MDPI

SUSTAINABLE DEVELOPMENT GOALS

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE

Transitioning to SUSTAINABLE INDUSTRY, INNOVATION AND INFRASTRUCTURE

Wojciech J. Cynarski and Bożena Gajdzik (Eds.)

Transitioning to **Sustainable Industry, Innovation and Infrastructure**

Transitioning to Sustainability Series: Volume 9

Series Editor: Manfred Max Bergman

Volumes in the series:

Volume 1: Transitioning to No Poverty
ISBN 978-3-03897-860-2 (Hbk);
ISBN 978-3-03897-861-9 (PDF)

Volume 2: Transitioning to Zero Hunger
ISBN 978-3-03897-862-6 (Hbk);
ISBN 978-3-03897-863-3 (PDF)

Volume 3: Transitioning to Good Health and Well-Being
ISBN 978-3-03897-864-0 (Hbk);
ISBN 978-3-03897-865-7 (PDF)

Volume 4: Transitioning to Quality Education
ISBN 978-3-03897-892-3 (Hbk);
ISBN 978-3-03897-893-0 (PDF)

Volume 5: Transitioning to Gender Equality
ISBN 978-3-03897-866-4 (Hbk);
ISBN 978-3-03897-867-1 (PDF)

Volume 6: Transitioning to Clean Water and Sanitation
ISBN 978-3-03897-774-2 (Hbk);
ISBN 978-3-03897-775-9 (PDF)

Volume 7: Transitioning to Affordable and Clean Energy
ISBN 978-3-03897-776-6 (Hbk);
ISBN 978-3-03897-777-3 (PDF)

Volume 8: Transitioning to Decent Work and Economic Growth
ISBN 978-3-03897-778-0 (Hbk);
ISBN 978-3-03897-779-7 (PDF)

Volume 9: Transitioning to Sustainable Industry, Innovation and Infrastructure
ISBN 978-3-03897-868-8 (Hbk);
ISBN 978-3-03897-869-5 (PDF)

Volume 10: Transitioning to Reduced Inequalities
ISBN 978-3-03921-160-9 (Hbk);
ISBN 978-3-03921-161-6 (PDF)

Volume 11: Transitioning to Sustainable Cities and Communities
ISBN 978-3-03897-870-1 (Hbk);
ISBN 978-3-03897-871-8 (PDF)

Volume 12: Transitioning to Responsible Consumption and Production
ISBN 978-3-03897-872-5 (Hbk);
ISBN 978-3-03897-873-2 (PDF)

Volume 13: Transitioning to Climate Action
ISBN 978-3-03897-874-9 (Hbk);
ISBN 978-3-03897-875-6 (PDF)

Volume 14: Transitioning to Sustainable Life below Water
ISBN 978-3-03897-876-3 (Hbk);
ISBN 978-3-03897-877-0 (PDF)

Volume 15: Transitioning to Sustainable Life on Land
ISBN 978-3-03897-878-7 (Hbk);
ISBN 978-3-03897-879-4 (PDF)

Volume 16: Transitioning to Peace, Justice and Strong Institutions
ISBN 978-3-03897-880-0 (Hbk);
ISBN 978-3-03897-881-7 (PDF)

Volume 17: Transitioning to Strong Partnerships for the Sustainable Development Goals
ISBN 978-3-03897-882-4 (Hbk);
ISBN 978-3-03897-883-1 (PDF)

Wojciech J. Cynarski and Bożena Gajdzik (Eds.)

Transitioning to Sustainable Industry, Innovation and Infrastructure

Transitioning to Sustainability Series

MDPI • Basel • Beijing • Wuhan • Barcelona • Belgrade • Manchester • Tianjin • Tokyo • Cluj

EDITORS
Wojciech J. Cynarski
Rzeszów University,
Rzeszów, Poland

Bożena Gajdzik
Silesian University of Technology,
Gliwice, Poland

EDITORIAL OFFICE
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

For citation purposes, cite each article independently as indicated below:

Author 1, and Author 2. Chapter Title. In *Transitioning to Sustainable Industry, Innovation and Infrastructure*. Edited by Wojciech J. Cynarski and Bożena Gajdzik. Transitioning to Sustainability Series 9; Basel: MDPI, Page Range.

© 2023 by the authors. Chapters in this volume are Open Access and distributed under the Creative Commons Attribution (CC BY 4.0) license, which allows users to download, copy and build upon published articles, as long as the author and publisher are properly credited, which ensures maximum dissemination and a wider impact of our publications.
The book taken as a whole is distributed by MDPI under the terms and conditions of the Creative Commons license CC BY-NC-ND.

ISBN 978-3-03897-868-8 (Hbk)
ISBN 978-3-03897-869-5 (PDF)
ISSN: 2624-9324 (Print)
ISSN: 2624-9332 (Online)
doi:10.3390/books978-3-03897-869-5

Contents

About the Editors

Wojciech J. Cynarski PhD is a Full-Professor with degrees from the University of Technology in Rzeszow (building engineering), the University of Rzeszow in Rzeszow (sociology), and doctoral studies at University of Physical Education in Warsaw (physical culture sciences). Since 2005, he has worked as a Professor at the University of Rzeszow and was appointed Head of Chair of the Socio-Cultural Foundation for Physical Education and Sports. He has published over 800 scientific works, including 20 books (monographs and manuals). His major scientific interests concern sociology (of culture, tourism and sport), coaching and pedagogy, and martial arts.

Bożena Gajdzik, PhD, (hab.) Eng., is a Professor at the Silesian University of Technology, Gliwice, Poland. Her interests include manufacturing, management, restructuring, sustainability, industrial transformation, digitalization, resource management, human factor, energy consumption, decarbonisation, and industrial engineering. She is an expert on the steel market in Poland and collaborates with business practices, particularly with steel companies. She has experience in the industrial transformation of the European market and ranks second place in the list of top global scientists. She is the author/coauthor of more than 600 scientific publications, including 30 books and monographs. Her monographs concern the restructuring of the steel sector in Poland and the transformation of steel mills within Industry 4.0. Her writing centres on business management and organization development, as well as industry transformation to changing socioeconomic conditions. Her output includes ranked foreign and domestic scientific publications on the implementation of changes in manufacturing companies in hard and soft areas of management. She is a reviewer of scientific publications for recognised publishing houses. In recent years, she has reviewed extensively on papers of significance on green economy. She is a member of the Editorial Boards of recognized scientific journals. Her H-index is 19, with more than 800 citations on WoS.

Contributors

BARTOSZ ORZEŁ
Dr., Silesian University of Technology, Faculty of Organisation and Management, Department of Economics and Informatics.

BOŻENA GAJDZIK
Informatics Engineering Department, Silesian University of Technology, Gliwice, Poland.

HASSANALI VIRANI
Professor, Electronics and Telecommunications Dept, Goa College of Engineering, Goa, India.

LESZEK WOŹNIAK
Department of Entrepreneurship, Management and Ecoinnovations, Rzeszow University of Technology, Rzeszów, Poland.

RADOSŁAW WOLNIAK
Silesian University of Technology, Faculty of Organisation and Management, Department of Economics and Informatics.

SONIA KUWELKAR
Associate Professor, Electronics & Telecommunications Dept, Goa College of Engineering, Goa, India.

WARREN VAZ
Assistant Professor of Engineering, Department of Engineering and Engineering Technology, University of Wisconsin Oshkosh, Fox Cities Campus, Menasha, Wisconsin, United States.

WOJCIECH J. CYNARSKI
Institute of Physical Culture Studies, College of Medical Sciences, University of Rzeszów, Rzeszów, Poland.

Abstracts

Innovation in Urban Infrastructure for Development of Physical Culture: An Example of a Little Town in Poland
by Wojciech J. Cynarski and Leszek Woźniak

Improving the sports infrastructure (and more broadly - in the field of physical culture) in the urban space contributes to the improvement of the living conditions of the inhabitants. How does it work in a small town? This is a case study of the city of Strzyżów (Podkarpackie Voivodeship, Poland). The indicated town has created an interesting sports, recreational and tourist base. The plan for the sustainable development of the city and the commune took into account the needs in this respect. This applies to encouraging civic and recreational activity in free time. Sports and tourism for all are developed, as well as rehabilitation of disabled people. Recreational physical activity in the open space (cycling, horseback riding, other open space sports) simultaneously serves social health, the growth of physical culture and the sustainable development of the city and the commune.

Corporate Social Responsibility Reporting in the Context of Striving to Achieve the Sustainable Development Goals
by Bartosz Orzeł and Radosław Wolniak

This paper is a study on corporate social responsibility as part of a sustainable approach to modern management. In the first part, the literature analysis was carried out. We included the issues related to different ways of achieving sustainable development goals by enterprises. The next part of the paper contains the literature analysis about different kinds of non-financial activities, which can lead business entities to improve in the field of corporate social responsibility reporting quality. The issues connected to effectiveness in environmental and social efforts taken by enterprises were raised. The most common ways and areas of non-financial data reporting by enterprises were introduced and statistical data of corporate social responsibility reporting in different European were presented. The paper is much focused on the corporate social responsibility principles and Corporate Social Responsibility reporting impact on sustainable development goals achieving. In this part of the publication, both aspects of corporate social Responsibility reporting

principles and the idea of corporate social responsibility reporting's influence on sustainable development goals achieving were presented. Finally, in the paper, the conclusion and findings were introduced.

Changes in the Steel Industry in Poland in the Period 1990 to 2020: Innovation and Digitisation on the Way to Steel Mills 4.0

by Bożena Gajdzik

The article presents the development path of the steel industry in Poland. Metallurgy after each industrial revolution has become an increasingly strong strategic branch of industry. The national economy of any country cannot develop without securing supplies of steel and other metal products. Construction, transport, infrastructure development and various services and separate industries would suffer. Therefore, because of the above, this article aims to analysis of changes in metallurgy in the three decades 1990-2020, with a particular emphasis on changes that are part of the wide range of innovations of modern enterprises in the global economy. The technological investments implemented, especially in recent years, and the scope of activities in the field of R&D are a chance to build steelworks 4.0 in Poland. However, it should be emphasised that the Polish steel industry is made up of foreign capital groups (the largest steel plants are owned by foreign capital). Steel producers in Poland are in the structures of international capital groups with a high position in the global steel market. The development of the Polish steel sector is presented on the basis of statistical data. The chapter is a retrospective analysis in the period from 1990-2000. The stages of the evolution of the Polish steel industry were described in the context of Industry 4.0. The structure of the work was arranged chronologically according to the time periods: the first period from 1990 to 2000, the second period from 2000 to 2010 and the third period from 2010 to 2020. In each of the analysed periods changes that formed the innovative steel industry were indicated.

Unsustainable Development: a Case Study of Urban Planning History and Pandemic Trends in the United States

by Warren S. Vaz

The United States saw unprecedented growth after World War II in several key sectors including transportation. The boom in population was accompanied by a rise in huge, sprawling suburbs around hundreds of major cities. In addition to the inefficient use of resources, car-centric design is dangerous, causes pollution,and discourages walking and cycling. The diffuse nature of the population in these developments puts tremendous strain on infrastructure and local municipal budgets. This leads to neglected and decaying infrastructure and disproportionately affects segments of the population least able to effect change. This study examines the historical reasons for the current state of suburban development in the US. It explains several key features of urban planning, such as car-centric design and single-family zoning, and the issues they cause, namely rising home prices, pollution, and municipal insolvency. Case studies of recent infrastructure failures are cited. Changes in historical trends brought on by the COVID-19 pandemic are highlighted: migration out of cities, resultant effects on various industries, and changes in public transit. Finally, forthcoming policy and industry changes are discussed along with suggestions to address the problems described. Chiefly, these include rethinking urban design, making cities more pedestrian friendly, investing in public transit, and relaxing restrictive zoning laws to allow denser construction.

Enhancing the RPL Protocol Using an Artificial Neural Network for Sustainable IoT Infrastructure

by Sonia Kuwelkar and Hassanali Virani

Internet of Things, an ever-evolving communications paradigm, will play an eloquent role in sustainable development in near future. The backbone of IoT is a Low power and Lossy Network involving devices with constrained power, memory and processing capability interconnected over lossy links. The efficiency of the network largely depends on the design of the protocol at the network layer of the communication stack. To cater specific routing needs of such networks, the IETF has designed and standardized the IPv6 routing protocol for LLNs (RPL). RPL has proved efficient in tackling major issues but has certain routing gaps that need to be addressed for optimal performance. For instance, in standard RPL the routing decision is based on a single metric which leads to the selection of inefficient paths and reduces network lifetime. RPL suffers from unbalanced load distribution, slow convergence and inefficient bidirectional communication. Over the years, RPL has attracted many researchers who have contributed to improving this protocol to meet the requirements of energy efficiency, real-time, scalability and reliability. This chapter aims to provide a comprehensive review of the means and methods adopted by the researchers to enhance RPL protocol using soft computing techniques in an effort towards a sustainable IoT infrastructure. Initially, the enhancements done to RPL protocol using fuzzy logic technique are reviewed. In the later part, the role of evolutionary algorithms like Ant Colony Optimization, Genetic Algorithm and Firefly algorithm in RPL improvisation is reviewed. Finally, a novel Artificial Neural Network based method for improving RPL is proposed in this chapter. The proposed ANN based RPL is seen to improve network parameters like Energy efficiency, Packet delivery ratio, Latency and Control Overhead significantly thus directing towards sustainable IoT infrastructure.

Preface to Transitioning to Sustainable Industry, Innovation and Infrastructure

Wojciech J. Cynarski and Bożena Gajdzik

1. Introduction

Each of us intends to implement transformation in a sustainable manner. We are aware of our role for the environment and, in striving to be a leader in sustainable transformation, we know what a great responsibility we have to preserve the environment for ourselves and for future generations. The concept of sustainability, since its introduction (Our Common Future, Brundtland Report), has constantly been evolving. Sustainability is about intergenerational solidarity in finding solutions to ensure continued growth that allow organizations, companies and each of us to be proactive. Sustainability is an important part of economic systems and global law.

We believe that this volume is a systemic issue, taking into account the contexts of social ecology and the environment (Cynarski 2014; Eiglad 2015). New urban and industrial infrastructure and innovation in this area should take into account new urban plans for the creation of human-friendly spaces and smart cities (Azkuna 2012), as well as the impact of the development of tourism on the changes in this space and great sporting and cultural events (Sieber and Cynarski 2010; Edizel and Ward 2016). Facilities for people with disabilities are included in the infrastructure that is being built. Innovations are being made regarding the materials used and savings, including waste management, energy savings (preference for green energy) and other resources used in economies and industries (Gajdzik and Sroka 2021; Gajdzik et al. 2023).

2. Sustainability in a World of Modern Technology

In the past, sustainability was the doctrine of economics, which assumes a quality of life at the level allowed by the current development of civilization. The idea of sustainable development is summarized in the first sentence of the WCED—Our Common Future report: "At the current level of civilization, sustainable development is possible, that is, a development in which the needs of the present generation can be met without diminishing the chances of future generations meeting them" (Brundtland 1987). A sustainable economy (including industry) should balance economic growth, environmental protection, quality of life and human health. It is not only about the natural environment, but also the artificial, i.e., man-made (as in Chicago School's work on human ecology), environment. The doctrine of sustainable development strives for social justice by using environmental projects for higher efficiency. It is important to work and life now, but needs to factor in future generations and their heritage, both cultural and natural (cf. Kozłowski 2000, 2007; Caradonna 2014; Alhaddi 2015). The priority is to set ecological standards for preserving the homeostasis of the ecosystem.

In a world of modern technology (the fourth industrial revolution), the popularized concept of Industry 4.0 and rapid business development, the impact of industry, transport, cities, etc., on climate change and caring for the ecosystem as a whole are becoming increasingly important. Taking care of the needs of the present generation in a sustainable manner, as well as taking into account the environment and the future of future generations, is the strategic goal of modern civilization.

Modern business is becoming more and more digital and intelligent. Enterprises implement new technologies of the fourth industrial revolution in the sustainable environment. They use their own paths to Industry 4.0 (Gajdzik et al. 2021). Sustainable Industry 4.0 is a new concept for discussion by scientists and businesses (Gajdzik et al. 2020). This concept has been gaining more and more interest among scientists and practitioners in recent years because there is more and more information regarding Industry 4.0 (Kagermann 2013). Factories are becoming smarter, more efficient, safer and more environmentally friendly by linking and integrating production technologies and devices, information and communication systems and data and services into network infrastructures (Saniuk et al. 2020). New business models with cyber-physical systems (CPSs) are being built (Lee et al. 2015; Gajdzik 2020, chap. 3), but sustainability must not be forgotten in these models. In a new concept called Industry 5.0, sustainability has been given even more prominence. In the European document titled Industry 5.0: Towards more sustainable, resilient and human-centric industry (7 January 2021), we read (citation from Research and Innovation, European Commission) that "the common environmental goals can only be achieved by incorporating new technologies and rethinking the production processes with respect to the environmental impacts. Industry must lead by example in the Green transition".

