Article

Quantifying the Economic and Financial Viability of NB-IoT and LoRaWAN Technologies: A Comprehensive Life Cycle Cost Analysis Using Pragmatic Computational Tools

Bernhard Koelmel [1,5,6,*], Max Borsch[2], Rebecca Bulander [1], Lukas Waidelich[1], Tanja Brugger[1], Ansgar Kühn[1], Matthias Weyer[1], Luc Schmerber[3], Michael Krutwig[4]

1 Pforzheim University; bernhard.koelmel@hs-pforzheim.de
2 Wirtschaftsförderung Nordschwarzwald; Max.Borsch@nordschwarzwald.de
3 Luc Schmerber; luc@lucschmerber.com
4 Krumedia GmbH, michael.krutwig@krumedia.com
4 ISM International School of Management, bernhard.kolmel@faculty.ism.edu
4 Texas State University, bkoelmel@txstate.edu
* Correspondence: bernhard.koelmel@hs-pforzheim.de

Abstract: This paper focuses on quantifying the economic and financial viability of NB-IoT and LoRaWAN technologies, two low-power wide-area network (LPWAN) technologies with unique characteristics that make them suitable for IoT applications. The purpose of the study is to propose an artefact for performing life cycle cost analysis and demonstrate its application to these technologies. The methodology uses pragmatic computational tools to facilitate the analysis and considers all relevant economic and financial factors, such as operating costs, equipment costs, and revenue potential. The main finding of the study is that NB-IoT and LoRaWAN technologies have different cost structures and revenue potentials, which may affect their economic and financial viability for different IoT applications. Ultimately, the study concludes that a comprehensive life cycle cost analysis is critical to making informed decisions about technology adoption, and that the proposed methodology can be applied to other IoT technologies to gain insight into their economic and financial viability.

Keywords: Financial Viability; Life Cycle Cost Analysis; LPWAN; Pragmatic Computational Tools; Design Science Research, Data-driven decision making

1. Introduction

Innovation and technology adoption are fundamental drivers of business growth and remain critical to organizational success in today's dynamic environment [1]. However, successful technology adoption depends not only on technological capabilities, but also on financial viability [2]. Financial analysis, including life-cycle costing, is essential to ensure a comprehensive assessment of the costs and benefits associated with the adoption of a new technology [3, 4]. This paper aims to quantify the economic and financial viability of two promising IoT technologies, NB-IoT and LoRaWAN [5], through a comprehensive life-cycle cost analysis using pragmatic computational tools.

The life cycle cost analysis will assess the full range of costs and benefits associated with the deployment of NB-IoT and LoRaWAN technologies, including not only the upfront costs, but also the costs associated with operations, maintenance, and disposal [6]. The analysis will provide decision makers with an understanding of the total cost of ownership of these technologies and identify potential areas for cost savings [7].

Furthermore, this paper argues that financial analysis should accompany technology decisions to ensure that both aspects are addressed for the successful adoption of innovative technologies. In the context of the "not-invented-here" syndrome [8], which hinders good decisions about innovative technologies, a thorough financial analysis becomes critical. The syndrome can lead to the adoption of innovative technologies without proper financial analysis, resulting in inefficient use of resources, high costs, and ultimately technology adoption failure.

Therefore, this paper proposes a methodology for conducting a life-cycle cost analysis of NB-IoT and LoRaWAN technologies to quantify their economic and financial viability [9]. The methodology uses pragmatic computational tools to facilitate the analysis and ensure that it is comprehensive and efficient.

In conclusion, this paper argues that financial analysis is essential for technology adoption decisions, and a comprehensive life-cycle cost analysis can facilitate the decision-making process. Furthermore, the proposed methodology can be applied to other IoT technologies to provide valuable insights into their economic and financial viability. Ultimately, this can enable organizations to make informed technology adoption decisions, maximize the benefits of innovative technologies, and minimize financial risks [10].

2. Design science research as scientific approach

As a research method we employ design science research in developing the artefact "Life Cycle Cost Analysis Using Pragmatic Computational Tools." Design science research is a research paradigm that aims to produce innovative solutions to practical problems through the creation of new artefacts, such as models, methods, and tools [11-14]. The process involves identifying a problem, developing a solution, and evaluating its effectiveness. The use of design science research in information systems is increasingly popular due to its ability to produce practical and relevant solutions that can be implemented in real-world settings [15]. In this context, our artefact seeks to fill a significant research gap by providing a comprehensive life cycle cost analysis tool for IoT technologies such as NB-IoT and LoRaWAN.

