monitoring system study covering inland transport, utilities and telecommunications networks with the ambition to apply similar supervision concepts and techniques on different networks [3], [10]-[12]. Such index system can be exploited to evaluate performance of network elements and locations, and their performance trends over time and is prerequisite for effective design and preventive maintenance of power distribution grid.

## B. *Improving reliability*

Grid reliability can be improved by reducing the duration, frequency and magnitude of interruptions (Figure 2). Theoretically adding more customer connections may have also positive impact on reliability, but is difficult to achieve in real life.

Methods for reliability improvement include, but are not limited to [13]:

- Underground cables and insulated overhead lines. This method is among the most effective way of improving reliability. E.g. failure rate of MV overhead lines is 3-5 times greater than underground cables.
- Reserve connections and new substations. This technique is useful especially in urban environments. The length of visible interruptions decreases when the number of reserve interconnections is growing.
- Compensating the earth fault current. Most common fault type in distribution grid is single phase to earth fault. Major advantage of this method is avoiding customer interruptions when fault is being fixed.
- Distribution automation. Implementation of distribution automation helps to reduce interruption length. This method is usually less costly and less disruptive than major network refurbishments.
- Meshed grid. When interruptions occur on the radial grid then interruptions affect all customers connected to the feeder line. In meshed network a single failure does not cause an interruption. Reliable high-speed communication networks, differential protection relays and breakers on secondary substations are required to be able to operate meshed network.
- LV network monitoring and control. Besides energy measurement, Smart Meters contain functions to report different grid characteristics to support grid operations and strategic planning. LV grid monitoring enables to detect and resolve also MV grid faults.

This paper is focused on the last method as one of the most recent one.

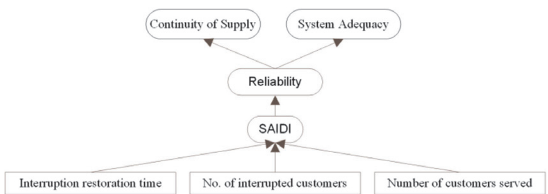


Figure 2. SAIDI in the context of performance index tree.

Standalone power grid reliability improvement is not correct goal of a utility company. It must be seen in the context of other performance indicators (Fig. 2) to avoid customer service under or over delivery and waste of valuable resources affecting the sustainability of the company or society as a whole. Technical measures do not guarantee better reliability with most optimal cost without the understanding of the performance of the distribution grid in detailed level.

## III. METHOD

Smart meters are the closest measurement devices to the end customers. Functionalities offered by meters vary slightly, but the base set is similar for all state of art meters, including:

- Energy measurement,
- Load profiles,
- Time-of-use tariffs,
- Voltage level bypass,
- Phase asymmetry,
- Phase loss and
- Interruption events.

Case study is performed using large homogenous meter network covering 60% of the total LV power grid usage point population (Table II). The meters are distributed across the grid evenly. In time, smart meter network of the selected distribution network operator will reach 100% coverage. Due to country and grid specific, majority (62%) of the metering points are situated in rural areas behind long feeder lines.

TABLE II. DATA SUMMARY

| Parameter | Value (Millions) |
|---|---|
| Total metering point count | 0.70 |
| Reporting metering point count | 0.42 |
| Reporting metering points in urban areas | 0.26 |
| Meter event records in measurement period | 200.94 |

Meter Data Collection System (MDCS) used in this study exposes meter events according to IEC61968-9 standard. Measurement dataset contains raw information about first 10 months of the selected calendar year. Total amount of different meter events during the period exceeds 200 million. Meters are configured to send out events according to EN 50160. Time is synchronized between MDCS and field equipment over Network Time Protocol (NTP). Time synchronization malfunction is monitored and reported.

Power quality related meter events in such setup are reported in multiple ways. Typically problem start and end are registered in separate records (Table III). Depending on meter and communication technical setup, events may be reported repeatedly until the problem (e.g. missing voltage) is cleared. Event data normalization process was performed to filter out all interruptions related meter events from the full dataset and find correct start and end times. The interruption event is stored as one record and enriched with LV grid topology (i.e. substation, transformer, feeder line and metering point) information. Interruption in this context can be defined as a data record containing start and end dates, phase and electrical location where customer loss of service occurred.

CEER [14] and IEEE [15] studies show that the most popular sustained interruption index amongst European and US utilities is SAIDI followed by SAIFI, CAIDI and ASAI. This paper focuses on the first one as an example. The method itself is applicable to calculate all of IEEE1366 reliability indexes or newer indexes such as CIC/kWh (Customer Interruption Cost per kWh) in temporospatially disaggregated way.