3. Contents of the Book

3.1. Towards Smart Steel Manufacturing

This book consists of five chapters. In the first chapter, the author of the chapter, B. Gajdzik, presents the path of transformation of the steel sector in Poland to Industry 4.0. Since 2011, when it was presented at the Hannover fair, the concept of Industry

4.0 has become more and more popular. Technologies described as the pillars of the concept are modern determinants of industrial development (Kagermann 2013; Schwab 2017). More and more companies in different industries are implementing these pillars because they want to create smart manufacturing strategies. One of these industries which is actively transforming towards smart is steelworks. Large capital groups of the global steel industry are investing in the latest generation of solutions to achieve smart steel manufacturing (Gajdzik 2022; Gajdzik and Wolniak 2021). One of the large capital groups also has plants in Poland. The transition of smelters in Poland to the use of smart requirements was preceded by a profound restructuring in the 1990s, and after that, when foreign capital entered the Polish market, the process of market transformation of Polish steelwork was initiated. The path of Polish steelwork to being competitive on the market was long (Gajdzik 2013). Currently, steel companies in Poland wish to become more and more smart. Changes to Industry 4.0 are implemented at the operational level (process optimization), and human reorganization occurs (Gajdzik and Wolniak 2022). If the demand for steel in consumer markets continues to grow, smelters can expect to co-create intelligent processes with consumers in 2030 (based on the results of filed research: see Gajdzik 2022, Monograph).

3.2. RPL Protocol and Internet of Things (IoT)

The second chapter of our book is about enhancing the RPL protocol using an artificial neural network to create sustainable IoT infrastructure. IoT is one of the pillars of Industry 4.0, a pillar that will play a telling role in sustainable development in the near future. The authors of the chapter, S. Kuwelkar and H. Virani, presented the protocol RPL. The protocol has been proven to be efficient in tackling major communication issues. The efficiency of the network largely depends on the design of the protocol at the network layer of the communication stack. Over the years, RPL has attracted many researchers who have contributed to improving this protocol in order to meet the requirements of energy efficiency, real-time implementation, scalability and reliability. The authors of the chapter present several methods by which to improve the protocol, and, in the final part of the section, point out the key prospect, neural networks. The authors stress the importance of an improved protocol in terms of improving energy efficiency.

3.3. Urban Planning in Sustainability

The author, W. Vaz, present the historical reasons for the current state of suburban development in the US. Vaz explains some of the key features of urbanism, such as automobile design and single-family zones, as well as the problems they cause, namely, rising home prices, pollution and municipal insolvency. Examples of recent infrastructure failures were cited. Changes in historical trends caused by the COVID-19 pandemic are highlighted: migration from cities, the resulting effects on various industries, and changes in public transportation. Finally, upcoming policy and industry changes are discussed, along with suggestions for addressing the described problems. These primarily include redesigning urban planning, making cities more pedestrian-friendly, investing in public transportation and relaxing restrictive zoning regulations to allow for denser building.

3.4. Innovation in Urban Infrastructure and Development of Physical Culture

In the fourth chapter, the authors, W. J. Cynarski and Leszek Woźniak, present the positive impact of improving sports infrastructure (physical culture) in urban spaces on the living conditions of residents. The city of Strzyżów (Podkarpackie voivodeship, Poland) was used as a case study. Recreational physical activity in the open air (cycling, horseback riding, other open-air sports) simultaneously serves social health, the development of physical culture and the sustainable development of the city and municipality. Residents of cities and towns want urban space for themselves, and they want that space to enable them to live active and healthy lifestyles. In modern cities and towns, sports and tourism infrastructure are being developed for everyone, including people with disabilities.

3.5. Corporate Social Responsibility Reporting

The chapter focuses largely on the principles of corporate social responsibility. The authors present the most common methods and areas of SCR reporting, focusing on non-financial data. The authors, B. Orzeł and R. Wolniak, presented statistical data on corporate social responsibility in various European countries. In 1987, the Bruntland Report defined sustainability as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” Since that year, everyone has participated in building sustainable economies and industries. Sustainability has become the key to many “doors.” One does not open a business door without a sustainable production strategy. One does not become a conscious citizen of the globe without waste segregation. We are all learning to conserve environmental resources. In the era of Industry 4.0, we expect the latest generation of technology to help us in this continuous transformation.

4. Conclusions

The principles of sustainable development have many addressees; thus, our book is not homogeneous. There are chapters on the impact of industry on sustainability (especially environmentally disruptive industries, e.g., the steel industry), chapters describing (presenting) scientific methods for measuring various aspects of sustainability, a chapter on urban planning (e.g., United States) as well as urban infrastructure (case study, Poland) and a chapter on corporate social responsibility.

The authors of the individual chapters have contributed to promoting the idea of sustainability. The content in the book follows a holistic approach, giving all people, regardless of economic or social factors, the opportunity to acquire the skills necessary to achieve sustainable personal development.

The authors of the book thank everyone for making their scientific work available for the promotion of sustainable development. As the title of the book, "Transitioning to Sustainable Industry, Innovation and Infrastructure," indicates, sustainability is an ongoing process for our benefit and that of future generations.

Author Contributions: Conceptualization, W.J.C. and B.G.; methodology, B.G.; formal analysis, W.J.C. and B.G.; writing—original draft preparation, B.G.; writing—review and editing, W.J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

Alhaddi, Hanan. 2015. Triple Bottom Line and Sustainability: A Literature Review. *Business and Management Studies* 1: 6–10. [CrossRef]

Azkuna, Iñaki, ed. 2012. *Smart Cities Study: International Study on the Situation of ICT, Innovation and Knowledge in Cities*. Bilbao: The Committee of Digital and Knowledge-based Cities of UCLG.

Brundtland, Gro Hamlem. 1987. *Our Common Future. WCED Report (Report of the World Commission on Environment and Development)*. Oslo: WCED. Available online: https://www.are.admin.ch/are/en/home/media/publications/sustainable-development/brundtland-report.html (accessed on 31 August 2023).

Caradonna, Jeremy L. 2014. *Sustainability: A History*. Oxford: Oxford University Press.

Cynarski, Wojciech J. 2014. The New Paradigm of Science Suitable for the 21st Century. *Procedia–Social and Behavioral Sciences* 149: 269–75. [CrossRef]

Edizel, Ozlem, and Ralph Ward. 2016. Sustainability and mega-event legacy. In *Mega-Event Cities: Urban Legacies of Global Sports Events*. Edited by Valerie Viehoff and Gavin Poynter. New York: Routledge.

Eiglad, Eirik. 2015. *Social Ecology and Social Change*. Porsgrunn: New Compass Press. ISBN 9788293064343.

Gajdzik, Bożena. 2013. The road of Polish steelworks towards market success—Changes after restructuring process. *Metalurgija* 3: 421–24.

Gajdzik, Bożena. 2020. Development of business models and their key components in the context of cyber-physical production systems in Industry 4.0. In *Scalability and Sustainability of Business Models in Circular, Sharing and Networked Economies*. Edited by Adam Jabłoński and Marek Jabłoński. Cambridge: Cambridge Scholars Publishing, chap. 3. pp. 73–94.

Gajdzik, Bożena. 2022. *Diagnosis of the steel Industry transformation direction in the Industry 4.0*. Gliwice: Wydawnictwo Politechniki Śląskiej. 468p, Monografia 945. ISBN 978-83-7880-850-3.

Gajdzik, Bożena, and Włodzimierz Sroka. 2021. Resource Intensity vs. Investment in Production Installations—The Case of the Steel Industry in Poland. *Energies* 14: 443. [CrossRef]

Gajdzik, Bożena, and Radosław Wolniak. 2021. Digitalisation and Innovation in the Steel Industry in Poland-Selected Tools of ICT in an Analysis of Statistical Data and a Case Study. *Energies* 14: 3034. [CrossRef]

Gajdzik, Bożena, and Radosław Wolniak. 2022. Smart Production Workers in Terms of Creativity and Innovation: The Implication for Open Innovation. *Journal of Open Innovation: Technology, Market, and Complexity* 8: 68. [CrossRef]

Gajdzik, Bożena, Sandra Grabowska, Sebastian Saniuk, and Tadeusz Wieczorek. 2020. Sustainable Development and Industry 4.0: A Bibliometric Analysis Identifying Key Scientific Problems of the Sustainable Industry 4.0. *Energies* 13: 4254. [CrossRef]

Gajdzik, Bożena, Sandra Grabowska, and Sebastian Saniuk. 2021. A Theoretical Framework for Industry 4.0 and Its Implementation with Selected Practical Schedules. *Energies* 14: 940. [CrossRef]

Gajdzik, Bożena, Radosław Wolniak, and Wiesław Wes Grebski. 2023. Electricity and Heat Demand in Steel Industry Technological Processes in Industry 4.0 Conditions. *Energies* 16: 787. [CrossRef]

Kagermann, Henning. 2013. Recommendations for Implementing the Strategic Initiative Industry 4.0: Securing the Future of German Manufacturing Industry. Final Report of the Industry 4.0 Working Group. *Acatech*. Available online: https://ia601901.us.archive.org/35/items/FinalReportRecommendationOnStrategicInitiativeIndustrie4.0/Final%2520Report_%2520Recommendation%2520on%2520strategic%2520initiative%2520Industrie_4.0.pdf (accessed on 31 August 2023).

Kozłowski, Stefan. 2000. *Ekorozwój—wyzwanie XXI wieku [Sustainable Development—The Challenge of the 21st Century]*. Warsaw: PWN. (In Polish)

Kozłowski, Stefan. 2007. *Przyszłość ekorozwoju [The Future of Sustainable Development]*, 2nd ed. Lublin: KUL. (In Polish)

Lee, Jay, Behrad Bagheri, and Hung-An Kao. 2015. Research Letters: A Cyber-Physical Systems Architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters* 3: 18–23. [CrossRef]

Saniuk, Sebastian, Sandra Grabowska, and Bożena Gajdzik. 2020. Social Expectations and Market Changes in the Context of Developing the Industry 4.0 Concept. *Sustainability* 12: 1362. [CrossRef]

Schwab, Klaus. 2017. *The Fourth Industrial Revolution*. New York: Crown Business.

Sieber, Lothar, and Wojciech J. Cynarski. 2010. Tourist qualities of Bavaria (Bayern) in the light of systemic and anthropologic conception of tourism. *Ido Movement for Culture Journal of Martial Arts Anthropology* 10: 128–32.

© 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Innovation in Urban Infrastructure for Development of Physical Culture: An Example of a Little Town in Poland

Wojciech J. Cynarski and Leszek Woźniak

1. Introduction

As Marc Louis (Louis 2009) stated: "By definition, sustainable development is based on the principle of intergenerational fairness. We must not make the earth uninhabitable for future generations. This also implies the idea of spatial fairness. Well-being must be shared by all, not only on a country-wide scale, but by the entire planet. Given the globalization of the economy, transportation and telecommunications, the world must actually now be considered a global village with the implication of an integration of levels of intervention and measures. In other words, the rule of 'think global—act local' should be applied."

Sustainable development in urban space concerns, among other things, the conditions for improving sports infrastructure, broadly understood, and tourism, in order to improve the physical culture and health culture of the inhabitants. Fitness clubs, rehabilitation centres, parks, swimming pools, gyms and other sport facilities put into concrete form the idea of the sport practice as a new right of citizenship extended to everybody. They meet the increasingly aware social needs. Therefore, "Sport in the City—Mobility, Urbanity and Social Change" was the subject of one of the EASS—the European Association for Sociology of Sport—conference (Evans et al. 2016; Cynarski 2016). This topic is interesting not only for sociologists, but also from the perspective of planning in urban space and management in physical culture.

On the basis of the theory of physical education and the theory of physical culture developed in Poland (Śniadecki 1805; Grabowski 1997; Pawłucki 2003; Krawczyk 2005; Cynarski 2014), we include among the manifestations of physical culture: physical education, competitive sports, physical recreation (free time physical activity), active forms of tourism, rehabilitation and anti-aging, as well as traditional martial arts, which have their own specificity (Obodyński and Cynarski 2007; Cynarski et al. 2013). Research in the field of physical culture should take into account both man and his various needs, as well as natural and anthropogenic space, in particular urban space with appropriate infrastructure, including appropriate architecture (Obodyński and Cynarski 2003; cf. Park 1952; Cynarski 2005).

Adequate infrastructure enables the development of physical culture in its individual manifestations, but also the economic growth of a given area thanks to the development of tourism (Obodyński and Cynarski 2009). In tourism, cultural and natural values, active and passive forms, often intertwine. As such, they act most strongly and attract people to a more attractive destination (Munsters 2008; Obodyński 2008). The fact that people try to actively rest, that they combine cognitive goals with leisure time physical activity, and that they increasingly appreciate physical culture (not only the sport of performance and competition) is a visible tendency. This is explained by the concepts from half a century ago concerning the needs of rest and the philosophy of spending free time (Nash 1953). Relatively new, less known earlier forms of physical recreation and tourism motives (aqua aerobics, exotic dances, health *taijiquan* and *qigong* exercises, Asian martial arts) are becoming especially popular (Moegling 2006; Munsters and Melkert 2015).

Physical culture is a subsystem of a more general axionormative order. Z. Krawczyk defines it as follows: "Physical culture is a relatively integrated and established system of behaviors in the field of caring for physical development, mobility, health, beauty, bodily perfection and human expression, following the patterns adopted in a given community, as well as the results of these behavior" (Krawczyk 1995). What factors particularly encourage physical activity? These are in particular:

- "Family social support, especially for women;
- Individuals who exercise with their parents;
- Moderate intensity, individually tailored, home-base exercise programmes;
- Simply programmes to improve fitness, such as walking, especially for older adults and low-income individuals;
- The availability and proximity of community facilities and safe environments;
- Linking physical activity to personal interests and pursuits that can be followed as a family over the entire lifespan;
- Targeted interventions which are theoretically based and provide printed support materials—these should include resource manuals describing activity options in the community, and offer no-cost organized events, such as fun walks;
- Physician-based counselling;
- Workplace-based exercise programmes and educational campaigns—these have been successfully used both to increase exercise behaviour among employees and reduce to costs associated with health insurance and absenteeism" (Bédard 1995).

There are no studies on the functioning of small towns similar to Strzyżów and the development of sports and tourist infrastructure there. The aim of the study is to present this very example.

2. The Case of a Small Town

In accordance with the principles of a single case study description (the qualitative method of single case study research, both the descriptive, interpretive and evaluative, e.g., by Skinner et al. 2015, pp. 116–33) (Skinner et al. 2015; Cynarski 2021), in adaptation of the issue discussed here, we present a description of the natural conditions, existing infrastructure and institutions operating in the area of free time—recreation, tourism, and rehabilitation in the discussed area.

This study is a case study of a small town (Figures 1–3). Strzyżów on the Wisłok River was built in the 13th century (Cynarski 1980). It is a town in south-eastern Poland. It has only about 9000 inhabitants. It is the seat of the rural and urban commune and the *poviat starostwo*. The commune is mainly agricultural, services are developed, and there is a small processing industry. As in the case of other cities in the region, there was a gradual increase in the number of people and development in the city and commune c (Malikowski 1992; Kut 2007). Since 2010, there has been a noticeable decline in the population (depopulation) and aging of the population, which is a pan-European trend. Detailed figures can be found in the link attached here (Strzyżow n.d.). A nice location in the Strzyżów foothills offers a chance for the development of tourism here, especially since the recreational infrastructure functions well here (Cynarski and Obodyński 2007a). The innovations applied here, at least as compared to the state before the political system changes, turned out to be effective. The town has become more attractive for tourists and for the inhabitants themselves. It also uses his natural conditions.

Natural conditions and fauna around Strzyżów create an interesting landscape and microclimate. Strzyżów is situated in a small valley surrounded by hills. The area is rich in numerous species of flora and fauna, so a landscape park has been established. "The Czarnorzecko-Strzyżowski Landscape Park protects the most valuable parts of the Strzyżowskie and Dynowskie Foothills, separated by the Wisłok gorge, making them available for study, tourism and leisure." (Czarnorzecko-Strzyżowski Park). The area of the Park is inhabited by 119 species of birds, including: roe deer, deer, wild boar, beaver, badger, otter, beech marten and pine marten. In addition, there is a natural, ecological farming, and ecological agritourism farms invite tourists. Together with the ecology of the landscape, it constitutes an excellent tourist and recreational potential (Woźniak et al. 2005).

(**a**)

(**b**)

Figure 1. (**a**,**b**) The "Otylia" Recreation and Rehabilitation Centre and Indoor Swimming Pool in Strzyżów, April 2021. Source: Photos by W.J. Cynarski.

Figure 2. Fragment of the town—a small street. In the distance—hills and forest, Strzyżów, April 2021. Source: Photo by W.J. Cynarski.

Figure 3. Trainers in a small park in Strzyżów, 2021. Source: Photo by W.J. Cynarski.

For 30–40 years, the sports tradition of Strzyżów has been volleyball, played by school students, and—secondly—jujutsu. The sports infrastructure consists of two large sports halls at two school complexes, a sports stadium, the Recreation and Rehabilitation Centre and the "Otylia" Indoor Swimming Pool (Figure 1a,b), a complex of sports fields with a seasonal artificial ice rink, a ski slope with a Ski School, recreational and bicycle paths and the Regional Integration Sports Park and Recreation. The design of this park won the competition of the Podkarpackie Voivodeship for the development of sports and recreation infrastructure. Therefore, children, adolescents and adults can use this park from spring to autumn to spend time actively outdoors. There is a slope with ski lifts and an ice rink in the ground. However, the swimming pool and gyms, sports and recreation clubs—all year round. It is also possible to ride a horse at a nearby private stud farm.