Design Science Research (DSR) or design-oriented research is a scientific method that aims to develop practice-oriented solutions to problems or challenges. In contrast to traditional scientific research, which aims to gain knowledge and develop theories, DSR focuses on the design and evaluation of artefacts. It aims to create new knowledge by developing artifacts such as models, methods, and tools that can be applied in real-world settings [16]. The central tenet of DSR is that the development of a novel artifact should be grounded in a problem domain and informed by an understanding of the state of the art in the relevant field. The DSR process typically involves the following steps: problem identification, design and development of the artifact, demonstration of its usefulness, and evaluation of its effectiveness [13]. In the problem identification phase, the researcher identifies a practical problem that can be addressed through the development of a new artifact. This problem should be grounded in a particular context and informed by existing literature and practice. Once the problem has been identified, the researcher moves to the design and development phase. Here the researcher uses existing knowledge and theory to design and develop an innovative artifact that addresses the identified problem. This phase may involve the creation of new theory or the adaptation and application of existing theory to a new context. The next phase of the DSR process involves demonstrating the usefulness of the artifact. In this phase, the researcher shows how the artifact can be used to address the practical problem identified in the first phase. This may involve testing the artifact in a simulated or real-world setting to show how it improves upon existing solutions or practices. Finally, the effectiveness of the artifact is evaluated. This evaluation may involve the use of quantitative or qualitative methods to assess the impact of the artifact on the problem domain. The evaluation should provide evidence of the artifact's usefulness and insights into its limitations and potential for further development [13-15].

DSR has been increasingly applied in the field of information systems and has proven to be effective in producing practical solutions to complex problems. The approach has been used to develop a wide range of artifacts, including software systems, decision support tools, and frameworks for guiding practice. DSR differs from traditional research approaches in that it places greater emphasis on the practical relevance of the research results. While traditional research may focus on

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 June 2023 doi:10.20944/preprints202306.0315.v1

developing theoretical models and testing them in a controlled setting, DSR seeks to develop solutions that can be implemented in real-world settings and have a measurable impact on practice.

3. State of the Art

3.1 IoT communication technologies for the Internet of Things

Low Power Wide Area Networks (LPWANs) have become a popular communication technology for the Internet of Things (IoT) due to their low power consumption and wide coverage area. Two of the most popular LPWAN technologies are LoRaWAN and NB-IoT [17-19].

LoRaWAN (Long Range Wide Area Network) is a wireless communication protocol based on the LoRa modulation technique. LoRaWAN has the ability to communicate over long distances, typically up to 10 km in rural areas and up to 2 km in urban areas. It operates in unlicensed frequency bands, which makes it a cost-effective solution. The LoRaWAN protocol is open-source and has a large community of developers. LoRaWAN is primarily used for battery-powered devices that require low data rates, such as environmental monitoring sensors, smart parking systems, and asset tracking [20, 21].

NB-IoT (Narrowband IoT) is a cellular technology designed for IoT devices within 5G cellular networks. It is a standardization effort by the 3GPP and is based on the LTE (Long-Term Evolution) technology. NB-IoT uses a narrow bandwidth of 200 kHz and can operate in licensed or unlicensed frequency bands. The main advantage of NB-IoT is its ability to operate in areas with weak signal strength and in underground locations. It can also support high data rates and has a low latency, making it suitable for applications that require real-time data, such as industrial automation and smart cities [22, 23].

Table 1. Selected properties of LoRaWAN vs. NB-IoT [20-24].

Property	LoRaWAN	NB-IoT
Modulation Technique	LoRa (Chirp Spread Spectrum (CSS))	QPSK (Orthogonal Frequency-Division Multiplexing (OFDM))
Frequency Range	868 MHz, 915 MHz, and 433 MHz	700 MHz, 800 MHz, 900 MHz, and 1.9 GHz
Frequency Bands	Unlicensed	Licensed and unlicensed
Network Topology	Star, Mesh, and Hybrid	Star and Point-to-Point
Coverage Area	10 km (rural), 2 km (urban)	10 km (rural), 1 km (urban)
Battery Life	Up to 10 years	Up to 15 years
Data Rate	0.3-50 kbps	50-250 kbps
Security	AES-128 bit encryption	AES-128 bit encryption
Deployment	Requires a gateway	Cellular network required
Scalability	Can support thousands of nodes	Can support thousands of nodes
Latency	Seconds to minutes	Sub-seconds
Use Cases	Environmental monitoring, smart parking, asset tracking	Industrial automation, smart cities, security and surveillance

One of the main advantages of LoRaWAN is its long-range communication capabilities, which make it suitable for use cases that require devices to be deployed in remote areas, such as environmental monitoring or asset tracking. Additionally, the unlicensed frequency bands used by LoRaWAN make it a cost-effective solution, as no licensing fees are required. However, the trade-off for this long-range communication is a low data rate and higher latency, which may not be suitable for applications that require real-time data [24].