TABLE III. IEC61968-9 ENDDEVICEEVENTTYPES

| EndDeviceEventType | Description |
|---|---|
| 3.26.0.85 | Power down |
| 3.26.126.85 | Missing voltage L1 |
| 3.26.134.85 | Missing voltage L2 |
| 3.26.135.85 | Missing voltage L3 |
| 3.26.0.216 | Power up |
| 3.26.131.37 | Voltage L1 resume |
| 3.26.132.37 | Voltage L2 resume |
| 3.26.133.37 | Voltage L3 resume |

For validation purposes, calculated indexes are compared against previous calendar year public SAIDI values of the same grid operator. The SAIDI values are reduced to the meter event data timescale. Linear SAIDI across the observation time and geography is assumed. Major event days are included in the calculation.

SAIDI is a reliability indicator (1) that shows system average interruption frequency. It denotes how often the average customer experiences an interruption over a predefined period of time.

$$SAIDI = \frac{\sum_{i \in I} r_i N_i}{N_T} \quad (1)$$

Where $i \in I$ denotes the interruption event, $r_i$ is restoration time for each interruption event, $N_i$ is number of interrupted customers for each interruption during selected period and $N_T$ is total number of customers served in selected area.

## IV. RESULTS

To calculate SAIDI over set of meter events $E \supseteq I$, we need to find start $e_{start} \in E$ and end $e_{end} \in E$ events from the event data set filtering by event type (Table III), and their corresponding start and end timestamps $t_{start}$, $t_{end}$. It is important to notice that $count(e_{start}) \in \{0,1\}$ and $count(e_{end}) \in \{0,1,..,\infty\}$. $N_{TS}$ represents the total population of Smart Meters in observed area. Such approach can be used if the ratio of Smart Meters is large enough to give adequate information about the total customer base.

$$SAIDI_E = \frac{\sum_{i \in I} (\max(t_{end,i}) - t_{start,i}) N_i}{N_{TS}} \quad (2)$$

Formula (2) takes into account possible event duplications caused by AMI technology. Normalization of the meter events and calculation of the power quality records reduces the amount of processed data 79% (Table IV) while calculation of the interruption events reduces data 89%. $SAIDI_E$ values in another hand remain high compared to official MV SAIDI numbers (Table V)

Case study dataset contains interruption events lasting from minimum 0 seconds until 10 months. Mean interruption length is 9568 seconds, median interruption length 450 seconds. Figure 3 illustrates probability distribution of the event durations. It can be seen that the frequency of interruptions lasting up to an hour is much higher compared to any other time period. Interruptions are approximately log-normally distributed.

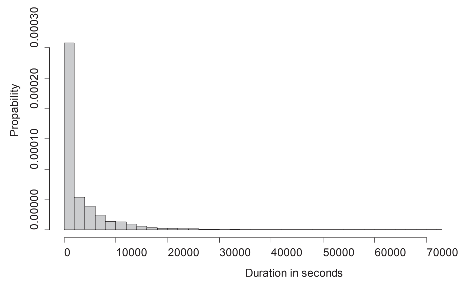


Figure 3. Probability distribution of interruption durations.

According to EN 50160, interruption events can be classified into two main categories: short interruptions up to 3 minutes, and long interruptions with duration more than 3 minutes. Zooming into the first hour of interruption duration histogram shows that during those 3 minutes we have the highest frequency of interruptions producing 6% of all normalized interruption events (Fig. 4, Table IV).

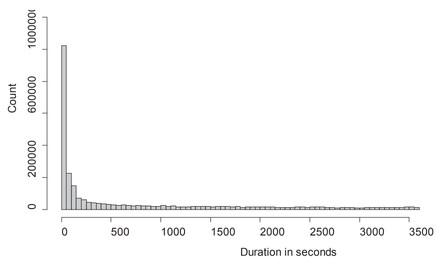


Figure 4. Distributon of interruptions (Δt < 1h).

Combining "power up" and "power down" events (Table III) forms the clearest power interruption pattern. Set P ⊒ I symbolize such interruption events. Those events can be taken into SAIDI calculation dataset using (2). Out of all single smart meter issues customer triggered interruption is the most common. Smart meter network operations work order dataset shows that 49% of the single customer long interruption reasons are related to customer main circuit breaker being switched off. Events belonging to set S ⊒ I must be excluded from index calculation dataset.