Tourist (sightseeing) and bicycle routes run through the most interesting parts of the Strzyżów commune. The most important are two hiking trails: (1) the green trail, which leads southwards from Strzyżów through Godowa-Brzeżanka, and enters the ridge of the Brzeżanka Range, where the black hiking trail from Babica comes. Then, the green trail goes down to Bonarówka, from where it leads to the ruins of the Kamieniec castle in Odrzykoń; (2) the black trail leads from Babica, through Lubenia, Połomia Działy to Żarnowa. It descends through the fields to the Stobnica valley, and then, along a steep road, climbs the Brzeżanki Range. There are complexes of educational and nature paths in the village of Łętownia. They are made up of a health path (1 km long) and a nature and educational path (2.5 km long). Another attraction of the Strzyżów commune is the four bicycle paths (Strzyżow n.d.).

Cultural tourism also has relatively large development opportunities here. In Strzyżów there is a large shelter tunnel for a staff train built in World War II, a historic Catholic church from the 15th century, a synagogue and a Jewish cemetery, mansions, chapels, palace complexes, and the Self-government Museum of the Strzyżów Land. The combination of attractions from the area of cultural tourism, recreational activities and natural conditions (forest areas on the hills surrounding the city) provide an interesting offer for both residents and tourists. The only limitation here is the lack of a well-developed hotel base. The *Development Strategy* referred to above does not provide for the construction of new facilities, but the maintenance of the existing ones.

It is worth adding that the city's advantage is civic activity. Many non-governmental organizations operate here, such as the Strzyżowska Land Lovers Society, Idokan Poland Association (Pawelec 2013; Kubala 2016), foundations, societies, sports clubs and other associations (over 30). Local authorities support their activities, albeit to a different extent. They also distinguish the most active with symbolic prizes, motivating them to act even better. The lack of this activity and the possibility of useful free time activities would probably cause even greater frustration of young people due to limited employment and promotion opportunities in a small town. The apathy of the authorities (central and local) would pose a threat to the departure of young people and depopulation.

The problem of used innovations in terms of the development of tourism and other forms of using free time can be discussed in many types, especially in relation to eco-innovations. The decisive significance of the use for recreation in free time may be new distinguished categories of innovation, including eco-system innovations, including social ones.

System eco-innovations may mean an innovative variant of combining many, even commonly used, solutions into a new, unprecedented solution (system). System eco-innovations are defined as a whole set of various eco-innovations, which as a result create new (radical eco-innovations) or improved systems aimed at minimizing or eliminating the negative impact of existing solutions on the environment. A classic example of them can be various variants of green cities (O'Brien and Miedziński 2012).

R. Kemp and S. Pontoglio distinguish incremental (incremental) and radical innovations. Incremental eco-innovations concern minor modifications of products, processes (also systems—own attention of the authors), while radical eco-innovations lead to the necessity to break with existing competences and competences (Kemp and Pontoglio 2011).

The introduction of the entire eco-innovation system conducive to the development of sport and tourism allows for innovative practices of using free time. This is of particular importance in small towns, where apathy and discouragement resulting from the lack of adequate infrastructure often appear.

It can be noticed that the principles of defining and measuring innovation (including eco-innovation) (OECD and Eurostat 2018) provided in the basic EU handbook (guide) (OECD and Eurostat 2018) are subject to some erroneous simplification. The novelty is still important, and at the same time quality is important in eco-innovation, sometimes even meaning a return to traditional solutions, but in a new version. Something like that is the return to the ecological principles of spending free time, under conditions of the possibility of using eco-innovative infrastructure, e.g., in a place for spending free time, mainly by young people, in the form of computer games.

3. Discussion

The social basis of eco-innovation, apart from the aspects of environments, may mean their special role in creating a new quality of life. Practicing joyful sport fulfils one of the foundations conducive to happiness according to the concept used in Buthan for years, which is practicing the logic of measuring the so-called Gross National Happiness Index (Centre for Bhutan Studies & GNH Research 2016). It seems that the use of the concept of shaping and quality of life similar to the Buthan solutions, which becoming more and more popular in the world, may in the future be of great importance in the proper development of small towns in Poland, especially in the context of the actual shaping of quality of life.

Nature and natural heritage become areas of ecology teaching and appropriate upbringing. It is a landscape, a scene, an area for various activities, particularly for outdoor physical activity (PA), also as a cultural creation, because such areas are specially protected (Eichberg 2007). PA deals with both planning in urban space and management. This applies to the responsibility for the health of the society and responsible management of human resources as well as in the use of the existing urban infrastructure (Louis 2009), or also in areas outside the urban agglomeration. Of course, the management itself should be carried out in accordance with the highest standards and efficiently, from providing information to crisis management when needed (cf. Krupa 2002).

In the case of small towns, whether in Central Europe, in Eastern Europe or outside Europe, opportunities should only be sought for towns and the communities living in them (Niyazbekova et al. 2018; Pfaff et al. 2019). Sometimes, after years of plunder or communism, it is necessary to revitalize a given area with care for the preserved heritage (Doroz-Turek 2019). This is helped by investments supported by EU funds for the preservation of cultural heritage or for the development of sports and recreational infrastructure (cf. Nová and Strachová 2017). It can be assumed that the town and commune of Strzyżów and the Strzyżów poviat made good use of this opportunity.

In the literature on the subject, we find similar examples of the usually positive impact of investments in sports facilities or the development of localities thanks to sports tourism and enriched recreational opportunities (PA) (Wojtas-Harań 2018; Garcia-Pascual et al. 2019). The social impact of a sports centre and a recreational or tourist base result from additional opportunities to improve the well-being of the inhabitants. At the same time, it is worth preserving the ecological, natural landscape and the natural surroundings of a given town. The new economy emphasizes economic activities with simultaneous care for the well-being of man and the natural environment (Cynarski and Obodyński 2007b).

4. Summary

The physical culture infrastructure is functioning properly in the town of Strzyżów. Two recreational parks with permanent trainers are constantly used by the elderly (anti-aging), mothers with children and other people of all ages. Cycling, cross-country, equestrian and skiing are developing, and hence sports conducted in open spaces. This serves in parallel social health, the growth of physical culture and the sustainable development of the commune. Other facilities built with EU funds also work well. This is a good example of using local opportunities in a provincial town that is threatened with youth departure and depopulation.

Further research should include monitoring of the situation in which the described infrastructure functions and the effectiveness of physical culture institutions in the area in question.

Author Contributions: conceptualization, W.J.C. and L.W.; methodology, W.J.C.; software, W.J.C.; validation, W.J.C. and L.W.; formal analysis, W.J.C.; investigation, W.J.C.; resources, W.J.C. and L.W.; data curation, W.J.C.; writing—original draft preparation, W.J.C.; writing—review and editing, L.W. and W.J.C.; visualization, W.J.C.; supervision, L.W.; project administration, W.J.C.; funding acquisition, W.J.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

Bédard, M. 1995. Physical Activity, Health and Well-being. Research Quarterly for Exercise and Sport 66 (4) (Québec, special issue).

Centre for Bhutan Studies & GNH Research. 2016. *A Compass Towards a Just and Harmonious Society 2015 GNH Survey Report*. Thimphu: Centre for Bhutan Studies & GNH Research.

Cynarski, Stanisław. 1980. *Studia nad dziejami Strzyżowa i okolic [Studies on the History of Strzyżów and the Surrounding Area]*. Rzeszów: Wydawnictwo Naukowe w Rzeszowie. (In Polish)

Cynarski, Wojciech J. 2005. Architektura a antropologia dalekowschodnich sztuk walki: Architektura dōjō–szkic z socjologii przestrzeni. *Ido Movement for Culture* 5: 75–95.

Cynarski, Wojciech J. 2014. Polish achievements in the theory of physical education and new directions. *Ido Movement for Culture. Journal of Martial Arts Anthropology* 14: 1–14. [CrossRef]

Cynarski, Wojciech J. 2016. Sport in urban space. Paper presented at 13th EASS Conference and 7th Congress, Copenhagen, Denmark, May 4–7.

Cynarski, Wojciech J. 2021. *Metodologia badań społecznych i antropologiczno-kulturowych w naukach o kulturze fizycznej i w obszarze turystyki*. Rzeszów: Rzeszow University Press.

Cynarski, Wojciech J., and Kazimierz Obodyński. 2007a. Turystyka zainteresowań sportowych na obszarach wiejskich [Tourism of sports interests in rural Areas]. In *Rozwój turystyki na obszarach wiejskich*. Edited by Mikołaj Jalinik. Białystok: Politechnika Białostocka, pp. 368–74. (In Polish)

Cynarski, Wojciech J., and Kazimierz Obodyński. 2007b. Towards economy oriented to man—On example of tourist economy. In *Ekonomia digitalnej ery. Problematika, Vychodiska, Aspekty*. Edited by Kazimierz W. Krupa. Poprad: Cezhranicny Vyskumny Ustav, pp. 259–72.

Cynarski, Wojciech J., Lothar Sieber, Milan Ďuriček, Marian Rzepko, and Paweł Król. 2013. Barriers to the development of Far Eastern martial arts in selected areas of Central Europe. *Ido Movement for Culture. Journal of Martial Arts Anthropology* 13: 10–16.

Czarnorzecko-Strzyżowski Park. 2021. Available online: https://parkikrosno.pl/475-parki/12514-czarnorzecko-strzyzowski-park-krajobrazowy/12559-przyroda-czarnorzecko-strzyzowskiego-parku-krajobrazowego.html (accessed on 17 February 2021).

Doroz-Turek, Malgorzata. 2019. Revitalisation of small towns and the adapticve reuse of its cultural heritage. In *3rd World Multidisciplinary Civil Engeneering, Architecture, Urban Planning Symposium (WMCAUS 2018)*. Book Series: IOP Conference Series—Materials Science Engeneering. Art. No. 052006. Paris: IOP.

Eichberg, Henning. 2007. Outdoor activities, green education and landscaping. *Ido Movement for Culture* 7: 132–42.

Evans, Adam B., Glen Nielsen, and Lone Friis Thing, eds. 2016. *Sport in the City—Mobility, Urbanity and Social Change*. 13th EASS Conference Book of Abstracts. Copenhagen: Univ. of Copenhagen.

Garcia-Pascual, Fernando, David Parra-Camacho, and Romulo Jacobo González-García. 2019. Validation of the scale to analyse residents' perceptions of the social impact of a sport centre. *Movimento* 25: e25043. [CrossRef]

Grabowski, Henryk. 1997. *Teoria fizycznej edukacji [Theory of Physical Education]*. Kraków: AWF.

Kemp, René, and Serena Pontoglio. 2011. The innovation effects of environmental policy instruments. A typical case of the blind men and the elephant? *Ecological Economics* 72: e.33. [CrossRef]

Krawczyk, Zbigniew. 1995. *Sociologia kultury fizycznej [Sociology of Physical Culture]*. Warsaw: AWF. (In Polish)

Krawczyk, Zbigniew. 2005. Selected Writings. In *Sport, Culture and Society. In Honour of Professor Zbigniew Krawczyk*. Edited by Jerzy Kosiewicz. Warsaw: AWF, pp. 21–161.

Krupa, Kazimierz. 2002. New management concept (selected tools). *Ido Movement for Culture* 3: 209–14.

Kubala, Krzysztof. 2016. Sympozjum Stowarzyszenia Idokan Polska [Symposium of the Idokan Poland Association]. *Gazeta Uniwersytecka UR* 3: 41. (In Polish).

Kut, Franciszek. 2007. *Strzyżowskie metamorfozy w II połowie XX wieku*. Strzyżów-Tuchów: Mała Poligrafia.

Louis, Marc. 2009. Responsibility in physical activity management. *Ido Movement for Culture* 9: 146–61.

Malikowski, Marian, ed. 1992. *Uwarunkowania i potrzeby rozwoju miast Polski południowo-wschodniej*. Rzeszów: WSP.

Moegling, Klaus. 2006. Bildung als Ausweg 'des Menschen aus seiner Selbstverschuldeten Unmündigkeit'—Zum Bildungsverständnis und zur Konzeption einer zeitgemäβen Sport- und Bewegungspädagogik [Education as a way out of 'a man from his self-incurred immaturity'—To form the understanding and design of a time-according to pedagogy of sport and exercises]. *Ido Movement for Culture* 6: 268–75. (In German).

Munsters, Wil. 2008. Culture and tourism: From antagonizm to synergism. *Ido Movement for Culture* 8: 165–73.

Munsters, Wil, and Marjan Melkert, eds. 2015. *Anthropology as a Driver for Tourism Research*. Garant: Antwerpen—Apeldoorn.

Nash, Jay Bryan. 1953. *Philosophy of Recreation and Leisure*. St. Louis: The C.V. Mosby Company.

Niyazbekova, R. K., Altyn Makhmudovna Yessirkepova, Zh T. Aliyeva, and Monika Jaworska. 2018. Typology of small cities in the sought Kazakhstan region. *Bulletin of the National Academy of Sciences of the Republic of Kazakhstan* 1: 23–31.

Nová, Jana, and Milena Strachová. 2017. Assessing the impact of European Union Funding for sport facilities et local level. Paper presented at 8th International Conference of Kinesiology, Opatija, Croatia, May 10–14; pp. 456–60.

O'Brien, Meghan, and Michal Miedziński, eds. 2012. *Europe in Transition. Paving the Way to a Green Economy throught Eco-Innovation*. Annual Report 2012. Brussels: Eco-Innovation Obsarvatory, Available online: https://www.eco-innovation.eu/index.php/reports/annual-reports (accessed on 24 February 2021).

Obodyński, Kazimierz. 2008. Encounters, conflicts, dialogues. Analysis of selected areas of physical culture and cultural tourism (a review). *European Journal of Tourism Research* 1: 161–63.

Obodyński, Kazimierz, and Wojciech J. Cynarski. 2003. Reflections about methodological and epistemological problems in sport sciences. *Research Yearbook. Studies in the Theory of Physical Education and Sport* 9: 37–43.

Obodyński, Kazimierz, and Wojciech J. Cynarski. 2007. Factors and barriers in the development of far easterm martial arts and combat sports. In *The Changing Role of Public, Civic and Private Sectors in Sport Culture*. Edited by Hannu Itkonen, Anna-Katriina Salmikangas and Eileen McEvoy. Jyväskylä: University of Jyväskylä, pp. 257–66.

Obodyński, Kazimierz, and Wojciech J. Cynarski. 2009. Współczesny rozwój turystyki i hotelarstwa—IV Międzynarodowa Konferencja Naukowa Uniwersytetu Egejskiego, Rodos 2009 [Contemporary development of tourism and hotel industry—IV International Scientific Conference of Aegean University, Rhodes 2009]. *Przegląd Naukowy Kultury Fizycznej UR* 12: 178–80.

OECD, and Eurostat. 2018. *Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation*, 4th ed. The Measurement of Scientific, Technological and Innovation Activities. Paris: OECD Publishing, Luxembourg: Eurostat.

Park, Robert Ezra. 1952. *Human Communities: The City and Human Ecology*. Glencoe: The Free Press.

Pawelec, Przemysław. 2013. Jubileusz dwudziestolecia Stowarzyszenia Idokan Polska [Twenty-year jubilee of the Idokan Poland Association]. *Waga i Miecz* 6: 38. (In Polish).

Pawłucki, Andrzej. 2003. *Personalism for Sport Pedagogy*. Gdańsk: AWFiS.

Pfaff, Maya C., Renae C. Logston, Serge Jpn Raemaekers, Juliet C. Hermes, Laura K. Blamey, Hayley C. Cawthra, Darryl R. Colenbrander, Robert J. Crawford, Elizabeth Day, Nicole Du Plessis, and et al. 2019. A synthesis of three decades of socio-ecological change in False Bay, South Africa: Setting the scene of multidisiplinary research and management. *Elementa-Science of the Anthropocene* 7: 32. [CrossRef]

Skinner, James, Allan Edwards, and Ben Corbett. 2015. *Research Methods for Sport Management*. London and New York: Routledge.

Śniadecki, Jędrzej. 1805. *O fizycznym wychowaniu dzieci [The Physical Education of Children]*. Wilno: Dziennik Wileński 5 and 6. (In Polish)

Strzyżow. n.d. Strategia Rozwoju Gminy Strzyżow na lata 2016–2025 [Strategy for the Development of the Strzyżow Commune for 2016–2025]. Available online: https://www.strzyzow.pl/files/web.strzyzow/upload/files/Informator%20gospodarczy/strategia%20zrownowazonego%20rozwoju/Strategia%20Rozwoju%20Gminy%20Strzyzow%20na%20lata%202016_2025.pdf (accessed on 10 April 2021). (In Polish).