On the other hand, NB-IoT offers high data rates, low latency, and reliable connectivity in areas with weak signal strength. Its cellular network infrastructure also provides a level of security and reliability that may not be possible with LoRaWAN. However, the licensing fees and higher deployment costs associated with NB-IoT may make it less cost-effective than LoRaWAN for certain applications [24].

In conclusion, both LoRaWAN and NB-IoT have their advantages and limitations, and the choice between them will depend on the specific requirements of the application. LoRaWAN is best suited for applications that require long-range communication and low data rates, while NB-IoT is ideal for applications that require real-time data and operate in areas with weak signal strength.

3.2 Assessing Financial Viability of innovative technologies

Life cycle costing (LCC) is a method for calculating the total cost of ownership of a product or service over its entire life cycle, from design and development to disposal. It is widely used in the field of advanced technologies, where the high initial cost and long life cycle of products require a comprehensive analysis of the total cost of ownership [25, 26].

One of the key benefits of LCC is that it provides a comprehensive view of the costs associated with a product or service. This includes not only the initial purchase price but also the costs of maintenance, repair, and replacement over the life of the product. LCC also takes into account the impact of factors such as energy consumption, environmental impact, and regulatory compliance.

Terotechnology is a related concept that refers to the application of engineering and management principles to optimize the life cycle costs of physical assets. It is based on the idea that the cost of ownership of an asset is not just the initial purchase price but also the cost of operating, maintaining, and disposing of the asset over its entire life cycle. Terotechnology considers the technical, economic, and social factors that affect the performance of an asset and seeks to optimize the cost-effectiveness of the asset throughout its life cycle [27].

While terotechnology has its merits, LCC is more pragmatic and has a better chance to be used in practice. This is because LCC is a more straightforward and easily understandable approach to calculating the total cost of ownership of a product or service. It is also more widely accepted and used in industry and government, with many organizations requiring LCC analyses as part of their procurement and purchasing processes.

One of the challenges of LCC is the need to gather accurate and reliable data on the costs associated with a product or service over its entire life cycle. This requires a detailed understanding of the product's design, manufacturing process, and operating characteristics, as well as the costs of maintenance, repair, and replacement over time. It also requires an understanding of the external factors that can affect the cost of ownership, such as changes in regulations, energy prices, and environmental policies [25, 26].

To overcome these challenges, organizations can use a variety of tools and techniques to gather and analyse data on the life cycle costs of their products or services. These include cost accounting systems, enterprise resource planning (ERP) software, and specialized LCC software tools. These tools can help organizations to identify areas where costs can be reduced and to make more informed decisions about the design, development, and procurement of products and services [26].

Overall, LCC is a valuable approach for assessing the total cost of ownership of advanced technologies. By taking a comprehensive view of the costs associated with a product or service over its entire life cycle, LCC can help organizations to make more informed decisions about the design, development, and procurement of products and services. While terotechnology has its merits, LCC is more pragmatic and has a better chance to be used in practice [25].

3.3 Financial Viability of selected IoT communication technologies

Life cycle costing is a crucial tool for making informed decisions about the economic feasibility of IoT communication technologies. IoT systems are typically composed of numerous devices with diverse functionalities and connectivity options, and estimating the total cost of ownership over the system's life cycle can be complex. Life cycle costing involves evaluating the costs of a system over its entire lifespan, from procurement and deployment to maintenance and disposal, taking into account all relevant cost components. By understanding the full cost profile of a technology, businesses can make more informed decisions about which IoT communication technologies are financially viable and sustainable in the long term.

Several studies have addressed the life cycle costs of various IoT communication technologies, including LoRaWAN and NB-IoT [28]. For example, the authors of a study have concluded that, among the plethora of low power wide area network (LPWAN) technologies, the cost-effectiveness of IoT is not certain for IoT service solutions

Another study conducted by the authors in 2020 [29] compared the applicability including costs LoRaWAN and NB-IoT for industrial applications.

However, it is worth noting that these studies have some limitations. For example, they focused primarily on specific applications and did not consider the impact of the size and scale of the IoT system on life cycle costs.