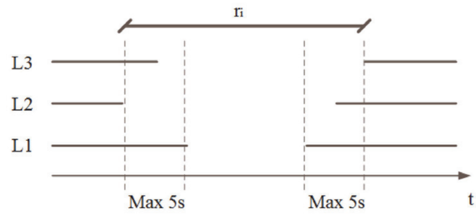


Figure 5. Merging multi-phase interruptions.

Simultaneous single customer multi-phase interruptions cause unsubstantiated increase in SAIDI value. Such events must be merged into one interruption event in index calculation dataset. Authors propose five second rolling time window that starts with the first Missing Voltage event (Table III) on any feeder line phase to begin counting interruption time and same size time window for Voltage resume events to close counting the length of interruption (Fig. 5). The proposal is based on IEC61000 rules for voltage sag classification as interruption to still be able to catch multiple short interruption events in a row. Let such events be part of set L ⊒ I. Single phase interruptions on L1, L2 and L3 that do not belong into L are part of set O ⊒ I.

Based on the argumentation above we can improve (2) with exclusions and construct (3):

$$SAIDI_{EE} = \frac{\sum_{i\in((P\cap L\cap O)\setminus S)} (\max(t_{end,i}) - t_{start,i}) N_i}{N_{TS}} \quad (3)$$

Applying (3) on normalized interruption event dataset reduces the amount of interruption events 98% (Table IV). Order of magnitude of interruption event count is similar to reference year official figures of chosen benchmarking grid.

TABLE IV. DATA AFTER CLEANSING

| Parameter | Value (Millions) |
|---|---|
| Total power quality events (normalized) | 41.41 |
| Interruption events (normalized) | 22.37 |
| Long interruptions (Δt >3min) | 20.93 |
| Short interruptions(Δt ≤3min) | 1.44 |
| Events after applying exclusions | 0.47 |

Cumulative ten-month SAIDI calculation values of the study object are correspondingly similar to reference year (Table V). Reliability improvement methods are ordinarily applied in urban areas justifying slightly lower SAIDI value. While in rural areas long overhead lines are causing reliability issues among other rationales. Similarly (3) can be applied to any geographical area or combination of areas allowing calculation of index values across management areas, municipalities, substation service area, feeder line service area or point locations such as transformers, reclosers or metering points. In benchmarking dataset we see SAIDI variations from minimum 0 seconds until maximum 3.1 days on different aggregation levels.

TABLE V. SAIDI CALCULATION RESULTS

| SAIDI | 2014 | 2015 | |
|---|---|---|---|
| | ***Yearly report (SAIDI)*** | ***Based on interruption events ($SAIDI_E$)*** | ***Exclusions applied ($SAIDI_{EE}$)*** |
| Country level | 163 | 1712 | 247 |
| Urban areas | 163 | 679 | 157 |
| Rural areas | 163 | 3370 | 390 |

Modern data processing architectures allow calculation and aggregation of indexes over any time window in near real-time [3]. However data delivery in smart meter networks is often not reliable, depending on the chosen communication technology and metering equipment quality. Faults occur and index recalculations are needed when delayed data arrives. Methods exist to build estimation models and predict missing values to fill gaps for index calculation [12]. The stability and accuracy of index values for management decisions depend on chosen technology, but also data delivery service level set for meter network operations team. It is recommended to always depict index value stability or estimated accuracy together with the value itself.

If meter communication technologies and data delivery targets are chosen appropriately, calculated index values can be used in grid operation management including grid state and fault management. Network planning function will benefit from such method regardless of the data arrival timespan. Comparing calculated index values to target values gives additional benefits. Deviation span will determine the severity of the issue. This allows positioning issues in the context of extensive grid problem set and enables to focus on the problems with most impact and criticality. Furthermore the above described method will have effect on issue classification, localization and restoration times; and supports more accurate long term grid investment planning.

## V. CONCLUSION

Modern society relies greatly on electricity. Power networks offer services to numerous end users, and disruptions have high socioeconomic cost. This paper is applying generic network industries performance monitoring system concepts and techniques on power distribution network to evaluate reliability of network elements and locations, and their performance trends over time.

Authors study the possibilities to compute temporospatially disaggregated power grid reliability indexes on all major topology levels of low voltage grid based on Smart Meter data. SAIDI is used as an example. Smart Meter events need proper cleansing and authors propose formula how to reduce flood of meter events in near real-time into usable dataset for SAIDI calculation using modern data processing tools. For validation purposes, calculated SAIDI values are compared to a grid operator official public data.