Wojtas-Harań, Anna. 2018. The concept of sustainable development in spatial management of mountain settlement units. In *10th Conference of Interdisciplinary Problems in Environmental Protection and Engeneering EKO-DOK 2018*. Book Series: E3S Web of Conferences. art. no. 00192. Paris: IOP, vol. 44.

Woźniak, Leszek, Marek Kuśnierz, and Rüdiger Trinks. 2005. The Scenery—Contemporary Trends of Transformations and Tourism. In *Regional Tourism versus European Integration and Globalization*. Edited by Kazimierz Obodyński and Wojciech J. Cynarski. Rzeszów: EACE and Rzeszow University Press, pp. 26–31.

© 2023 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Corporate Social Responsibility Reporting in the Context of Striving to Achieve the Sustainable Development Goals

Bartosz Orzeł and Radosław Wolniak

1. Introduction

Nowadays, more and more emphasis is placed on economic development in line with the idea of sustainable development. The growing energy demand and the increasing depletion of resources in the world have led international organizations and governments of various countries to take steps related to sound management and rationalization of resources (Chen et al. 2018). Corporate social responsibility seems to fit perfectly into the sustainable management of a company. According to research conducted by Činčalová and Prokop in 2020, the most accurate term to describe corporate social responsibility is "an optional concept of socially responsible conduct beyond the legitimate commitments of the company that integrates the social, environmental and economic part and therefore it satisfies the objectives of all the interested parties" (Činčalová and Prokop 2019). The year 2000 until now has been the time of business ethics transformation all over the world (Van Marrewijk 2003). From the business management point of view, corporate social responsibility (CSR) has become a strategic tool more than an option. Motivating factors for corporate social responsibility to undertake different activities include external and internal pressures and demands (Halkos and Nomikos 2021; Tai and Chuang 2014; Streimikiene et al. 2019; Lu et al. 2021). Many enterprises choose corporate social responsibility reporting because of the potential benefits connected to this activity. One of the main reasons is its usefulness for public relations. Effectively communicating social and ecological efforts, which corporate social responsibility reporting can carry out, is a great tool that works as customers' and stakeholders' "trust extractor" (Sprinkle and Maines 2010; Hąbek and Wolniak 2015; Navickas and Kontautiene 2012; Valackiene and Miceviciene 2011). It is worth noting that the economies of Central and Eastern Europe after the collapse of the Soviet Union first had to overcome the path of systemic transformation. At the time when corporate social responsibility was beginning to develop in Western countries and the first GRI (Global Reporting Initiative) guidelines were created, the free market economy was just beginning to exist in the countries of the former Soviet Union. This is a huge change that has opened up these markets to the rest of the world. Nevertheless, the regulations imposed by these governments, which often enforced some type of corporate social responsibility, have ceased to apply for some time (Aluchna et al. 2009). The very fast system transition and industrial restructuring process in connection to privatization has been one of the considerable causes for the following issues in the former Eastern Bloc countries (Aluchna et al. 2009; International Business Leaders Forum 2004; Belyaeva 2013):

- Higher than previous social costs;
- Unemployment;
- Corruption;
- Lack of social provision for vulnerable groups;
- Problems with social health;
- Unhealthy workforce;
- The rise in numerous non-government organizations competing for projects, private sector ownership, resources and agency fund ownership, and lack of social trust in these organizations;
- Lack of knowledge about foreign corporations, investors and how a partnership with them can increase the added value of a business.

Nevertheless, the globalization of industry, the flow of information and the benefits for enterprises and entire sectors of the economy that result from responsibly conducting business have made good business practices and concern present in an increasing number of enterprises belonging to both the public and private sectors (Kinderman 2011; Stoian and Zaharia 2012). There is a strong need to strive for sustainability, managing business activities in such a way as to ensure that the needs of the present generation are met without reducing the chances of meeting the needs of the next generations (Sarkar 2008). Reviewing the literature shows that there is a research gap in the area of a clearly defined correlation and connection between CSR reporting and the documentation and achievement of the Sustainable Development Goals by enterprises. It is necessary to sort and manage knowledge in this area and conduct research based on various methods and tools in the field of the impact of corporate social responsibility reporting and non-financial data on the achievement of the Sustainable Development Goals.

2. Results

This paper is a study on corporate social responsibility as part of a sustainable approach to modern management. In the first part, a literature analysis was carried out. We included issues related to the different ways in which enterprises can achieve the Sustainable Development Goals. The next part of this paper contains a literature analysis on different types of non-financial activities which can help business entities to improve the quality of their corporate social responsibility reporting. The issues connected to effectiveness in environmental and social efforts taken by enterprises are raised. The most common methods and areas of non-financial data reporting by enterprises are introduced, and statistical data of corporate social responsibility reporting in different European contexts are presented. This paper is focused on the corporate social responsibility principles and corporate social responsibility reporting impact on achieving the Sustainable Development Goals. In this part of the publication, both aspects of corporate social responsibility reporting principles and the idea of corporate social responsibility reporting's influence on achieving the Sustainable Development Goals are presented. Finally, the conclusion and findings are introduced.

The contemporary approach to corporate social responsibility reporting should be focused not so much on reporting non-financial data for the sake of mere fact, but on a clearly defined goal, which is the pursuit of sustainable development. The correct understanding of corporate social responsibility by customers and stakeholders is one of the ways to achieve the Sustainable Development Goals in the correct (ethic) way (Arenas et al. 2009). On the other hand, higher awareness of customers and stakeholders in the field of social responsibility makes enterprises have a limited ability to manipulate, conceal data or make empty promises, which turn out to be only marketing gimmicks (Servaes and Tamayo 2013). The research conducted by Servaes and Tamayo in 2013 was connected to the roles of customers and their awareness as impacts on organization value. The presented findings clearly showed the following (Servaes and Tamayo 2013):

- CSR activities successfully enhance the value of enterprises with high public awareness, as shown by advertising intensity;
- Organizations with higher public awareness are more exposed to the loss of social trust and more "painful" penalties when concerns about their CSR are voiced;
- For companies whose efforts in the field of corporate responsibility are unnoticed (low social awareness), the impact of CSR activities on the organization value is very low or negative;
- Advertising can harm reporting corporate responsibility and the company's image if there is any inconsistency between the organization's corporate responsibility and its overall reputation.

Awareness of CSR principles is established at the beginning of corporate social responsibility implementation. Companies which are not prepared to change their long-term strategy or organizational culture and which are not oriented to sustainability are at risk of encountering the above-mentioned issues. The level of these principles' application is institutional and is connected to the company's basic obligations as a business organization. Principles define business entities and their social relationships. The major elements of corporate social responsibility principles are as follows (Hopkins 2004; Blindheim and Langhelle 2010; Wood 1991):

1. Legitimacy—treat the business as a social institution and create pillars for analyzing each relationship between the organization and society;
2. Public responsibility concerns the individual business entity and its processes, with scores for the meaning of rules in terms of the work the business conducts;
3. Managerial discretion, relating to managers and other members of the organization. All members of organizations are responsible for their behavior and moral acts.

The other aspect of participating in corporate social responsibility is reporting non-financial data. According to the GRI guidelines, there are six major reporting principles which have a significant impact on corporate social responsibility reporting quality. In Table 1, these principles are introduced with descriptions.

Research conducted by Moravcikova in 2015 showed that corporate responsibility is present in annual financial reports in 51% of all researched companies. According to this paper, the audit consulting company KPMG surveyed the 100 largest companies (according to their incomes) across 41 countries. Corporate responsibility reporting in these companies was investigated based on detailed research on each company in terms of the efficiency of reporting non-financial data. Additionally, issues such as factors which influence CSR (corporate social responsibility) reporting, sector variances and use of GRI standards and guidelines were mentioned in the publication (Lu et al. 2021, Lu et al. 2021). The other interesting results introduced in this paper were the rates of corporate responsibility reporting in European countries in 2011 and 2013. According to the article, most companies reporting CSR in Europe are active in the USA (76%), in Europe (73%), in the Middle East and in Africa (54%) (Moravčíková et al. 2015). The rate of CSR reporting in the year 2013 in Europe is shown in Figure 1.

Table 1. Corporate social responsibility reporting principles according to the GRI guidelines.

Rule	Description of Rule Defining Quality
Balance	The report should contain both positive and negative aspects of an organization's activity to allow holistic assessment of a score.
Comparability	The organization should consequently choose, develop and present information. Reported information should be presented in a way which allows stakeholders to analyze score changes over time and in comparison with other organizations.
Punctuality	Organizations should prepare reports punctually for time-adequate information.
Clearness	Organizations should provide information in a way which is clear and understandable for a report.
Credibility	Organizations should gather, record, compile, analyze and disclose information and processes used during the creation of a report in a way which provides a high quality and importance of the presented information and check it.

Source: Authors' compilation based on: GRI 2000–2006 (Orzeł 2020), (Orzeł 2020; Global Reporting Initiative 2006).

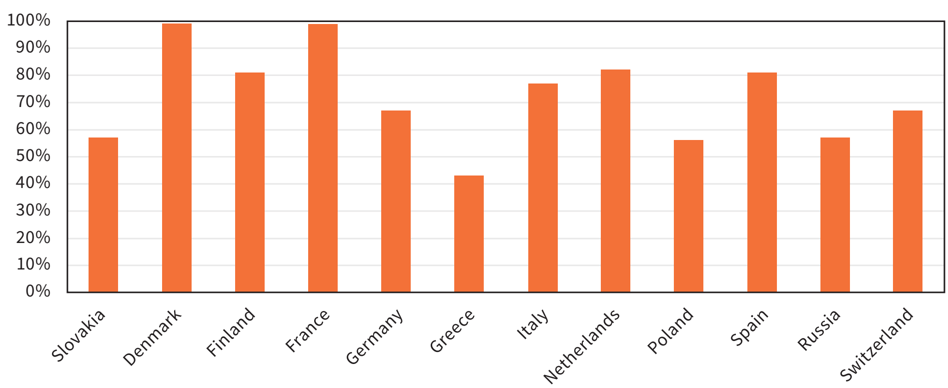


Figure 1. Corporate social responsibility reporting in different countries of Europe in the year 2013. Source: Authors' compilation based on Moravčíková (2015).

In the next figure (Figure 2), the number of reports submitted in chosen European countries is presented.

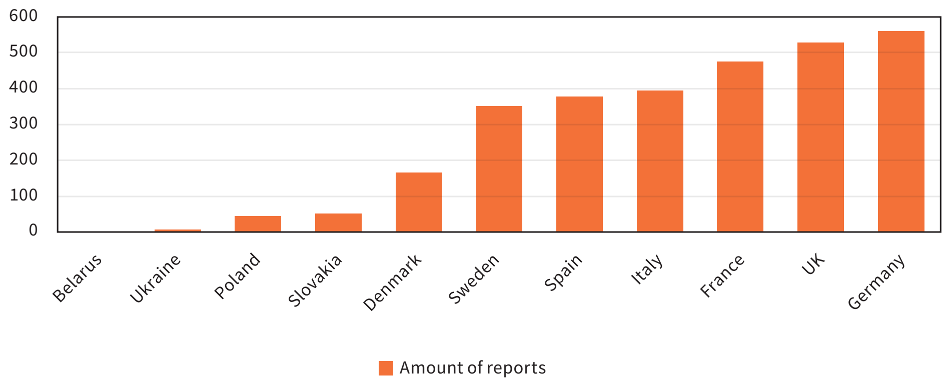


Figure 2. Corporate social responsibility report numbers in different countries of Europe in the year 2013. Source: Authors' compilation based on Orzeł (2020).

The other important issue connected to corporate responsibility is employees' satisfaction and awareness of "meaningful work". This is an issue closely related to a phenomenon concerning the organizational culture. Both the issue and theoretical model were described by Raub in the article "The Power of Meaningful Work" in the year 2013. The theoretical model was based on the correlation between CSR awareness, task significance and job satisfaction connected to these positive issues. In the model, five hypotheses were introduced (Raub and Blunschi 2014):

1. "Awareness of CSR activities is positively related to perceived task significance".
2. "Task significance is positively related to job satisfaction".
3. "Task significance is positively related to helping behavior, voice behavior, and personal initiative".
4. "Task significance is negatively related to emotional exhaustion".
5. "Awareness of CSR activities is positively related to job satisfaction, helping behavior, voice behavior, personal initiative and negatively related to emotional exhaustion and its relationship is at least partly mediated by task significance".

The research was conducted in four hotels with a total of 330 employees, which were asked to participate in the survey. Descriptive statistics and analysis showed that, from the point of view of hospitality industry practice, added value may be achieved when employees are aware of their workplace's participation in corporate social responsibility. Employees can gain numerous benefits in the form of greater engagement in discretionary work behaviors and improved job attitudes. This, in turn, directly translates into general job and life satisfaction (Supanti and

Butcher 2019; Binswanger 1998). This issue has become extremely important in the case in which sustainable development is understood as a healthy workforce, non-exploitation and all ethical issues related to work, decent wages and employment (Feng and Saini 2015; Vance and Paik 2015; Virakul et al. 2009). Therefore, one of the socially responsible corporate activities begins in the center of the organization—in employment rules and ethics of work. Such an approach is part of human rights responsibility (Eun et al. 2013). Enterprises showing a willingness to conduct business in a socially responsible manner and to report non-financial data in this area may take advantage of the many opportunities and ways to implement elements of the pursuit for sustainable development. In Table 2 the different categories of corporate social responsibility and examples of activities are presented (Tilt 2016; Corporate Financial Institute (CFI) 2021).

Table 2. Corporate social responsibility categories and examples.

Category of CSR	Description	Example of Activity
Environmental responsibility	Aims on pollution reduction, reducing greenhouse gas emissions and sustainable use of natural resources.	Using renewable resources instead of non-renewable.
Human rights responsibility	Providing fair labor practices, for example, equal price for work, fair trade practices, disavowing child labor.	Fair trade practices during coffee production process.
Philantropic responsibility	Funding educational programs, supporting health initiatives, donating to causes and also supporting community beautification projects.	Financing school equipment for children from poor families.
Economic responsibility	Focused on company's improvement in the field of activity in the context of sustainable practices.	Using manufacturing processes based on recycling to minimize waste.

Source: Authors' compilation based on Corporate Financial Institute (CFI) (2021); Tilt (2016).

However, activities assigned to specific areas of corporate social responsibility must have their order and hierarchy to maximize the degree to which activities related to corporate social responsibility correspond to the actual capabilities of the enterprise (Faracane 2015). In Figure 3, the hierarchy of corporate social responsibility categories in the form of a pyramid is presented (Carroll 1991).

Figure 3. Hierarchy of corporate social responsibility categories. Source: Adapted from Faracane (2015); Carroll (1991).

Studies conducted by Carroll in 1991, which were connected to the elements of corporate social responsibility, described the importance of economic, legal, ethical and philanthropic responsibility issues. These "important elements" seem to still be present nowadays and can be considered as guidelines for the effective undertaking of socially responsible activities that can bring sustainability and benefits to both the entire society and the company. These components are introduced in Table 3.

Table 3. Corporate social responsibility types.

Economic Responsibilities	Legal Responsibilities	Ethical Responsibilities	Philantropic Responsibilities
Performing in a manner consistent with maximizing earnings per share.	Performing in a manner consistent with expectations of government and law.	Performing in a manner consistent with expectations of societal and ethical norms.	Performing in a manner consistent with expectactions connected to society's charitable expectations.
Committing to being as profitable as possible.	Complying with global and local regulations.	It is important to prevent ethical norms from being compromised.	Assisting the fine and performing arts.
Maintaining a strong competitive position.	Abiding by the law is important to corporate citizens.	Preventing ethical norms from being compromised in order to achieve the company's goals.	Managers and employees participating in voluntary and charitable activities within their local communities.
Maintaining a high level of operating efficiency.	Successful company is defined as one that fulfills legal obligations.	Defining good corporate citizenship as doing what is expected morally or ethically.	Providing assistance to private and public educational institutions.
Defining a "successful" company as consistently profitable.	Providing goods and services that at least meet minimal legal requirements	Recognizing corporate integrity and ethical behavior go beyond mere compliance with laws and regulations.	Voluntarily assisting projects that enhance a society's quality of life.

Source: Authors' compilation based on Carroll (1991).

The other aspect of corporate social responsibility is non-financial data reporting and its quality as part of sustainability. The quality of corporate social responsibility reports is determined on the path from data processing, through implementation and reporting, to the final result. The quality of these reports can be viewed as equal to the completion of information that the reports contain (Orzeł 2020; Hąbek and Wolniak 2015; Szczepańśka 2018; Wolniak 2018; Tschopp and Huefner 2015). The research conducted by van Buuren in 2019 clearly showed that most companies which report non-financial data used GRI (Global Reporting Initiative) and SDG (Sustainable Development Goal) standards. More companies decided to focus on "sustainable targets" on which they want to work and in the field they want to improve. GRI (Global Reporting Initiative) standards were also used for reporting by 59% of the researched companies in comparison to the previous years (49%). Nevertheless, SDG standards seemed to be slightly more popular. GRI standards were used by 59% and SDG standards by 70% of the researched business entities. It is worth adding that these are increases of +7% and +12% in comparison to the previous year. According to the presented research, there is a trend in the evidence towards aligning the strategy of the company with the SDGs. The author of the report "Survey on CSR Reporting in Europe" carried out a survey to assess the current sustainability reporting status of 312 European companies (Tschopp and Huefner 2015). Additionally, the tendency to accept targets of sustainability is still present. Data connected to companies' interest in sustainable energy usage target declarations are very interesting. Nearly 45% of companies are interested in renewable energy targets, 90% in greenhouse gas emissions and 41% in supplier audits (van Buuren 2019). These data are presented in Figure 4.