To address these limitations, a holistic approach to life cycle costing is needed, one that takes into account not only the economic but also the environmental and social impacts of IoT communication technologies. While there are some studies that have applied life cycle costing to IoT systems in general, there is currently a lack of a holistic artefact that specifically addresses the economic and financial viability of LoRaWAN and NB-IoT technologies. Such an artefact would provide a comprehensive framework for evaluating the life cycle costs of these technologies, taking into account all relevant cost components. Additionally, it would allow for the comparison of the economic and financial viability of LoRaWAN and NB-IoT across a range of applications and scenarios.

4. Approach to constructing the scientific artifact "Pragmatic Computational Tool" for calculating the life cycle costs of IoT devices based on design science research

The present study aimed to develop a pragmatic computational tool using a design science research (DSR) approach for calculating the life cycle costs of IoT devices based on relevant parameters such as hardware (sensors, gateways), software costs, server costs, personnel-related costs, etc. The first step in the DSR approach was problem identification, which highlighted the lack of a comprehensive tool for life cycle cost analysis of IoT devices. The proposed tool aimed to fill this gap by providing a user-friendly and reliable way to calculate the life cycle costs of IoT devices that could be customized as per users' needs [30].

The design phase involved creating a model of the proposed artifact, which was a computational tool capable of taking various inputs, such as hardware, software, server, and personnel-related costs, and generating outputs, including the total cost of ownership, return on investment, and payback period. The tool was designed to be customizable, which enabled users to tailor the inputs and outputs to suit their specific needs [13].

The next step involved the implementation of the model in the form of a working prototype. The prototype was evaluated to ensure that it met the needs of the stakeholders, which included IoT device manufacturers, system integrators, and end-users. The prototype was evaluated based on its functionality, usability, and usefulness, using methods such as user testing, expert reviews, and other forms of feedback [13].

Based on the feedback received, the prototype was refined and improved through an iterative process until it met the needs of the stakeholders. This iterative process of refinement and improvement is a hallmark of DSR. The final product was reliable, user-friendly, and met the needs of the stakeholders [13].

The development of the tool involved problem identification, model creation, implementation, evaluation, refinement, and communication of the results. The proposed tool fills a significant research gap and provides a customizable, user-friendly, and reliable way to calculate the life cycle costs of IoT devices [13-15].

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 5 June 2023 doi:10.20944/preprints202306.0315.v1

5. Constructing the scientific artifact "Pragmatic Computational Tool" for calculating the life cycle costs of IoT-devices

The "Pragmatic Computational Tool" for calculating the Life of IoT devices was constructed using Microsoft Excel. The tool was designed to provide a practical and user-friendly way to estimate the life cycle costs of IoT devices. The tool uses different categories of costs, including procurement costs, training and usage costs, maintenance costs, disposal costs, and external project costs, to estimate the total cost of ownership (TCO) for an IoT device over its lifetime.

To construct the tool, the first step was to create a worksheet in Excel with different categories of costs as column headers.

Formally, a section consists of: a heading, a finer subdivision of the costs, fields for entries and fields for the calculated costs (c.f. Figure 1).

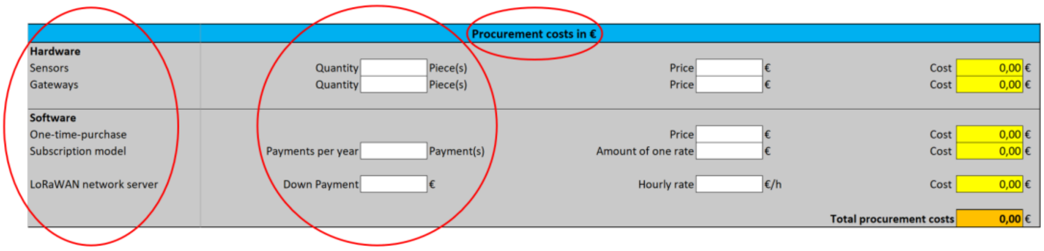

Figure 1. Design of the cost calculator.

The columns were labeled as procurement costs, training and usage costs, maintenance costs, disposal costs, and external project costs. The rows were labeled with specific tasks that are required to maintain and operate IoT devices. For example, tasks such as hardware and software installation, training and support, device maintenance, disposal, and project management were included. Once the categories and tasks were identified, the next step was to assign cost values to each of them. The costs of a row are always summarized in a yellow field in the right column, the cost of all lines in a section is displayed in orange box (c.f. Figure 1).