Proposed method guarantees better visibility and offers possibility to drill down from overall system level performance index to a specific area or object that is causing deviation from target. Similar method applies to other power quality measurement metrics. Method will have effect on issue classification, localization and restoration times; and supports long term grid investment planning.

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**Publication IV**

**Kuhi, K.**; Kaare, K.; Koppel, O. (2018). Ensuring Performance Measurement Integrity in Logistics Using Blockchain. Proceedings of the 2018 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI 2018): 31 July - 2 August 2018, Singapore. IEEE, 260−265.

# Ensuring performance measurement integrity in logistics using blockchain

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***Abstract*— Information and communication technology has been a positive dynamic force behind improving performance. Simultaneously enabling digital business ecosystems to become an increasingly popular concept for modelling and building distributed systems in heterogeneous, decentralized and open environments. These business solutions have created an opportunity for automated business relations and transactions as well as implementing blockchain based performance measurement systems (PMS), allowing PMS to be more advanced giving validation and verification of received data hence the indicators. This paper evaluates feasibility of blockchain based PMS for logistics industry. Today the performance of supply chain stakeholders including transport logistics is lacking transparency and restraining innovative digital improvements towards a connected, smart and efficient ecosystem. Current public blockchains are not feasible for given use case due to limited throughput, and transaction cost. In this paper we have evaluated different technological alternatives and found several new developments that make blockchain technology suitable for ensuring logistics sector performance measurement integrity. Validated indicators can add trustworthiness and visibility to management and process improvement decisions, as well as be subject to smart contracts and monetary transactions.**

***Keywords—supply chain, blockchain technology, performance measurement, valid performance indicators***

## I. Introduction

Traditional business strategy, IT strategy and digital business strategy are merging and forming new digital business ecosystems. These ecosystems are driven by the business environment demanding more intuitive, real-time, integrated solutions and services to deliver greater value. Brynjolfsson & McAfee [1] noted "Everything that can be digitized will be digitized. Everything that can be automated will be automated". We have entered an era of digital transformation that profoundly changes the business and organisational activities as well as competences and models to exploit the new digital technologies developing a more visible, agile hyper-connected ecosystem.

Supply chain is defined as the line of various points involved in producing and delivering goods, from the procurement stage to the end customer consisting of various stages and locations. The supply chain today is a series of largely discrete, siloed steps taken through marketing, product development, manufacturing, and distribution, and finally into the hands of the customer.

These different stages usually involve different stakeholders with their internal systems not integrated through the supply chain. Therefore, it has been difficult to track, trace and manage events in the entire chain. Moreover, due to the lack of transparency and integrated IT platforms in the supply chain may result in inefficientnt management and poor performance.

Today's supply chains are becoming more complex and the visibility of key information, events and collaboration across organizational boundaries is increasingly viewed as essential criteria to the long-term competitiveness of the supply chain network. Managers in many industries, especially in manufacturing, are trying to better manage supply chains by putting together roadmaps of digitalizing supply chains. Digitization overcomes these barriers and the chain becomes a completely integrated ecosystem that is fully transparent to all the players involved — from the suppliers of raw materials, components, and parts, to the transporters of those supplies and finished

The vision of Industry 4.0 is to have most enterprise processes to become more digitized. From Industry 4.0 has merged the concept of Logistics 4.0 using technical solutions like: the cyber physical systems, the wireless networks, the Internet of Things, Big Data/Data Mining and cloud computing, blockchain technology etc. A critical element will be the evolution of traditional supply chains toward a connected, smart, and highly efficient digital supply chain ecosystem. These digital supply chains will dissolve silos and enable visibility and better management and performance. These changing supply chains open new possibilities to changes in business processes [2].

In today's digital business reality most old rules of logistics and supply chain management still are valid. The 7Rs (seven rights) as coined by Coyle et al. [3] in logistics go back a long time: the right product/item in the right quantity to the right customer in the right condition at the right place, right time and right cost. Measuring the right time and right place in our new digital era means data from sensors, from other databases, applied prediction models and using insights based upon data analytics or digitized information across the supply chain.

With the expectation that what is measured can be better managed, performance measurement is being implemented as a core component of management processes in public sector agencies. In the face of growing challenges, performance measurement is attracting growing interest from transportation agencies. Performance measurement has been enclosed long time in the pavement management and bridge management systems. The learnings are taken now into applications and processes in construction and maintenance management systems, operations and safety programs, and administrative structures and processes.