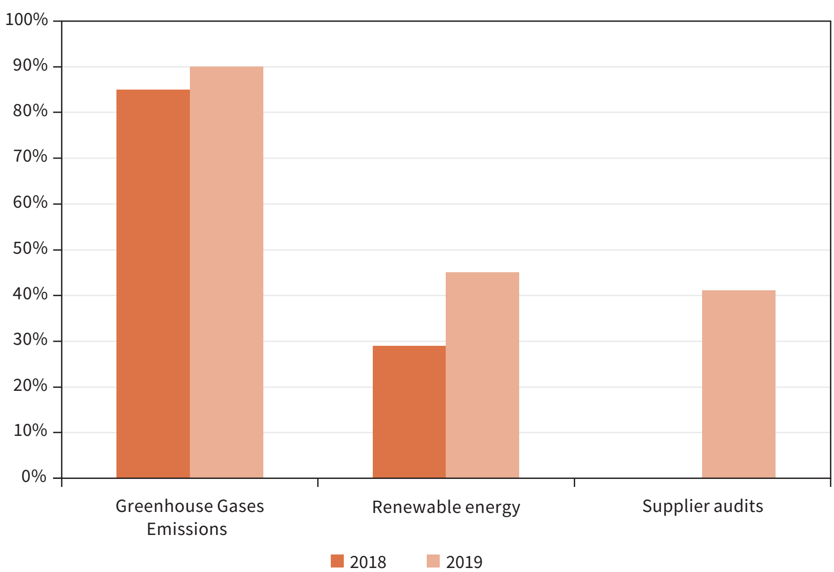


Figure 4. Targets declared by companies in the field of sustainability (environment). Source: Reprinted from van Buuren (2019).

Only 43% of all researched organizations communicate multiple measurable non-financial targets. Reducing greenhouse gas emissions is the most popular target among companies. Activities connected to social targets are less popular than "ecological" targets. The other aspects are the areas of corporate social responsibility targets set by enterprises. The percentages of companies that declared CSR targets in different areas in the year 2019 are presented Figure 5.

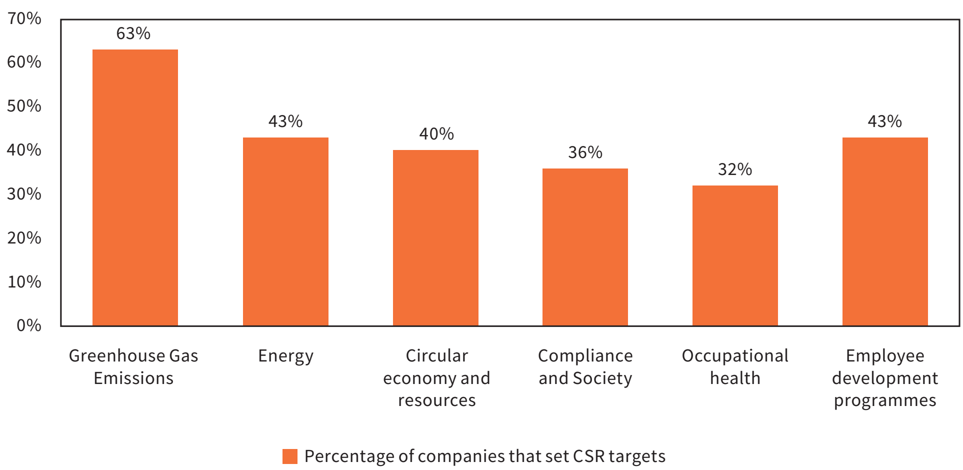


Figure 5. Percentages of companies which set CSR targets in different areas. Source: Authors' compilation based on van Buuren (2019).

Between different countries, a few large differences can be observed. Portugal and Italian companies' information about their sustainability targets is very rare. France and Switzerland have a great score in this aspect. Organizations from sectors such as consumer staples, industrial and utilities achieve the highest level of reporting their sustainability targets. Companies from sectors such as energy, consumer discretionary and financial are worse in this issue (Tschopp and Huefner 2015; van Buuren 2019). However, despite the higher scores in the level of non-financial data reporting than in previous years, there are a few challenges and issues which need improvement (van Buuren 2019):

1. Improvement in sustainability performance communication.

The clearness of reports could be at a better level. Many companies do not provide a summary of their sustainability achievements at the beginning of their reports.

2. Improvement in performance data communication.

Numerous enterprises show their raw data in reports. However, there is a lot to achieve in this area, especially according to the renewable energy issue, material usage and supplier audits. The issue of greenhouse gas emissions is the issue most often reported and presented.

3. Low differentiation in non-financial data reporting types.

Only 43% of all companies communicate multiple measurable non-financial targets. Greenhouse gas emissions are the most disclosed target. Social targets are the least frequently declared as the goal of sustainable development.

4. The need for materiality communication expands.

A total of 54% of researched companies communicate areas of importance. Topics such as economic and social issues appear most often. Environmental issues are least commonly found on the Top 5 priority lists.

5. Disproportionate interest and reporting.

Even though social topics are at the top of the "Top 5 priority lists", companies have trouble effectively communicating quantitative social data in comparison to environmental data and targets. Instead of social data, companies prefer to report environmental data.

3. Discussion and Conclusions

Reporting non-financial data is becoming more and more popular in many countries, both in Europe and around the world. Attention should be paid to the reliability of data reporting by enterprises, and to the goals they set. The completeness of the information contained in the reports, particularly compliance with the GRI (Global Reporting Initiative) and SDG guidelines, plays a huge role in reporting corporate social responsibility. Referring to the data presented in this publication, it can also be observed that the European leading countries in submitting corporate social responsibility reports are Germany and the United Kingdom. Additionally, studies have shown that the process of corporate social responsibility should be rooted in the organization's culture and long-term strategy. The other aspect is the hierarchy of responsibility. Companies must firstly pay attention to economic aspects, and then legal, ethical and philanthropic aspects. This order of the analyzed categories was presented in the form of a pyramid. Next, principles of different aspects of responsibility were described and examples were introduced. The analyzed literature shows that properly prepared and truthful CSR reports can be considered as a source of useful documentation, and because of this, we can observe the positive contributions of a company's efforts to building a business aimed at sustainability. The types of help for companies which want to report corporate social responsibility in the proper way are the GRI and SDG standards. They are very helpful, and most companies are now reporting their non-financial data according to these principles. The introduced results of previous research also show that there is a correlation between companies' "sustainable" strategy and the reporting of corporate responsibility according to reporting standards. Another result found in the literature analysis is the fact that enterprises most willingly report data related to greenhouse gas emissions and measurable environmental issues, although social issues are very high in the hierarchy of goals defined by companies and the most important in the context of activities for sustainable development. However, their reporting is much less popular among enterprises than environmental data.

The presented studies introduced various research results, which come from the big business sector. It is also worth researching the approach of medium and small enterprises to sustainability in the context of corporate social responsibility reporting. Research conducted by Linch in 2011, and also by Kechiche and Soparnot in 2012 using a similar methodology, which is based on a literature review, presented the different aspects of corporate social responsibility in the medium and small enterprise sector. The conclusions drawn were as follows (Kechiche and Soparnot 2012; Vo 2011):

- In medium and small enterprises, managers often treat corporate social responsibility as part of the management and business routine, not as something extra to management.
- The practices can be divided into three major categories: the internal social dynamic, the external social dynamic and the environmental dynamic.
- In the medium and small enterprise sector, the areas in corporate social responsibility introducing barriers are a lack of knowledge of and time dedicated to sustainability goals.
- The other problem in small and medium enterprises relates to the application of environmental activities by local laws and regulations.

Another study conducted by Stekelorum in 2020 showed that medium and small enterprises have a significant impact on CSR due to their role in supply chains. The author emphasized that issues such as owner management, limited resources, personal relationships and informality are reflected in the management practices of small and medium-sized enterprises. Additionally, the author conducted a study on the types of methods which are used in papers connected to corporate social responsibility submitted to different journals. The results showed that most research papers in this field use case studies and survey methods (see Figure 6) (Stekelorum 2020).

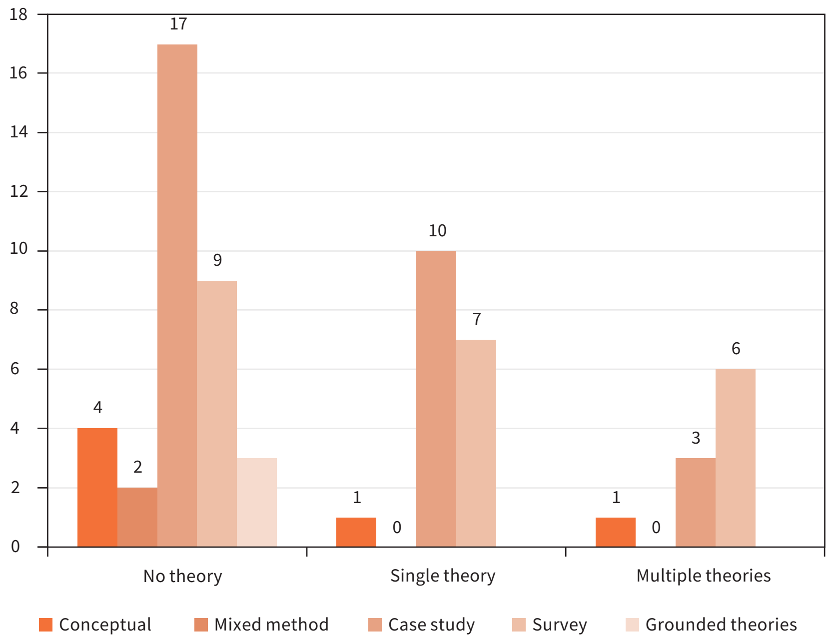


Figure 6. Different types of methods which are used in papers in the CSR reporting field. Source: Reprinted from Stekelorum (2020).

The influence of corporate social responsibility on sustainable development with the example of the Global Reporting Initiative reporting guidelines was presented in the publication titled "Global Reporting Initiative (GRI) as recognized guidelines for sustainability reporting by Spanish companies on the IBEX 35: Homogeneity in their framework and added value in the relationship with financial entities". This research presented an interesting approach to non-financial data reporting, which shows that the GRI guidelines can be treated as help in the process of reporting on sustainability by companies (Ortiz and Salvador 2014). It is worth paying attention to the votes for and against CSR. The research conducted by Kopeć in 2016 indicated a different point of view regarding CSR. In her publication, Kopeć distinguished the following groups of arguments against CSR (Kopeć 2016);

- Socio-economics arguments: These represent the approach and point of view of people who believe that the company should focus on bringing profit, acting only in accordance with applicable law and social and ethical standards. Each time there is commitment to social rights, etc., it is dictated by the desire for profit.

- Arguments of a practical nature: These represent an approach indicating that the concept of corporate social responsibility is not specifically defined.
- Arguments of a normative nature: These represent an approach that emphasizes that the implementation of social goals should be the role of the state, not businesses.

Another issue that concerns CSR is the accompanying business behavior. The authors of this article also conducted a literature review on greenwashing and plan to develop research towards its impact on achieving dishonestly better results in reporting corporate social responsibility. The aforementioned publication concerns an overview of the tools, forms and strategies used by enterprises to unfairly obtain a competitive advantage. Greenwashing itself can affect the reliability of CSR reporting and distort the true image of a company's environmental activities in the eyes of customers and shareholders (Orzeł and Wolniak 2019).

Author Contributions: Conceptualization, B.O. and R.W.; methodology, B.O.; software, B.O. and R.W.; validation, B.O. and R.W.; formal analysis, B.O.; investigation, B.O. and R.W.; resources, B.O. and R.W.; data curation, B.O.; writing—original draft preparation, B.O.; writing—review and editing, B.O. and R.W.; visualization, B.O.; supervision, R.W.; funding acquisition, B.O. and R.W. All authors have read and agreed to the published version of the manuscript.

Funding: The analysis in this publication was conducted in the course of the internal research project of Silesian University of Technology project 13/010/BK_21/0057. The analysis in this publication was conducted in the course of the Polish government project: "Inicjatywa Doskonałości, Uczelnia Badawcza", title: Badanie Poziomu Jakości Świadczenia Usług w Śląskich Przychodniach w Czasie Pandemii COVID-19.

Conflicts of Interest: The authors declare no conflict of interest.

References

Aluchna, Maria, Krista Jaakson, Maaja Vadi, and Katrin Tamm. 2009. Organizational culture and CSR: An exploratory study of Estonian service organizations. *Social Responsibility Journal* 5: 6–18. [CrossRef]

Arenas, Daniel, Joseph M. Lozano, and Laura Albareda. 2009. The role of NGOs in CSR: Mutual perceptions among stakeholders. *Journal of Business Ethics* 88: 175–97. [CrossRef]

Belyaeva, S. Zhanna. 2013. Transformation processes of the corporate development in Russia: Social responsibility issues. *Systemic Practice and Action Research* 26: 485–96. [CrossRef]

Binswanger, C. Hans. 1998. Making sustainability work. *Ecological Economics* 27: 3–11. [CrossRef]

Blindheim, Bjørn-Tore, and Oluf Langhelle. 2010. A reinterpretation of the principles of CSR: A pragmatic approach. *Corporate Social Responsibility and Environmental Management* 17: 107–17. [CrossRef]

Carroll, B. Archie. 1991. The pyramid of corporate social responsibility: Toward the moral management of organizational stakeholders. *Business Horizons* 34: 39–48. [CrossRef]

Corporate Financial Institute (CFI). 2021. Corporate Social Responsibility (CSR). Available online: https://corporatefinanceinstitute.com/resources/knowledge/other/corporate-social-responsibility-csr/ (accessed on 17 May 2021).

Chen, Yi-Chun, Mingyi Hung, and Yongxiang Wang. 2018. The effect of mandatory CSR disclosure on firm profitability and social externalities: Evidence from China. *Journal of Accounting and Economics* 65: 169–90. [CrossRef]

Činčalová, Simona, and Martin Prokop. 2019. *How is Corporate Social Responsibility Meant: Analysis of 100 Definitions*. Jihlava: College of Polytechnics Jihlava, March. [CrossRef]

Eun, Mi Lee, Seong-Yeon Park, and Hyun Jung Lee. 2013. Employee perception of CSR activities: Its antecedents and consequences. *Journal of Business Research* 66: 1716–24. [CrossRef]

Faracane, Nicoletta. 2015. History of Corporate Social Responsibility Concept. *Annales Universitatis Apulensis Series Oeconomica* 17: 31–48. [CrossRef]

Feng, Migmimng, and Jagjit S. Saini. 2015. Monetary compensation, workforce-oriented corporate social responsibility, and firm performance. *American Journal of Business* 30: 196–215. [CrossRef]

Global Reporting Initiative. 2006. Corporate Social Reporting Guidelines, Global Reporting Initiative. Available online: https://www.globalreporting.org/ (accessed on 11 March 2022).

Hąbek, Patrycja, and Radosław Wolniak. 2015. Assessing the quality of corporate social responsibility reports: The case of reporting practices in selected European Union member states. *Quality & Quantity* 50: 399–420. [CrossRef]

Halkos, George, and Stylianos Nomikos. 2021. Corporate social responsibility: Trends in global reporting initiative standards. *Economic Analysis and Policy* 69: 106–17. [CrossRef]

Hopkins, Michael. 2004. *Corporate Social Responsibility: An Issues Paper*. Working Paper No. 27. Geneva: Policy Integration Department, World Commission on the Social Dimension of Globalization International Labour Office, May.

International Business Leaders Forum. 2004. The IBLF in Central and Eastern Europe, Regional Context. Available online: www.iblf.org/csr/csrwebassist.nsf/content/f1c2b3b4.html. (accessed on 13 May 2021).

Kechiche, Amina, and Richard Soparnot. 2012. CSR within SMEs: Literature review. *International Business Research* 5: 97. [CrossRef]

Kinderman, P. Daniel. 2011. *Why Do Some Countries Get CSR Sooner, and in Greater Quantity, than Others? The Political Economy of Corporate Responsibility and the Rise of Market Liberalism Across the OECD: 1977–2007*. WZB Discussion Paper No. SP III 2009-301. Berlin: WZB.

Kopeć, Katarzyna. 2016. *The Pros and Cons of Corporate Social Responsibility. Zeszyty Naukowe Uniwersytetu Przyrodniczo-Humanistycznego w Siedlcach*. Seria: Administracja I Zarządzanie, vol. 108, pp. 127–38.

Vo, C. Linch. 2011. Corporate social responsibility and SMEs: A literature review and agenda for future research. *Problems and Perspectives in Management* 9: 89–97.