Visually, the calculator is kept in unobtrusive gray, while headings are highlighted in light blue. In addition, the color of individual fields varies depending on their meaning, ranging from to be filled in, via calculated automatically to the sum above everything (c.f. Figure 2).

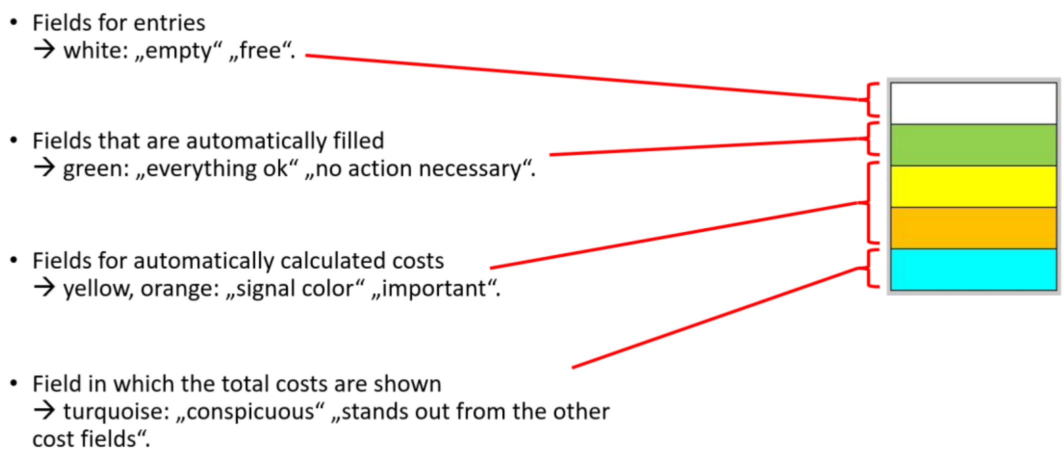

Figure 2. Color scheme of the cost calculator.

To make the tool even more user-friendly, symbols were used to represent the different types of costs. For example, a dollar sign (€) was used to indicate procurement costs, a wrench symbol was used to indicate maintenance costs, and a recycle symbol was used to indicate disposal costs.

 doi:10.20944/preprints202306.0315.v1

In addition to assigning costs to each task, the tool also included units of measurement. This helped users understand the scale of the costs associated with each task. Once all the costs were assigned and the tool was complete, it was tested and validated to ensure its accuracy and usability. The tool was tested using different scenarios to determine its effectiveness in estimating the TCO of IoT devices. Feedback was collected from users to identify any areas of improvement, and the tool was updated accordingly.

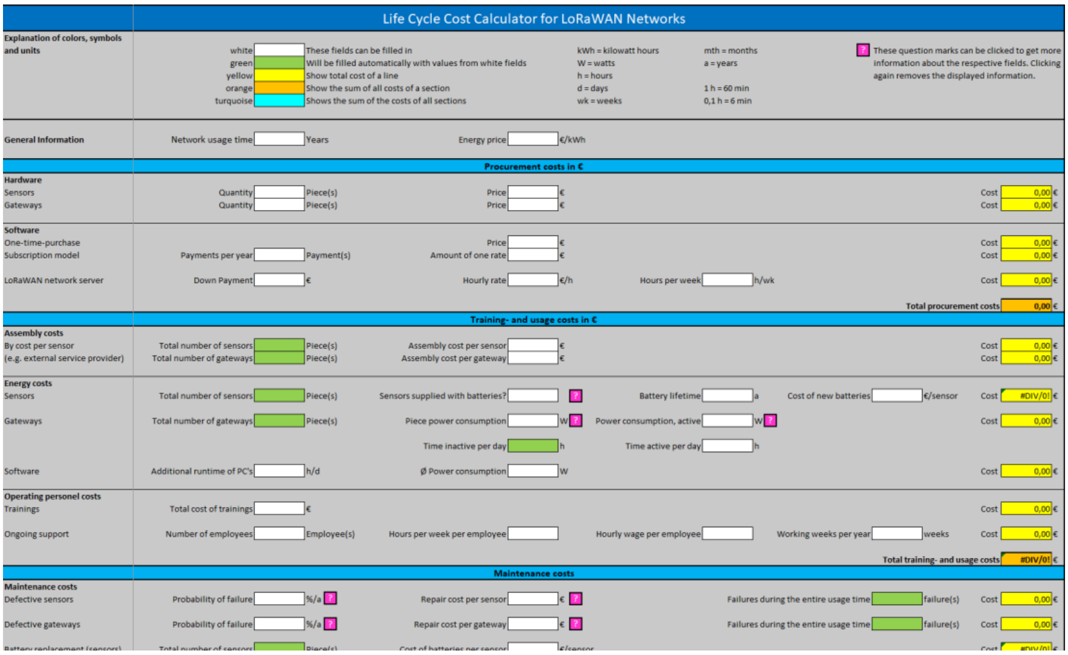

Figure 3. Interface for the life cycle cost calculator for LoRaWAN.