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Performance monitoring and performance management are sometimes used as synonyms, but they are not. Performance measurement is quantifying, either quantitatively or qualitatively, the input, output or level of activity of an event or process. Performance management is action, based on performance measures and reporting, which results in improvements in behavior, motivation and processes and promotes innovation. They also add a third strand of performance reporting – recording performance, possibly against a target or including analysis [4]-[5].

Performance measurement provides the means to assess the effectiveness of an organization's operations from different perspectives. It is used to provide feedback at all levels – strategic, tactical or operational, project level – on how well strategies and plans are being met. Performance feedback provides the information necessary to improve decision making within the organization and further on government level, to enable proactive problem correction and to promote continuous improvement [5].

Traditional performance management is not enough for many companies in the era of new technologies and digital performance management has become the solution to aligning infrastructure and operations with business goals.

Logistics performance measurement and management is regular monitoring of every aspect of the supply chain. This process includes collecting data surrounding all logistical activities including inbound and outbound transportation, fleet management, warehousing, inventory management, materials handling, order fulfillment, supply and demand planning, 3PL management, logistics network design and other support services – essentially anything that has an impact on cost or performance [6].

Abovementioned data can be collected, processed and analyzed by using digitalized supply chains, sensor networks, internal and external databases.

## II. Blockchain Technology

Blockchain represents the key element for the creation of the digital supply chain. Blockchain technology is disrupting society by enabling new kinds of disintermediated digital platforms. The disruptive technology is regarded as a potential means of establishing the integration of the different actors in the supply chain, enhancing the information flow among them and ensuring the security as well as the cost effectiveness.

Current digital economy is based on the reliance on a certain trusted authority – all online information relyes on someone giving us trustworthy information. As individuals and businesses we rely on a third entity for the validity, security and privacy of our digital assets and in most areas do not take into account that these third party sources can be hacked, manipulated or compromised. Blockcahin technology has a dual effect of removing the need for actively intermediated data-synchronization and concurrency control.

Although blockchain has only become hot technology in recent years, Estonia has been testing the blockchain technology since 2008. Since 2012, blockchain has been in production use in Estonia's data registries, such as the national health, judicial, legislative, security and commercial code systems, with plans to extend its use to other spheres such as personal medicine, cybersecurity and data embassies [7].

The original blockchain concept developed by a group of people under the name Satoshi Nakamoto was a fully public one, 100% decentrally controlled. However, this structure is not applicable for all possible timestamped ledger applications. Different applications require different levels of security. Therefore, a classification of the different blockchain architecture styles can be made based on a two-dimensional classification system: public/private and permissioned/permissionless [8].

Blockchain is a transactional database, which is distributed among nodes linked in a peer-to-peer (P2P) communication network. [9] The access to the network is based on a permission mechanism, which enables the nodes to perform transactions that hold validity based on a consensus mechanism. The key feature of Blockchain technology resides in its distributed nature. Different from centralized and decentralized networks, a distributed computing network system is a system where data and resources are spread out on various hardware nodes. Moreover, each node maintains a database of historical and valid transactions, which are sent among the nodes in the network. Despite every node holds a copy of the ledger, only those users that hold the signature on it can access the information [10].

As described by Morabito [11] the blocks composing the shared ledger can be seen as containers where data is stored. However, these containers are sealed and their content can only be seen by those who hold the permission. The nodes identify each other by their address, while users address to each other through their public key. Each node represents a physical/virtual machine that communicates via computer network with other nodes. Therefore, each node can send a transaction to every other node in the network if it knows the receiver's public key, without any central authority involved in the transaction.

Blockchain value lies in increased level of trust between members of the network. Transactions are interdependent of all the previous transactions, any exploitation is immediately evident, and visible to every participant. The self-protection mechanism of blockchain makes the existing legal or government safeguards for business transactions irrelevant. The community of participants does that. Where third-party oversight is required, blockchain reduces the burden on the regulatory system by making it easier for auditors and regulators to review relevant transaction details and verify compliance [12].

Blockchain builds trust through the following five attributes [13]:

- Distributed and sustainable;
- Secure, private, and indelible;
- Transparent and auditable;
- Consensus-based and transactional;
- Orchestrated and flexible.

The ledger is shared between participants, it is updated when transactions occur, and replicated amid contributors. Public blockchain is not owned or controlled by any single organization, the continued survival of the platform isn't dependent on any individual party. Transaction parties have access to all records and can validate and verify identities or ownership without the need for third-party intermediaries. Transactions are time-stamped and can be verified whenever needed in time. Unauthorized access to the network is prevented by permissions and cryptography. The authentication is built in and guaranteed.