Lu, Jianto, Mengshang Liang, Chong Zhang, Dan Rong, Hailing Guan, Kristina Mazeikaite, and Justas Streimikis. 2021. Assessment of corporate social responsibility by addressing sustainable development goals. *Corporate Social Responsibility and Environmental Management* 28: 686–703. [CrossRef]

Moravčíková, Katarina, Lubica Gajanova, and Martina Rypáková. 2015. CSR Reporting as an Important Tool of CSR Communication. *Procedia Economics and Finance* 26: 332–38. [CrossRef]

Navickas, Valentinas, and Rima Kontautiene. 2012. The influence of stakeholder-company relationship on the competitiveness of company. *Economics and Management* 17: 1010–15. [CrossRef]

Ortiz, Esther, and Marin Salvador. 2014. Global Reporting Initiative (GRI) as recognized guidelines for sustainability reporting by Spanish companies on the IBEX 35: Homogeneity in their framework and added value in the relationship with financial entities. *Intangible Capital* 10: 855–72. [CrossRef]

Orzeł, Bartosz. 2020. Non-financial Value Creation Due to Non-financial Data Reporting Quality. Scientific Papers of Silesian University of Technology, Organization and Management Series. *Silesian University of Technology Publishing House* 148: 605–17. [CrossRef]

Orzeł, Bartosz, and Radosław Wolniak. 2019. Overview of greenwashing methods and tools used in Polish and world enterprises. Zeszyty Naukowe. *Organizacja i Zarządzanie/Politechnika Śląska* 138: 211–219. [CrossRef]

Raub, Steffen, and Stephan Blunschi. 2014. The power of meaningful work: How awareness of CSR initiatives fosters task significance and positive work outcomes in service employees. *Cornell Hospitality Quarterly* 55: 10–18. [CrossRef]

Sarkar, Santanu. 2008. Industrial social work to corporate social responsibility: A transformation of priority. *Journal of Human Values* 14: 31–48. [CrossRef]

Servaes, Henri, and Ane Tamayo. 2013. The Impact of Corporate Social Responsibility on Firm Value: The Role of Customer Awareness. *Management Science* 59: 1045–61. [CrossRef]

Sprinkle, Geoffrey B., and Laureen A. Maines. 2010. The benefits of corporate social responsibility. *Business Horizons* 53: 445–53. [CrossRef]

Stekelorum, Rébecca. 2020. The roles of SMEs in implementing CSR in supply chains: A systematic literature review. *International Journal of Logistics Research and Applications* 23: 228–53. [CrossRef]

Stoian, Carmen, and Rodica. M. Zaharia. 2012. CSR development in post-communist economies: Employees' expectations regarding corporate socially responsible behaviour–the case of Romania. *Business Ethics: A European Review* 21: 380–401. [CrossRef]

Streimikiene, Dalia, Zaneta Simanaviciene, and Ruslan Kovaliov. 2019. Corporate social responsibility for implementation of sustainable energy development in Baltic States. *Renewable and Sustainable Energy Reviews* 13: 813–24. [CrossRef]

Supanti, Daraneekorn, and Ken Butcher. 2019. Is corporate social responsibility (CSR) participation the pathway to foster meaningful work and helping behavior for millennials? *International Journal of Hospitality Management* 77: 8–18. [CrossRef]

Szczepańśka, Maria. 2018. Principles for defining integrated report quality. *Research Papers of Wrocław University of Economics* 503: 445–53.

Tai, Fang-Mei, and Shu-Hao Chuang. 2014. Corporate Social Responsibility. *iBusiness* 6: 117–30. [CrossRef]

Tilt, Carol A. 2016. Corporate social responsibility research: The importance of context. *International Journal Corporate Social Responsibility* 1: 2. [CrossRef]

Tschopp, Daniel, and Ronald J. Huefner. 2015. Comparing the Evolution of CSR Reporting to that of Financial Reporting. *Journal of Business Ethics* 127: 565–77. [CrossRef]

Valackiene, Asta, and Diana Miceviciene. 2011. Methodological Framework Analysing a Social phenomenon: Stakeholder Orientation Implementing Balanced Corporate Social Responsibility. *Inzinerine Ekonomika-Engineering Economics* 22: 300–08. [CrossRef]

van Buuren, Erik. 2019. *Survey on CSR Reporting in Europe: Progress is Being Made, PR Square*. Berlin: Perception & Reality Square GmbH.

Van Marrewijk, Marcel. 2003. Concepts and Definitions of CSR and Corporate Sustainability: Between Agency and Communion. *Journal of Business Ethics* 44: 95–105. [CrossRef]

Vance, Charles M., and Yongsun Paik. 2015. *Managing a Global Workforce*. New York: Routledge.

Virakul, Busaya, Kalayanee Koonmee, and Gary N. McLean. 2009. CSR activities in award-winning Thai companies. *Social Responsibility Journal* 5: 178–99. [CrossRef]

Wolniak, R. 2018. The corporate social responsibility practices in Australian mining sector. In *Contemporary Management in Extractive Industries—Multidimensional and Practical Approach*. Edited by Izabela Jonek-Kowalska. Gliwice: Publishing House of Silesian University of Technology, vol. 795, pp. 205–17.

Wood, J. Donna. 1991. Corporate Social Performance Revisited. *Academy of Management Review* 16: 691–718. [CrossRef]

© 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Changes in the Steel Industry in Poland in the Period 1990 to 2020: Innovation and Digitisation on the Way to Steel Mills 4.0

Bożena Gajdzik

1. Introduction

In times of economic system transformation in Poland (such as in the 1990s), enterprises functioning across all branches of industry have transformed considerably. The transformations to market economy have a deep and radical character. The range of restructuring comprises all areas of the functioning of Polish enterprises. The restructuring changes are in technology, production, work, organisation and management. The changes were also present in the steel industry in Poland. The restructuring process in the steel industry consisted of the de-indebtedness of enterprises, reduction in employment, reduction in production volumes, withdrawal of old (uneconomic) technologies and enhancing productivity. Before the transformation of the economy in Poland (before 1989), there were no economic incentives for cost reduction, process optimisation, efficiency or profitability. Business objectives very often had political significance (Krajewski 2009). Production costs were high, too many workers were employed in steel mills, and the manufacturing technology was outdated and degraded the natural environment. Restructuring of the metallurgy industry in Poland started after 1990. Government programmes for the steel sector were implemented after that year. The time of restructuring of the steel industry in Poland included several distinct periods: In the first period, from 1992 to 1997, the Restructuring Programme for the Polish Steel Industry—developed in 1996 as part of the 1997 Industrial Policy—was implemented. In the second period, from 1998 to 2020, the "Restructuring Programme of the Iron and Steel Industry in Poland" was implemented. The document complied with European Union policy (this was during the period of Polish accession to the EU). The main objectives of the programme were the reduction in employment and the privatisation of steel mills. The next versions of the programme were presented under simplified titles: "Update 2001", "Update 2002", "Modification 2002". In the third period, from 2003 to 2007, the last programme "Restructuring and development of the steel industry until 2006" was implemented (Gajdzik 2012). In 2007, the European Commission recognised the completion of the restructuring process of Polish metallurgy (document: COMP/2006/SI2.435836). In the period 2007 to 2010, the EU continued to monitor the situation in the steel sector in Poland. The supervised restructuring of the steel industry in Poland was therefore finally completed in 2010 (Szulc 2014). The steel industry was adopted to situate itself in the European steel market (Gondys and Ślusarczyk 2010); In the next decade (2010 to 2020), Polish steel mills, already privatised and integrated into the structures of strong foreign capital groups in the global steel market (the largest steel producers in Poland belong to foreign owners: ArcelorMittal, CMC, Celsa) (Gajdzik and Sroka 2012), began their path to building competitiveness in the steel market. Building competitiveness, steel mills have implemented new technological investments (BAT) according to the principles of sustainability (Gajdzik and Burchart-Korol 2011; Kłosok-Bazan et al. 2015). The quality of steel products and innovative products play a special role in conducting business. Steel mills value human resources (mainly the knowledge and competences of employees and leadership skills of managers) and intangible resources (e.g., market position, organisational values, intellectual capitals, advanced technologies, and know how). Innovation and resources are very important in building the competitiveness of steel mills. In a market economy and under conditions of strong competition, innovation is understood very broadly, e.g., the implementation of new or improved products and services, better processes, new methods and techniques, new organisational and economic practices, better workplaces, and new relationships in the value chain (Popa et al. 2010). The purpose of this article is to present the path of change in the Polish steel sector from the 1990s to now. The current activities of the steel branch in the world are aimed at creating steel mills 4.0, according to the concept of Industry 4.0 (I 4.0) (Peters 2017; Zeman 2017). In 2011, Professor Henning Kagermann proposed the German term: "Industrie 4.0". The term evolved into a strategy for the development of German industry. Industry 4.0 is, first, new technologies, such as robotics and automation, 3D printing, collaborative robots (cobots), cloud computing and the Internet of Things (IoT). Moreover, Industry 4.0 is a new paradigmatic concept of changes in factories towards smart factories in the future (Kagermann et al. 2011, 2013a, 2013b). The practical part of the chapter is divided into three parts. The first covers the period 1990 to 2000, the second from 2000 to 2010, and the third until 2020. The main aim of this chapter is a presentation of the level of digitalisation in the steel industry in Poland. At present, in Poland, the steel sector is investing more strongly in IC systems and digital technologies. Currently, Polish mills are considered to be operating as steel mills 3.0, similarly to many European steel mills (Peters 2016), and strategies moving towards Industry 4.0 have been adopted and implemented in the steel mills.

As digitisation prepares the environment for Industry 4.0, it is necessary to analyse the level of development of digital technology in separate industries in order to determine the level of maturity (Schumacher et al. 2019).

2. Background of the Topic: Innovation and Digitisation on the Way to Steel Mills 4.0

Around the world, the Fourth Industrial Revolution is underway, which is building Industry 4.0. In Industry 4.0, there will be constant communication and data exchange between sensor and sensor networks and management software throughout the entire production process, from research and product development to post-sales services. Real-time data will not only be collected, but also analysed and converted into immediate reactions that will be enacted between smart factories, products and users throughout the production chain, as well as throughout the product life cycle. Failure to implement Industry 4.0 solutions, i.e., multiple innovations and digitalisation in factories and companies, will cause the organisation to stagnate in relation to its competitors. In a market economy, companies successfully apply the latest products and IT solutions. Industry 4.0 is based on many pillars. Erboz (2017), and Burrell (2019), (as well as many other authors not cited here) have described the main pillars of Industry 4.0 in their publications. Technological innovations related to Industry 4.0 do not concern one group of technologies, but many technological solutions, referred to as technological components. The technology of Industry 4.0 consists of technologies connecting physical and digital objects, advanced network solutions, data processing technologies, and technologies relating to physical and digital processes (Culot et al. 2020). Although digitisation was one of the technical achievements of the Third Industrial Revolution, it has gained more application in the Fourth Revolution, now it is highly intelligent. The impact of digitisation is major; many companies believe it is vital to follow digitisation trends in order to stay competitive in terms of effectiveness, growth and prosperity (Vernersson et al. 2015; BCG 2017). Digitisation together with the Internet, mobile application, Industrial Internet of Things (IIoT) and services (IIoS) are building new communication environments (Wollschlaeger et al. 2017). This new digitisation is smarter and more intelligent, but as cited by Darvishi et al. (2021), many technical aspects have not yet been explored in terms of usability, e.g., sensor defect detection. Industrial digitalisation working together with Industry 4.0 technology is the basis for a mature model of manufacturing companies (Schumacher et al. 2019). According to Schumacher et al., the maturity of companies using digitalisation concerns many aspects of business, e.g., communication (Weber et al. 2017), Maintenance

4.0 (Nemeth et al. 2018), business processes (Jochem et al. 2011), Internal Logistics 4.0 and the supply chain (Klötzer and Pflaum 2017) using digital information systems (Proença and Borbinha 2016), software landscapes (Leyh et al. 2017), and big data (Comuzzi and Patel 2016). Digitalisation in manufacturing requires the use of modern production management systems and software, enabling the real-time observation of processes and immediate reactions to undesirable actions. In the steel sector, digital technologies can be applied in order to increase the flexibility and reliability of industrial processes and improve the product quality. Digital technology can also be used for monitoring and assessing the environmental performance of steel industry organisation processes improving control levels of production and of auxiliary processes that have major environmental impacts (Peters et al. 2019). Those technologies should also provide key performance indicators for resources efficiency, e.g., energy (Wolniak et al. 2020; Gajdzik and Sroka 2021). Digital business respects the principles of sustainability. The popularized concept of Industry 4.0 is based on the goals of sustainable business (Gajdzik et al. 2020). Digital technology improves operational performance and reduces process safety accidents (Lee et al. 2019). Steel mills using digitalisation can expect, similarly to other companies, benefits such as reduced resource consumption and process optimisation, shorter machine downtime and longer machine life, higher employee productivity, reduction in time between different production stages, reduction in overproduction, acceleration of R&D processes thanks to 3D printing, elimination of supply constraints, lower inventory storage costs, and better production quality (Gajdzik and Sitko 2014). Such benefits are possible because modern digitalisation solves problems and eliminates errors in real time. In today's digital economy, the link between demand and supply is better. Companies use various methods to analyse and create demand (marketing automation systems). Technology improves demand forecasting quality and reduces the time to market. With 3D printing or concurrent engineering, it is possible to prototype new products very quickly and enter the market with them. Digitisation is also a better after-sales service and service, thanks to remote servicing or guided self-service using augmented reality (more information is in the IDC report, and the report on gov.pl). Enterprises in Industry 4.0 have initiated the digitisation in manufacturing and are striving to be a part of the digital ecosystem.

3. Polish Steel Industry in the Period 1990 to 2000: A Brief Description of Difficult Ways to Market

In the first decade analysed, many quantitative changes were realised in steel mills in Poland. In 1990, the sector employed 147,000 people. In 2000, there were

38.7 thousand people employed. The reduction in employment was accompanied by a decrease in steel production, which increased productivity (amount of steel per employee). In 1990, 13.6 million tonnes of steel were produced 10.5 million tonnes of crude steel, productivity 271.3 tonnes per employee, compared to 91.9 tonnes per employee in 1990, an increase of 179.4 tonnes per employee (Gajdzik 2013). More automatic operations were introduced into the applied steel melting technology. The production lines in mills were extended with BOF technology—these were the so-called continuous casting lines (Polish abbreviation: COS). The share of this technology in the production of semi-finished steel products in the mills in the early 1990s did not exceed 5%. Expenditure on investments in technologies, products and processes in Polish steel branch in the years from 1992 to 2000 amounted to PLN 7.5 billion. At that time, many steel mills in Poland had financial debts to suppliers and organisations. These debts were repaid by, for example, selling off the steel mills' redundant assets, in particular, non-productive assets (non-core business). In the 1990s, outsourcing activities—the separation of companies from production enterprise—intensified in Poland (Foltys 2007). Steel mills that did not achieve profitability or did not cope in the market with the new unbundled, self-managed business went bankrupt. This was the most difficult period of transition for the Polish steel sector (Pałucha 2012). Figure 1 compares the expenditure on technological investment in the Polish steel industry with productivity (amount of crude steel per employee) in the analysed period.

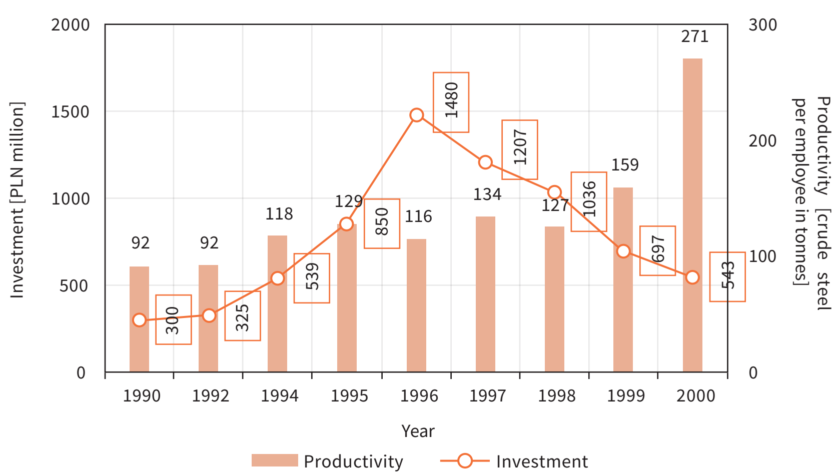


Figure 1. Investment and productivity in the Polish steel industry in the period 1990 to 2000. Source: Author's compilation based on data from HIPH (n.d.). Reports: *Polish steel industry.*

4. Polish Steel Industry in the Period 2000 to 2010: Visible Indicators of Competitiveness

During this period, many changes were introduced to improve the competitiveness of steel plants, and foreign capital contributed to these changes. The most important event of this period was the purchase of steel plants by foreign investors. In 2004, Mittal, now ArcelorMittal, entered the Polish market (on 29 May 2007, a steel producer brand named ArcelorMittal was officially launched on the Polish market) (Ślusarczyk and Kot 2011). A year earlier (in 2003), the CMC group (Commercial Metals Company) appeared. In the same year, the Spanish Celsa acquired the Ostrowiec steel mill. Foreign capital owns the largest steel mills in Poland (Gajdzik and Sroka 2012). The open market economy with external and internal factors inspired the steel enterprises in Poland to introduce changes. The changes introduced in steel enterprises are shown in Figure 2. The main areas of change included: product range, manufacturing technology, organisation and management, and even company culture.