Due to the different cost structures between IoT devices and gateways, it was necessary to construct separate calculators for each. As such, separate calculations are necessary to accurately estimate the total cost of ownership for each type of device (c.f. Figure 3).

Additionally, external project costs may also differ between IoT devices and gateways. For instance, the installation of gateways may require more specialized expertise and equipment, resulting in higher costs.

Overall, the "Pragmatic Computational Tool" provides a practical and user-friendly way to estimate the life cycle costs of IoT devices. It is easy to use, with well-explained colors, symbols, and units, making it an effective tool for decision-makers in the IoT industry.

6. Validating and discussing the scientific artifact "Pragmatic Computational Tool" for calculating the life cycle costs of IoT-devices in a smart city environment

The validation of the scientific artifact "Pragmatic Computational Tool" for calculating the life cycle costs of IoT devices was conducted using several use cases from different domains, including smart city, environmental monitoring, energy management, citizen science, and traffic management. The objective of the validation was to assess the accuracy and usability of the tool in various real-world scenarios and to identify any limitations or areas for improvement [31].

The smart city use case focused on monitoring traffic flow, parking, and air quality. The environmental monitoring use case involved monitoring air and water quality, weather conditions, and noise levels. The energy management use case aimed to optimize energy consumption and production in buildings and industrial facilities. The citizen science use case focused on monitoring biodiversity and wildlife habitats. Finally, the traffic management use case aimed to optimize traffic flow and reduce congestion in urban areas.

In each use case, the tool was used to calculate the life cycle costs of the IoT devices, including procurement costs, training and usage costs, maintenance costs, disposal costs, and external project costs. The tool used different cost assumptions and parameters for each use case, depending on the specific requirements and characteristics of the scenario.

The validation of the tool involved several steps, including verifying the accuracy of the calculations, assessing the usability and accessibility of the tool, and analyzing the results to identify any patterns or trends across the different use cases [32].

To verify the accuracy of the calculations, the tool was compared to other established methods for calculating life cycle costs, such as the traditional cost accounting approach and the Total Cost of Ownership (TCO) framework. The results showed that the tool was able to produce accurate and reliable cost estimates for each use case, and that the results were consistent with the results obtained from other methods.

To assess the usability and accessibility of the tool, the tool was evaluated by a group of experts in each use case domain. The experts were asked to evaluate the tool based on several criteria, including ease of use, clarity of instructions, and accessibility of the tool for non-experts. The feedback from the experts was positive, and they found the tool to be user-friendly and intuitive, with clear instructions and a simple interface.

Finally, the results of the life cycle cost calculations were analyzed to identify any patterns or trends across the different use cases. One interesting finding was that for scenarios with fewer than 5000 sensors, NB-IoT was generally less expensive than LoRaWAN. However, for scenarios with more than 5000 sensors, LoRaWAN was generally less expensive than NB-IoT. This finding highlights the importance of considering the specific requirements and characteristics of each scenario when selecting the most appropriate IoT communication technology.

One of the main reasons for the better cost performance of NB-IoT in scenarios with fewer sensors is due to the fact that LoRaWAN requires more specialized employees with a higher skill set to operate and maintain the network. In addition to the higher costs associated with skilled labor, LoRaWAN also requires higher hardware costs per device due to the use of gateways. On the other hand, NB-IoT can be easily integrated into existing cellular networks, which results in lower hardware and installation costs. However, as the number of devices increases, LoRaWAN becomes more cost-effective due to the use of lower-cost devices and the ability to support a higher number of devices per gateway. This highlights the importance of carefully analyzing the specific use case and requirements before deciding on the most appropriate IoT communication technology.

7. Conclusion

In conclusion, the validation of the "Pragmatic Computational Tool" for calculating the life cycle costs of IoT devices was successful, and the tool was found to be helpful, reliable, and user-friendly. The results of the validation also provided useful insights into the costs of IoT devices in different real-world scenarios and the relative cost-effectiveness of different IoT communication technologies.