When terms are agreed, parties can't tamper with a record; modification can be corrected only with new transactions. Network parties must agree that a transaction is valid. It is accomplished using consensus algorithms. Blockchain networks can grow to support end-to-end business processes, legal and monetary transactions if smart contracts ecosystem evolves. Blockchain technology enables to solve data sharing amongst a network of untrusted participants without bringing a central authority in both in case of internal data sharing and reporting in a company or as largely as across the entire supply chain.

## III. Research

### A. Research Design

This research is based on earlier cross-industry performance measurement harmonization work [14]-[16]. Constant performance evaluation of network industries enables their more effective and efficient lifecycle management. The unified conceptual model of performance measurement as a system covering network industries should be used to understand and compare the performance inside and across network industries in a regulation realm to secure efficient and optimal investments into the structure and functioning of network industries. Validated indicators with guaranteed integrity adds trustworthiness and visibility to management and process improvement decisions, as well as be subject to smart contracts and monetary transactions.

Transaction throughput and cost modelling is performed for blockchain networks. Case study is implemented using subset of SmartLog project [17] scope for model verification and as an illustrative example of the challenges that are faced while trying to preserve integrity in practice in logistics industry.

Fig. 1 schematic drawing shows the role of blockchain in a supply chain value chain, guaranteeing the visibility and integrity of the whole ecosystem.

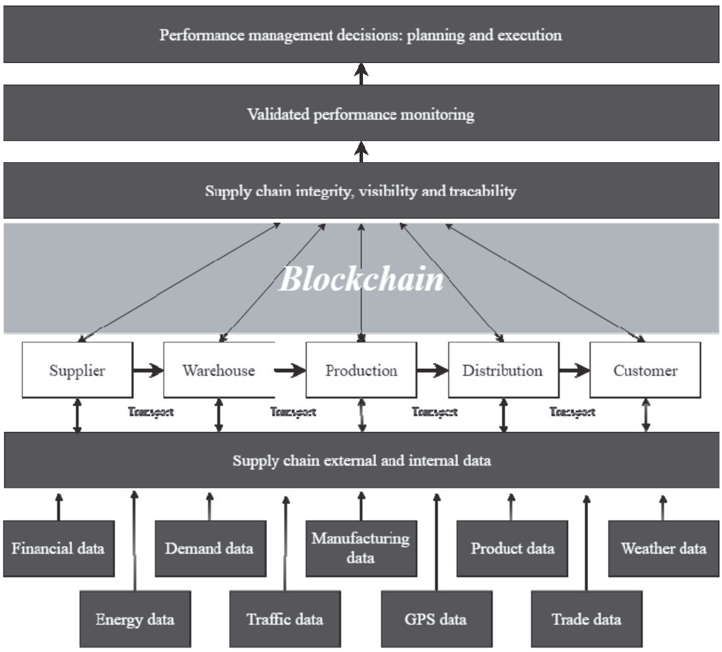


Fig. 1. The role of blockchain in the supply chain value chain

In the logistics industry, performance indicators are defined for inbound, outbound and intralogistics. On Fig. 2 is depicted a more detailed and hierarchical approach to supply chain performance generating an overall general performance index (GPI) from key performance indicators (KPI) and KPI from performance indicators (PI). PIs are calculated from measured technical parameters (TPs) of the involved asset. Transport performance is chosen from the full system of indicators as an example.

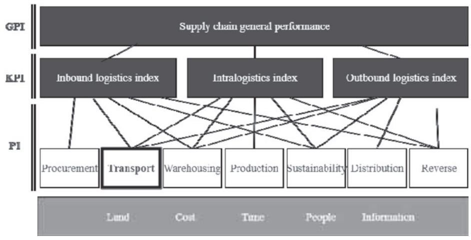


Fig. 2. Supply chain performance model

Fig. 3 zooms into the transport PIs hierarchy. Here is shown how from different data sets three most important indicators are created: timeliness, lead time and sustainability. Traffic and weather information affects the output of all the above-mentioned indicators. The performance is aggregated on different ecosystem participants: overall fleet, single vehicle, single driver, monthly shipments or shipment unit, such as package, pallet or container. Measures chosen to document quality are valid as determined by validity of the denominator, the numerator, the frequency and the measure itself.