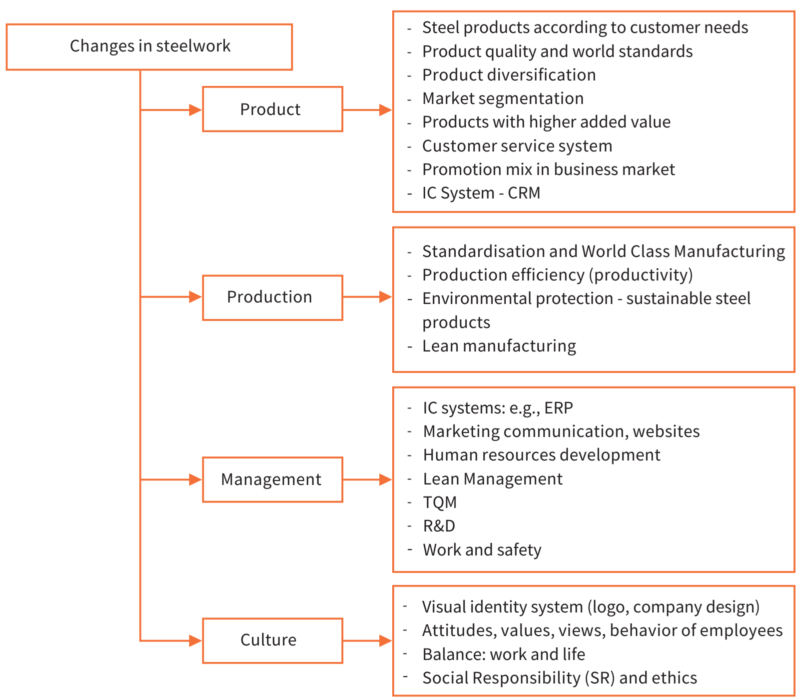


Figure 2. The key fields of changes in steel mills in Poland on their way to competitiveness. Source: Figure by author.

In 2002, the technology—created by Martin Siemens—for smelting steel in open-hearth furnaces was withdrawn. Since 2003, crude steel in Poland has been produced using only two processes: EAF and BOF. The volume of steel produced is constantly adjusted to market demand. The trend in steel production has seasonal variations (cycles). Figure 3 shows the volume of manufactured crude steel in Poland from 2000 to 2020.

In the period 2001 to 2010, investment expenditure amounted to PLN 8.8 billion. Expenditure on technological investments and process innovations resulted in an increase in labour productivity (Figure 4).

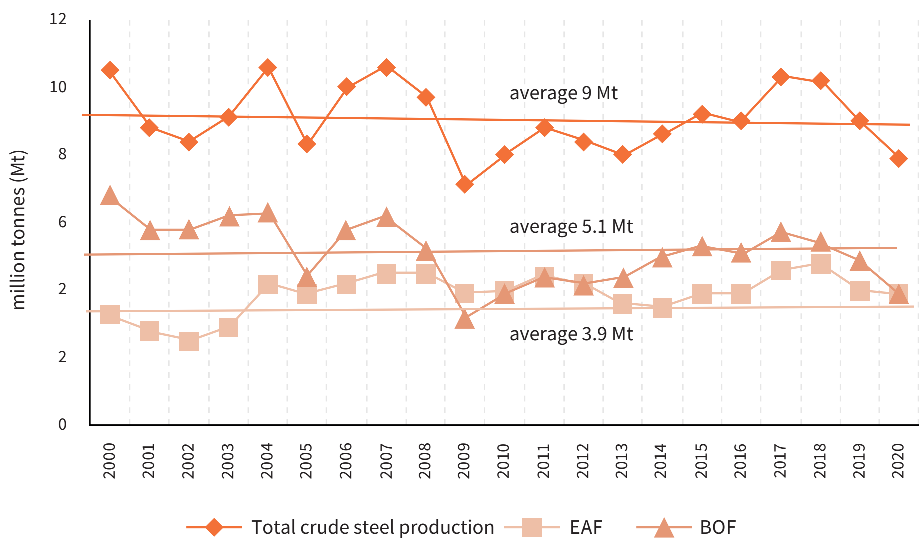


Figure 3. Manufactured crude steel in Poland in the period 2000 to 2020. Source: Author's compilation based on data from yearly reports 2000–2020 (WorldSteel Association n.d.).[1]

[1] Steel in figures from 2000 to 2020. Available online: https://www.worldsteel.org/steel-by-topic/statistics/World-Steel-in-Figures.html (accessed on 23 September 2021).

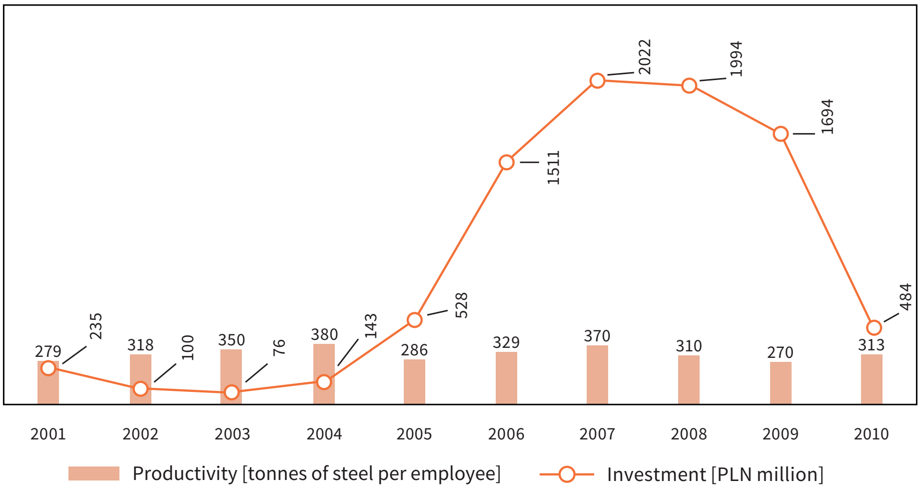


Figure 4. Investment and productivity in the Polish steel industry in the period 2001 to 2010. Source: Author's compilation based on data from the Polish Steel Association yearly reports 2001–2010 (HIPH n.d.).[2]

5. Steel Industry in Poland in the Period 2010 to 2020: Innovation and Digitisation Determinants for the Strategic Direction of Steel mills 4.0

The year 2009 (two years after the global financial crisis—GFC, that started in the United States) was difficult for Polish steel mills—a drop in production (Figure 3) was caused by the global financial crisis of 2007–2008. In 2010, investment expenditures of steel mills were four times lower than in 2007 (when expenditures were the highest—Figure 4). During the crisis management period, the steel mills in Poland introduced cutting strategies (Gajdzik 2014). In investments, the increase in spending started from 2011 in the Polish steel sector (Figure 5). From 2005 to 2018, there was an increase in R&D spending (almost sixfold) (Figure 6).

---

2 https://www.hiph.org/ANALIZY_RAPORTY/liczby.php (accessed on 29 September 2021).

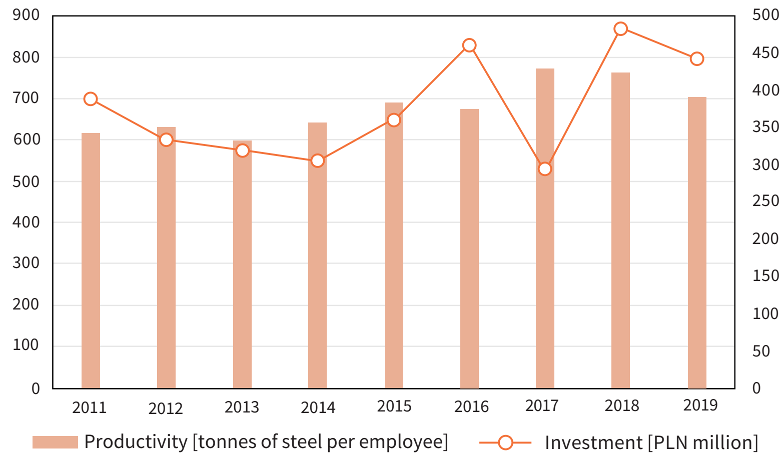


Figure 5. Investment and productivity in the Polish steel industry in 2011–2019. Source: Author's compilation based on data from the Polish Steel Association yearly reports 2011–2019 (HIPH n.d.).

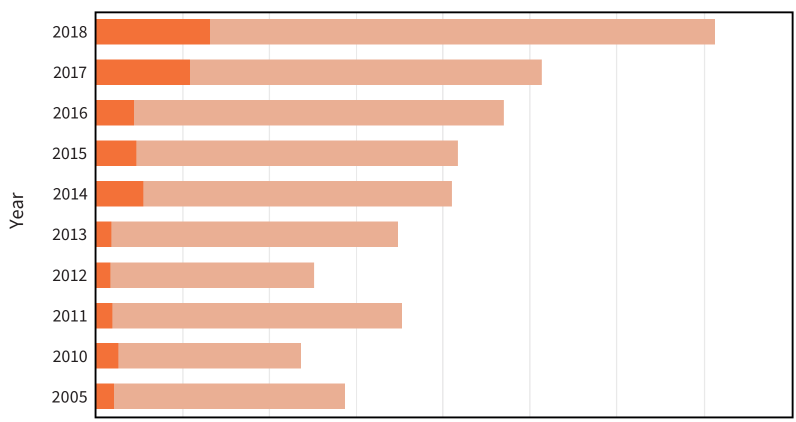


Figure 6. Expenditure on R&D and innovation in the Polish steel industry in 2005–2018. Source: Author's compilation based on data from Statistics Poland (2020).[3]

[3] Use of information and communication technologies in enterprises in 2020. Available online: https://stat.gov.pl/obszary-tematyczne/nauka-i-technika-spoleczenstwo-informacyjne/spoleczenstwo-informacyjne/wykorzystanie-technologii-informacyjno-komunikacyjnych-w-jednostkach-administracji-publicznej-przedsiebiorstwach-i-gospodarstwach-domowych-w-2020-roku,3,19.html (accessed on 23 September 2021).

Expenditure on innovation in the steel industry in Poland doubled in the period 2005 to 2018 (Figure 7). New products, processes, services have had a positive impact on the steel business in Poland. Product and process innovation are closely linked with IT. Digitalised plants use sensor technology, digital production-controlling tools and AI diagnostics to monitor smart components. Each process in the plant is continually analysed and refined for incremental improvements in efficiency. Output is optimised for maximum overall performance.

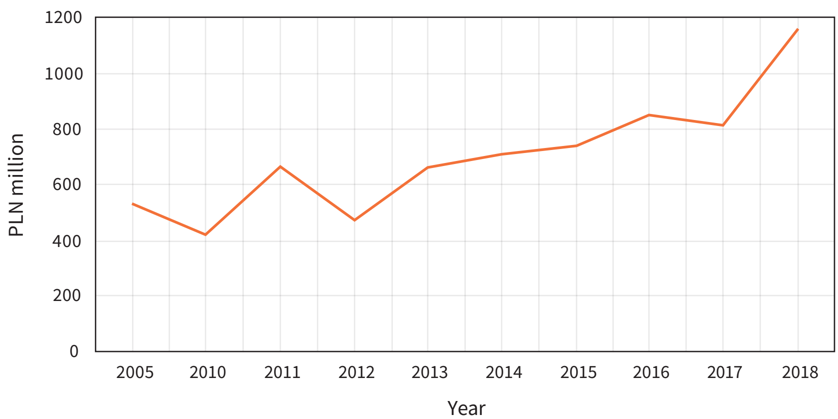


Figure 7. Expenditure on innovation in the Polish steel industry in the period 2005 to 2018. Source: Author's compilation based on data from Statistics Poland (2020).

In the analysed period, steel mills in Poland invested heavily in digitalisation. Information and communication technologies used in the steel industry in Poland involve computers; Internet access, including broadband and mobile; companies' own websites; e-government/administration; enterprises purchasing cloud computing services; enterprises using social media; ERP systems; and CRM systems. Based on statistical data, the usage of ICT in the steel industry is presented (Figure 8).

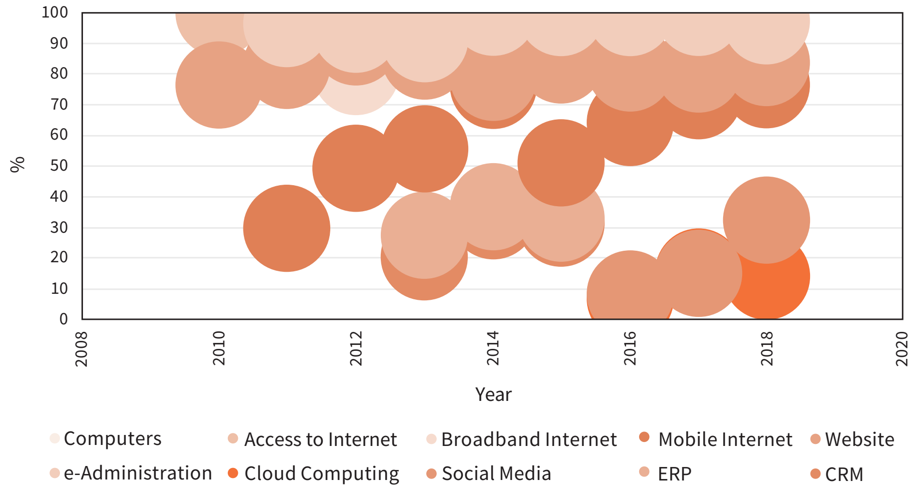


Figure 8. Use of ICT in the metal industry in Poland. Source: Author's compilation based on data from Statistics Poland (2020).

The use of computers, e-government, collaboration and communication via the Internet, including broadband, is growing year on year in steel mills in Poland. Technological advances are boosting the efficiency in industries. Technology of the Fourth Industrial Revolution is allowing working in ever-closer harmony with different processes of steel and metal production, transforming the way steel is made. Zeman (2017) points out that the steel industry is now halfway between Steelwork 3.0 and Steelwork 4.0. The strengths of the mills of the future are: "deep" automation, digitisation, virtualisation, simulation, processing of data in real time, machine communication and artificial intelligence. Peters (2017) said that "Currently, mills are at the beginning of a long-term evolution with steelwork 3.0 to steelwork 4.0". Progress to Steelwork 4.0 has been halted by the COVID-19 crisis. The year 2020 has been called the COVID-19 year. In 2020, the Polish industry sharply reduced its demand for steel (Gajdzik and Wolniak 2021). However, compared to 2009, the year in which the Polish steel sector was affected by the financial crisis, the decrease in steel production was smaller (Gajdzik and Wolniak 2021). At the end of 2020 (November–December), steel production in Poland increased compared to the previous year (Gajdzik 2021). The COVID-19 crisis and the downturn in the European steel market caused by the surplus of steel production (supply exceeding demand), as well as rising environmental costs (CO_2 emission reduction policy), are dampening investments by Polish steel mills. However, the strategic (long-term) direction of change—steel Industry 4.0—has been continued (fraunhofer.de 2018): the COVID-19 crisis has reinforced the steel mills' belief that the digitisation and automation of steel production will enable them to operate through periods of face-to-face shortages and job cuts. Steel producers in Poland have been implementing digital and technological innovations for several years. Examples of activities include mobile inspections, integrated information and computer systems (SAP), remote measurement and data collection systems, computerised equipment control, 3D printing, and 3D visualisation. The varieties of applied Industry 4.0 technologies create nine pillars (Erboz 2017; Burrell 2019), and digitalisation (Kagermann 2015) enables steel mills to realise several pilot programs (start-ups) and segment the application and implementation of new techniques in the steel industry (Gajdzik et al. 2021). As well as converting traditional steel mills into highly automated "smart" plants, digitalisation enables the different parts of the manufacturing process to interact and perform at their full potential. The share of companies that systematically introduced innovative or improved products or new or improved processes reached 50% of the total number of companies in the Polish steel (metal) industry (Figure 9).

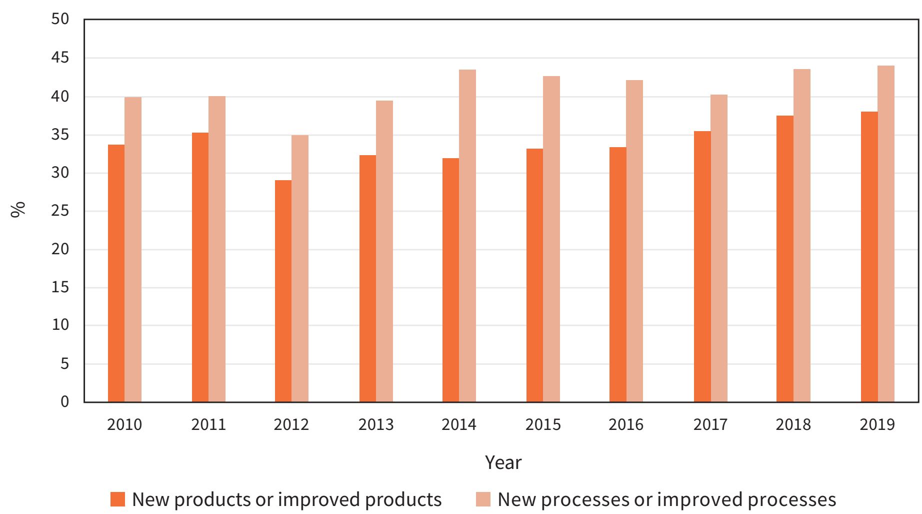


Figure 9. New and improved products or new and improved processes in the metal industry in Poland in the period 2010 to 2019. Source: Author's compilation based on data from Statistics Poland (2020).