Further research is needed to validate the tool in other use cases and to refine the tool to better reflect the specific requirements and characteristics of each scenario. The cost calculators developed for NB-IoT and LoRaWAN aim to provide a quick and efficient way to estimate the expected costs of these networks. The calculators are designed to provide a clear overview of where and in which phase these costs are incurred, as well as to compare the two network types in terms of costs.

However, it is important to note that the calculators are not intended to evaluate the suitability of a particular technology and should not be used as a substitute for later cost accounting. Additionally, the calculators cannot map all contingencies and special cases that may arise during the implementation and operation of these networks.

Furthermore, certain aspects are not considered in the cost calculators. These include the cost of capital, interest payments, depreciation, inflation/deflation rate, electricity price development, revenue generated by the network (in the case of LoRaWAN), safety aspects, network coverage, and other technical aspects of the networks. Therefore, it is important to use the calculators in conjunction with other tools and resources to fully evaluate the costs and suitability of each network type for a particular use case.

References

1. Kumar Basu, K. The Leader's Role in Managing Change: Five Cases of Technology-Enabled Business Transformation. Glob. Bus. Organ. Excel. 2015, 34 (3), 28–42. https://doi.org/10.1002/joe.21602.
2. Foster, A. D.; Rosenzweig, M. R. Microeconomics of Technology Adoption. Annu. Rev. Econom. 2010, 2 (1), 395–424. https://doi.org/10.1146/annurev.economics.102308.124433.
3. Chakravarty, A.; Debnath, J. Life Cycle Costing as a Decision Making Tool for Technology Acquisition in Radio-Diagnosis. Med J. Armed Forces India 2015, 71 (1), 38–42. https://doi.org/10.1016/j.mjafi.2014.10.004.
4. Brown, R. J. A New Marketing Tool: Life-Cycle Costing. Ind. Mark. Manag. 1979, 8 (2), 109–113. https://doi.org/10.1016/0019-8501(79)90050-6.
5. Sinha, R. S.; Wei, Y.; Hwang, S.-H. A Survey on LPWA Technology: LoRa and NB-IoT. ICT Express 2017, 3 (1), 14–21. https://doi.org/10.1016/j.icte.2017.03.004.
6. Senthil Kumaran, D.; Ong, S. K.; Tan, R. B. H.; Nee, A. Y. C. Environmental Life Cycle Cost Analysis of Products.
7. Degraeve, Z.; Roodhooft, F. Improving the Efficiency of the Purchasing Process Using Total Cost of Ownership Information: The Case of Heating Electrodes at Cockerill Sambre S.A. Eur. J. Oper. Res. 1999, 112 (1), 42–53. https://doi.org/10.1016/s0377-2217(97)00383-4.
8. Ashton, J. R. Not Invented Here. J. Epidemiol. Community Health 2002, 56 (7), 481-a-481. https://doi.org/10.1136/jech.56.7.481-a.
9. Breidenbach, D. P. Life Cycle Cost Analysis. In Proceedings of the IEEE National Aerospace and Electronics Conference; IEEE, 2003.
10. Huisman, K. J. M.; Kort, P. M. Strategic Technology Adoption Taking into Account Future Technological Improvements: A Real Options Approach. SSRN Electron. J. 2000. https://doi.org/10.2139/ssrn.246980.
11. Carstensen, A.-K.; Bernhard, J. Design Science Research – a Powerful Tool for Improving Methods in Engineering Education Research. Eur. J. Eng. Educ. 2019, 44 (1–2), 85–102. https://doi.org/10.1080/03043797.2018.1498459.
12. Goecks, L. S.; Souza, M. de; Librelato, T. P.; Trento, L. R. Design Science Research in Practice: Review of Applications in Industrial Engineering. Gest. Prod. 2021, 28 (4). https://doi.org/10.1590/1806-9649-2021v28e5811.
13. Dresch, A.; Lacerda, D. P.; Antunes, J. A. V., Jr. Design Science Research. In Design Science Research; Springer International Publishing: Cham, 2015; pp 67–102.
14. Hevner, A.; Chatterjee, S. Design Science Research: Looking to the Future. In Integrated Series in Information Systems; Springer US: Boston, MA, 2010; pp 261–268.
15. Hevner, A.; Chatterjee, S. Design Science Research in Information Systems. In Integrated Series in Information Systems; Springer US: Boston, MA, 2010; pp 9–22.
16. Hatchuel, A.; Le Masson, P.; Reich, Y.; Subrahmanian, E. Design Theory: A Foundation of a New Paradigm for Design Science and Engineering. Res. Eng. Des. 2018, 29 (1), 5–21. https://doi.org/10.1007/s00163-017-0275-2.
17. Shetty, S. H.; Rao, A.; Gatti, R. R. State of the Art Review of IIoT Communication Protocols. In Transforming the Internet of Things for Next-Generation Smart Systems; IGI Global, 2021; pp 37–48.
18. Bahashwan, A. A.; Anbar, M.; Abdullah, N.; Al-Hadhrami, T.; Hanshi, S. M. Review on Common IoT Communication Technologies for Both Long-Range Network (LPWAN) and Short-Range Network. In Advances on Smart and Soft Computing; Springer Singapore: Singapore, 2021; pp 341–353.
19. Čolaković, A.; Hasković Džubur, A.; Karahodža, B. Wireless Communication Technologies for the Internet of Things. Sci. Eng. Technol. 2021, 1 (1), 1–14. https://doi.org/10.54327/set2021/v1.i1.3.
20. Basford, P. J.; Bulot, F. M. J.; Apetroaie-Cristea, M.; Cox, S. J.; Ossont, S. J. J. LoRaWAN for Smart City IoT Deployments: A Long Term Evaluation. Sensors (Basel) 2020, 20 (3), 648. https://doi.org/10.3390/s20030648.
21. Ertürk, M. A.; Aydın, M. A.; Büyükakkaşlar, M. T.; Evirgen, H. A Survey on LoRaWAN Architecture, Protocol and Technologies. Future Internet 2019, 11 (10), 216. https://doi.org/10.3390/fi11100216.
22. Beyene, Y. D.; Jantti, R.; Tirkkonen, O.; Ruttik, K.; Iraji, S.; Larmo, A.; Tirronen, T.; Torsner, A. J. NB-IoT Technology Overview and Experience from Cloud-RAN Implementation. IEEE Wirel. Commun. 2017, 24 (3), 26–32. https://doi.org/10.1109/mwc.2017.1600418.
23. Ratasuk, R.; Vejlgaard, B.; Mangalvedhe, N.; Ghosh, A. NB-IoT System for M2M Communication. In 2016 IEEE Wireless Communications and Networking Conference Workshops (WCNCW); IEEE, 2016.