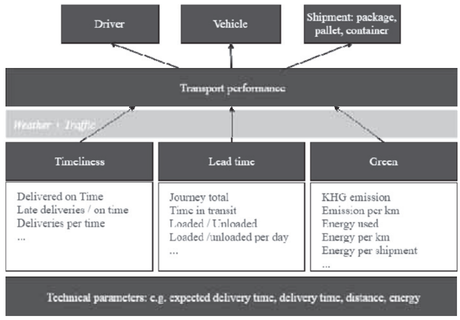


Fig. 3. Transport performance indicators hierarchy

## B. *Choosing Blockchain Techology*

Ethereum and Hyperledger have been considered as candidates to be used in the SmartLog project. We take Ethereum's baseline for public blockchain network and Hyperledger as private network.

Ethereum smart contracts functionality is powerful and makes it a sound platform for different kind of applications. However, Ethereum's permissionless mode of operation and its total transparency comes at the cost of performance scalability and privacy [8].

TABLE I. PERSPECTIVE BLOCKCHAIN TECHNOLOGIES

| | Ethereum | Hyperledger | Ethereum casper | NEM Catapult | EOS | Hashgraph |
|---|---|---|---|---|---|---|
| **Created date** | July 2015 | July 2017 | Autumn 2018 | March 2018 | June 2018 | |
| **Governance** | Ethereum Developers | Linux Foundation & IBM | Ethereum Developers | NEM developers | Block producers | Hedera Hashgraph Council |
| **Concensus protocol** | PoW (Proof of Work) | PBFT (Practical Byzantine Fault Tolerance) | Hybrid PoW/PoS Consensus Model | Proof-of-importance | Delegated Proof of Stake (DPOS) | Swirlds hashgraph consensus algorithm |
| **Network** | Permissionless, public | Permissioned, private | Permissionless, public | Permissioned or permissionless | Public permissioned | Private, permissioned |
| **Smart Contracts** | Solidity, Seperant | Chaincode | Solidity, Viper | REST API | C++ | Solidity |
| **Currency** | ETH | - | ETH | XEM | EOS | - |

Hyperledger solves performance scalability and privacy issues by permissioned mode of operation and specifically by using a BFT algorithm and fine-grained access control. Further, the modular architecture allows Hyperledger to be customized to a multitude of applications. An analogy to a versatile toolbox can be drawn [12].

We also look into several interesting new developments that have the potential to solve issues with current blockchains. Table I lists the technologies found and compares their basic features.

## C. *Transaction Model*

Transaction troughput $\tau$ per chosen time period (1) shows how many transactions is needed to write supply chain performance measurement data into blockchain.

$$\tau = \chi * \sigma * \pi \quad (1)$$

Where $\chi$ is shipment units per route per time period (e.g. per year or day); $\sigma$ is number of stops on the route; $\pi$ is number of technical parameters (e.g. expected delivery time, delivery time).

Single write operation transaction cost ω in case of Ethereum network can be modelled as following (2).

$$\omega = \gamma * \theta * 10^{-9} * \varepsilon \quad (2)$$

Where γ is Gas used per write operation; θ is Gas price in ETH; ε is ETH price in selected flat currency.

Overall blockchain cost ξ is multiplication of τ and ω (3).

$$\xi = \tau * \omega \quad (3)$$

In case of using Hyperledger the write operations have no transaction cost, making the direct overall blockchain transaction cost zero.

### *D. Case Study: SmartLog*

Project SmartLog [17] is about introducing a blockchain technology application into the logistics business operational data transfer traffic – not just as a commercial, proprietary application suite, but rather as an industry-wide open solution to which every interested and involved party can join and from which every involved party can directly benefit from.

The specific metrics needed to involve are the measurements regarding the end-to-end transit times of cargo along the two relevant TEN-T core network corridors in the Baltics, namely the Scandinavian – Mediterranean and the North Sea – Baltic (Fig. 4). The project aims to reduce cargo transit times on those corridors, according to the EU policy objectives [17].

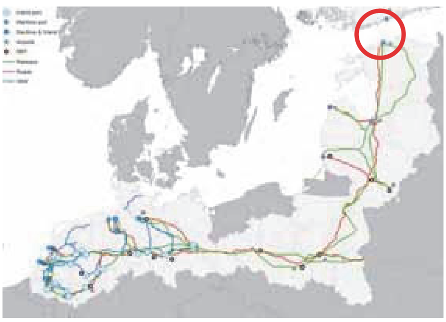

Fig. 4. TEN-T North Sea – Baltic Core Network Corridor [18]

Among all the core network corridors the 3,200 km long North Sea – Baltic corridor has the potential of becoming one of the most economically diverse corridors in the European Union. He has 16 international airports, 13 ports, 18 river ports, and 17 rail-road terminals. The Corridor connects the capitals of all eight countries: Finland, Estonia, Latvia, Lithuania, Poland, Germany, Belgium and Netherlands [18].