24. Ballerini, M.; Polonelli, T.; Brunelli, D.; Magno, M.; Benini, L. Experimental Evaluation on NB-IoT and LoRaWAN for Industrial and IoT Applications. In 2019 IEEE 17th International Conference on Industrial Informatics (INDIN); IEEE, 2019.
25. Pererva, P. G.; Kosenko, A. P.; Kobielieva, T. A.; Tkachev, M. M.; Tkacheva, N. P. Financial and Technological Leverage in the System of Economic Evaluation of Innovative Technologies. Financ. Credit Act. Probl. Theory Pract. 2017, 2 (23), 405–413. https://doi.org/10.18371/fcaptp.v2i23.121920.
26. Hunkeler, D.; Rebitzer, G. Life Cycle Costing — Paving the Road to Sustainable Development? Int. J. Life Cycle Assess. 2003, 8 (2), 109–110. https://doi.org/10.1007/bf02978435.
27. Kelly, A. Eastburn, K. Terotechnology. A modern approach to plant engineering (1982)
28. Hossain, M. I.; Markendahl, J. I. Comparison of LPWAN Technologies: Cost Structure and Scalability. Wirel. Pers. Commun. 2021, 121 (1), 887–903. https://doi.org/10.1007/s11277-021-08664-0.
29. Ballerini, M.; Polonelli, T.; Brunelli, D.; Magno, M.; Benini, L. NB-IoT versus LoRaWAN: An Experimental Evaluation for Industrial Applications. IEEE Trans. Industr. Inform. 2020, 16 (12), 7802–7811. https://doi.org/10.1109/tii.2020.2987423.
30. Dimache, A.; Dimache, L.; Zoldi, E.; Roche, T. Life Cycle Cost Estimation Tool for Decision-Making in the Early Phases of the Design Process. In Advances in Life Cycle Engineering for Sustainable Manufacturing Businesses; Springer London: London, 2007; pp 455–459.
31. Vaishnavi, V. K. Design Science Research Methods and Patterns: Innovating Information and Communication Technology; Auerbach Publications, 2007.
32. Indulska, M.; Recker, J. Design Science in IS Research: A Literature Analysis. In Information Systems Foundations: The Role of Design Science; ANU Press, 2010.