In year 2016 close to 326,600 units were transported, in the Tallinn–Helsinki direction approximately 156,600 units and in the Helsinki–Tallinn direction approximately 170,000 units (Table II). In year 2016 on average 854 trucks per day were transported. In the both Helsinki–Tallinn and Tallinn–Helsinki directions the cargo volumes and the number of units are quite similar. By the year 2050 those numbers are expected to grow 86%-121% dependent on different scenarios [18].

TABLE II. COST MODELLING FOR HELSINKI-TALLINN ROUTE

| Route | Parameters | | Trucks | | Pallets | |
|---|---|---|---|---|---|---|
| | ***Shipments (year)*** | ***TPs*** | ***Cost (day)*** | ***Cost (year)*** | ***Cost (day)*** | ***Cost (year)*** |
| Helsinki-Tallinn | 170,000 | 4 | 224 | 81,600 | 7,378 | 2,692,800 |
| Tallinn-Helsinki | 156,000 | 4 | 205 | 74,880 | 6,770 | 2,471,040 |

End-to-end transit time and deviations for the expected transit time were taken as most important PIs for cargo transit in this project. Testing on a simplified case decomposing those indicators into TPs, we established four parameters that need to be written into the blockchain: sceduled pick-up time and real pick-up time, scheduled delivery time and real delivery time. In reality a shipment along these corridors needs 4-32 parameters written in blockchain depending on the complexity of its transport. Those parameters allow us to calculate several indicators for transport performance timeliness and transit time and allow better optimization along the supply chain.

Applying our transaction throughput and cost model on this project, we can see that Ethereum network can easily handle the volumes of the transactions, the transaction cost will be an issue when we want to achieve bigger granularity of shipment tracking.

At the same time, Hyperledger fails already in the begining with being visible only for selected market participants. This is not important in the scope of the SmartLog project, but becomes imperative when larger scale visibility is needed.

One learing from SmartLog project is that there is no stability of the interfaces needed to develop on top of the Hyperledger. When Fabric releases change, then significant amount of work needs to be re-done in order to stick with envisioned functionality.

### *E. New Technology Horizon*

The Proof-of-Work (PoW) paradigm to reaching consensus leads to consumption of vast amounts of energy. The miners dominate the block-creation process.

Alternative Proof-of-Stake (PoS) technology is more energy-efficient. However, the proportion of tokens determines who will control the block-creation process. New blockchain technologies have been risen that mostly leverage on some variety of PoS.

The new algorithms promise also significant savings on transaction time, cost and throughput which is exactly what is needed for guaranteed performance monitoring use case.

Table III summarizes the promises of new perspective algorithms. However, today, it is very difficult to test and verify the promises due to unavailability of the technology stack and test networks.

TABLE III. PERSPECTIVE BLOCKCHAIN TECHNOLOGIES

| Technology | Throughput (TPS) | Cost |
|---|---|---|
| Etherium | 5-30 | High |
| Hyperledger | Thousands | 0 |
| Etherium casper | 300k - 1M | Low |
| NEM | 100k | Low |
| EOS | 3-4k | Low |
| Hashgraph | 250k | Low |

## IV. CONCLUSIONS

Public blockchain networks currently, for instance Ethereum network, do not suit well for practical large scale logistics implementations mainly due to high transaction cost. Transaction throughput will become bottleneck when either larger amount of cargo is transported, higher granularity for shipment tracking is needed or more technical parameters per transported unit is observed.

Available private blockchains, e.g. Hyperledger satisfies small scale impementations from throughput and cost perspective, but lacks public visibility for all the market participants. Upcoming technologies however have potential to resolve the fundamental issues and enable the applications for logistics use cases. Blockchain enabled performance monitoring application for logistics is possible to deploy in case of limited transit volumes already today.

Time in various forms and location are core technical parameters in supply chain PMS. Validated performance monitoring provides necessary credibility to make optimization decisions concerning critical supply chains and is especially applicable where human life or safety is involved. Co-product of validated performance monitoring implementation is efficiency of business processes and transparency and reliability of decisions.

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# Curriculum vitae

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