6. Discussion

Global industry and that in Europe are changing dynamically all the time. In Poland, we are dealing with the transformation of industry. These changes in industry are accompanied by progressive automation and digitalisation. The steel industry in Europe and Poland plays a major role in GDP and employment. In Poland, steel industry account for about 3.5% of GDP and employ over 20,000 people. Steel production is interrelated with other market sectors. Consumers of steel include the automotive industry, construction, engineering, transport and other sectors. For every person employed in steel plants, there are four persons employed in other sectors. Annually, the Polish steel industry produces more than nine million tonnes of steel, and its capacity (production capacity) is even higher. Nowadays, digitalisation and automation are essential elements to be taken into account in business decisions. In the Polish steel market, there are strong foreign capital groups which invest in the development of steel mills. The main trend of digitalisation in metallurgy concerns the management and optimisation of production through real-time data analysis. The second trend is maintenance using data, predicting and preventing machine failures and downtime. A distinctive feature of metallurgy is the optimisation of furnace parameters, taking into account the type of material used. In Poland, just over 50% of steel is produced using BF+ BOF technology, and almost 50% is produced using EAF technology. Digitalisation used in steel melting technology optimises processes, improves steel quality and increases work safety. In Poland, significant challenges remain with the control of working time, and the introduction of digital logbooks with tasks for maintenance. An employee receives a task and reports its completion via the system, which can assess the status of work in real time and plan further activities. These are not revolutionary innovations, but they may significantly change the work environment in steel mills. Digitisation of steel production can be seen as the consistent application of new technologies to meet steelmakers' requirements for quality, flexibility and productivity (Herzog et al. 2017). Digitisation is not only a matter of purchasing new equipment, but of developing human resources. Major resources invested in the purchase of equipment, and automation, must go hand in hand with proper communication with employees and a training system in order for their potential to be fully exploited. Competencies are charisma, relationship building, curiosity about the world, openness to change, emotional intelligence, inspiring others, kindness, sense of responsibility, quality orientation, and digital agility. Machines take over repetitive activities, so that work loses its routine character, and the tasks of workers progress to problem-solving, designing, communicating and interpreting information (Romero et al. 2016; Ruppert et al. 2018). Digitalisation in Industry 4.0 creates new challenges for leaders. Leaders 4.0 need to be more flexible and open to working with employees (Oosthuizen 2017). The staff in steel mills in Poland need to be rejuvenated. There is a generation gap in large steel mills in Poland—there are more employees aged over 45 than young people (Gajdzik and Szymszal 2015).

The future of digitalisation in steel mills will primarily be sustainable production. Important environmental aspects of steel mills are reduced energy consumption (renewable electricity) and the reduction in CO_2 emissions (e.g., capturing CO_2 from BF and converting it into hot reducing gas). Sustainability is strongly linked to Industry 4.0, especially in the context of the green economy. Investments are being made in research and development that will, in future, enable steel mills not to use fossil fuels, but to use hydrogen instead of coke, for example. Decarbonised steel production on a mass scale is a challenge for the steel industry. New steel production processes will create new areas for digitisation in steel mills.

7. Conclusions

Research has shown that technological investments and the use of ICT, R&D, and improved products and processes foster innovation in the Polish steel industry. However, these are fragmented studies, limited to statistical summaries. There has been no analysis simultaneously covering all the issues of innovativeness of the Polish steel industry in order to answer the question about the readiness of steel mills in Poland for Industry 4.0. The three periods of analysis used in this paper show the transformation of the steel industry. There were state-owned steel plants in a centrally managed economy; now, their owners are capital investors, and plants realise their business in markets. Steel mills in Poland, through many years of investment, have become able to set the course for development as steel mills 4.0. In line with the aim of the analysis and on the basis of statistical data, a conclusion has been drawn that steel mills in Poland should build an environment for Industry 4.0.

The application of digital technology in Industry 4.0 is very broad. The baseline stage is the digitisation of production. The next steps are the construction of a digital environment for the consumer and supplier. Additionally, the final solution is a digital ecosystem with interfaces for suppliers, partners and customers; the product will be embedded in an ecosystem for co-creation and additional new value capture. The entry of digitalisation into the new technology environment of Industry 4.0 requires investments. The existing technologies give way to new ones, which are promoted in the Fourth Industrial Revolution.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

BCG. 2017. The Boston Consulting Group. Industry 4.0-Przemysł 4.0 PL. Szansa czy zagrożenie dla rozwoju innowacyjnej gospodarki? Available online: http://image-src.bcg.com/Images/BCG-Przemysl-4-PL_tcm78-123996.pdf (accessed on 20 April 2018).

Burrell, David. 2019. Principles of Industry 4.0 and the 9 Pillars. Available online: https://www.plextek.com/insights/insights-insights/industry-4-0-and-the-9-pillars/ (accessed on 7 February 2019).

Comuzzi, Marco, and Anit Patel. 2016. How organisations leverage big data: A maturity model. *Industrial Management & Data Systems* 116: 1468–92.

Culot, Giovanna, Guido Nassimbeni, Guido Orzes, and Marco Sartor. 2020. Behind the Definition of Industry 4.0:Analysis and Open Questions. *International Journal of Production Economics* 226: 107617. [CrossRef]

Darvishi, Hossein, Domenico Ciuonzo, Eivind Rosón Eide, and Pierluigi Salvo Rossi. 2021. Sensor-Fault Detection, Isolation and Accommodation for Digital Twins via Modular Data-Driven Architecture. *IEEE Sensors Journal* 21: 4827–38. [CrossRef]

Erboz, Gizem. 2017. How To Define Industry 4.0: Main Pillars of Industry 4.0. Paper presented at 7th International Conference on Management (ICoM 2017), Nitra, Slovakia, June 1–2. Available online: https://www.researchgate.net/publication/326557388_How_To_Define_Industry_40_Main_Pillars_Of_Industry_40 (accessed on 9 June 2019).

Foltys, Joachim. 2007. *A Multifaceted Outsourcing Model Using the Example of the Iron and Steel Sector*. (In Polish:Wieloaspektowy model outsourcingu na przykładzie sektora hutnictwa żelaza i stali). Katowice: Uniwersytet Śląski.

fraunhofer.de. 2018. Industry 4.0 in the European Iron and Steel Industry: Towards an Overview of Implementations and Perspectives. Available online: https://www.isi.fraunhofer.de/content/dam/isi/dokumente/cce/2018/Industry-4-0-Implementation-and-Perspectives_Steel-Industry_Working%20document.pdf (accessed on 10 January 2021).

Gajdzik, Bożena. 2012. *A Metallurgical Plant after Restructuring*. (In Polish: Przedsiębiorstwo hutnicze po restrukturyzacji). Monograph. Gliwice: Silesian University of Technology.

Gajdzik, Bożena. 2013. *Restructuring of Metallurgical Enterprises in Statistical Data and Empirical Approach*. (In Polish: Restrukturyzacja przedsiębiorstw hutniczych w zestawieniach statystycznych i badaniach empirycznych). Monograph. Gliwice: Silesian University of Technology.

Gajdzik, Bożena. 2014. Crisis management in metallurgical enterprises. *Metalurgija* 53: 391–94.

Gajdzik, Bożena. 2021. *Covid-19 Crisis vs. Financial Crisis of 2008 in Steel Industry in Poland*. (In Polish: Kryzys Covid-19 vs. kryzys finansowy z 2008 w sektorze stalowym w Polsce). Katowice: PTE.

Gajdzik, Bożena, and Dorota Burchart-Korol. 2011. Eco-innovation in manufacturing plants illustrated with an example of steel products development. *Metalurgija* 50: 63–66.

Gajdzik, Bożena, and Jacek Sitko. 2014. An analysis of the causes of complaints about steel sheets in metallurgical product quality management systems. *Metalurgija* 53: 135–38.

Gajdzik, Bożena, and Włodzimierz Sroka. 2012. Analytic study of the capital restructuring process in metallurgical enterprises. *Metalurgija* 51: 265–68.

Gajdzik, Bożena, and Włodzimierz Sroka. 2021. Resource Intensity vs. Investment in Production Installations. The Case of the Steel Industry in Poland. *Energies* 14: 443. [CrossRef]

Gajdzik, Bożena, and Jan Szymszal. 2015. Generation gap management in restructured metallurgical enterprises in Poland. *International Journal of Management and Economics* 47: 107–20. Available online: http://www.sgh.waw.pl/ijme/ (accessed on 20 January 2018). [CrossRef]

Gajdzik, Bożena, and Radosław Wolniak. 2021. Influence of the COVID-19 Crisis on Steel Production in Poland Compared to the Financial Crisis of 2009 and to Boom Periods in the Market. *Resources* 10: 4. [CrossRef]

Gajdzik, Bożena, Sandra Grabowska, and Sebastian Saniuk. 2021. A Theoretical Framework for Industry 4.0 and Its Implementation with Selected Practical Schedules. *Energies* 14: 940. [CrossRef]

Gajdzik, Bożena, Sandra Grabowska, Sebastian Saniuk, and Tadeusz Wieczorek. 2020. Sustainable Development and Industry 4.0: A Bibliometric Analysis Identifying Key Scientific Problems of the Sustainable Industry 4.0. *Energies* 13: 4254. [CrossRef]

Gondys, Katarzyna, and Beata Ślusarczyk. 2010. Steel sector in Poland and its conditions after accession to the European Union Annales Universitatis Apulensis Series. *Oeconomica* 12: 570–74.

Herzog, Kurt, Günther Winter, Gerhard Kurka, Kai Ankermann, Raffael Binder, Markus Ringhofer, Andreas Maierhofer, and Andreas Flick. 2017. The Digitization of Steel Production. *BHM* 162: 504–13. [CrossRef]

HIPH (Polish Steel Association in Katowice, Poland). n.d. *Reports: Polish Steel Industry from 2000 to 2020*. Katowice: HIPH. Available online: https://www.hiph.org/ANALIZY_RAPORTY/liczby.php (accessed on 29 September 2021).

Jochem, Roland, Dennis Geers, and Priscilla Heinze. 2011. Maturity measurement of knowledge intensive business processes. *The TQM Journal* 23: 377–87. [CrossRef]

Kagermann, Henning. 2015. Change Through Digitization—Value Creation in the Age of Industry 4.0. In *Management of Permanent Change*. Wiesbaden: Springer.

Kagermann, Henning, Johannes Helbig, Ariane Hellinger, and Wolfgang Wahlster. 2013a. Recommendations for Implementing the Strategic Initiative Industry 4.0: Securing the Future of German Manufacturing Industry. Final Report of the Industry 4.0 Working Group Forschungsunion. Available online: http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Material_fuer_Sonderseiten/Industrie_4.0/Final_report__Industrie_4.0_accessible.pdf (accessed on 2 February 2020).

Kagermann, Henning, Wolfgang Wahlster, and Johannes Helbig. 2013b. *Recommendations for Implementing the Strategic Initiative INDUSTRIE 4.0—Securing the Future of German Manufacturing Industry*. Final Report of the Industrie 4.0 Working Group. München: Acatech-National Academy of Science and Engineering. Available online: https://en.acatech.de/publication/recommendations-for-implementing-the-strategic-initiative-industrie-4-0-final-report-of-the-industrie-4-0-working-group/ (accessed on 10 January 2020).

Kagermann, Henning, Wolfgang Wahlster, and Johannes Helbig. 2011. Recommendations for Implementing the Strategic Initiative Industrie 4.0: Final Report of the Industrie 4.0 Working Group. Available online: http://www.vdi-nachrichten.com/artikel/Industrie-4-0-Mit-dem-Internet-der-Dinge-auf-dem-Weg-zur-4-industriellen-Revolution/52570/1 (accessed on 20 January 2020).

Kłosok-Bazan, Iwona, Bożena Gajdzik, Joanna Machnik-Słomka, and Wioletta Ocieczek. 2015. Environmental aspects of innovation and new technology implementation in metallurgy industry. *Metalurgija* 54: 433–36.

Klötzer, Christoph, and Alexander Pflaum. 2017. Toward the Development of a Maturity Model for Digitalization within the Manufacturing Industry Supply Chain. In *Proceedings of the 50th Hawaii International Conference on System Sciences 2017*. Honolulu: University of Hawaii at Manoa, pp. 4210–19.

Krajewski, S. 2009. *Privatisation, Restructuring, Competitiveness of Polish Companies*. (In Polish: Prywatyzacja, restrukturyzacja, konkurencyjność polskich przedsiębiorstw). Warsaw: PWE.

Lee, John, Ian Cameron, and Maureen Hassall. 2019. Improving process safety: What roles for Digitalization and Industry 4.0? *Process Safety and Environmental Protection* 132: 325–39. [CrossRef]

Leyh, Christian, Thomas Schäffer, Katja Bley, and Sven Forstenhäusler. 2017. Assessing the IT and Software Landscapes of Industry 4.0-Enterprises: The Maturity Model SIMMI 4.0. In *Information Technology for Management: New Ideas and Real Solutions*. Edited by Ewa Ziemba. Cham: Springer, February. [CrossRef]

Nemeth, Thomas, Fazel Ansari, Wilfried Sihn, Bernhard Haslhofer, and Alexander Schindler. 2018. PriMa-X: A Reference Model for Realizing Prescriptive Maintenance and Assessing its Maturity Enhanced by Machine Learning. *Procedia CIRP* 72: 1039–44. [CrossRef]

Oosthuizen, Jacobus. 2017. The Determinants of Fourth Industrial Revolution Leadership Dexterity: A Proposed Framework for 4IR-Intelligence and Subsequent 4IR Leadership Development. Paper presented at the 4th International Conference on Responsible Leadership, Johannesburg, South Africa, March 16.

Pałucha, Krzysztof. 2012. Selected problems of development of the steel industry in Poland. *Metalurgija* 51: 357–60.

Peters, Harald. 2016. Application of Industry 4.0 concepts at steel production from an applied research perspective. Paper presented at 17th IFAC Symposium on Control, Optimization, and Automation in Mining, Mineral and Metal Processing 2016, Vienna, Austria, August 31–September 2. Available online: https://tc.ifac-control.org/6/2/files/symposia/vienna-2016/mmm2016_keynotes_peters (accessed on 10 January 2021).

Peters, Harald. 2017. How could Industry 4.0 transform the Steel Industry? Paper presented at Future Steel Forum, Warsaw, Poland, June 14–15. Available online: https://futuresteelforum.com/content-images/speakers/Prof.-Dr-Harald-Peters-Industry-4.0-transform-the-steel-industry.pdf (accessed on 10 January 2021).

Peters, Klaus, Enroco Malfa, and Valentina Colla. 2019. The European steel technology platform's strategic research agenda: A further step for the steel as backbone of EU resource and energy intense industry sustainability. *La Metallurgia Italiana* 111: 5–17.

Popa, Ioan Lala, Gheorghe Preda, and Monica Boldea. 2010. A theoretical approach of the concept of innovation. *Managerial Challenges of the Contemporary Society* 2010: 151–56.

Proença, Diogo, and José Borbinha. 2016. Maturity models for information systems-A state of the art. *Procedia Computer Science* 100: 1042–49. [CrossRef]

Romero, Diaz, Johan Stahre, Thorsten Wuest, Ovidiu Noran, Peter Bernus, Åsa Fast-Berglund, and Dominic Gorecky. 2016. Towards an Operator 4.0 Typology: A Human-Centric Perspective on the Fourth Industrial Revolution Technologies. Paper present at International Conference on Computers and Industrial Engineering (CIE46), Tianjin, China, October 29–31; Volume 11, pp. 1–11.

Ruppert, Tamás, Szilárd Jaskó, Tibor Holczinger, and János Abonyi. 2018. Enabling Technologies for Operator 4.0: A Survey. *Apply Science* 8: 1650. [CrossRef]

Schumacher, Andreas, Tanja Nemeth, and Wilfried Sihn. 2019. Roadmapping towards industrial digitalization based on an Industry 4.0 maturity model for manufacturing enterprises. *Procedia CIRP* 79: 409–14. [CrossRef]

Ślusarczyk, Beata, and Sebastian Kot. 2011. The consolidation influence on performance results in steel industry. Paper present at Metal 2011: 20th Anniversary International Conference on Metallurgy and Materials, Brno, Czech Republic, May 18–20; pp. 1–6.

Statistics Poland (GUS). 2020. Use of Information and Communication Technologies in Enterprises in 2020 or 2019, 2014. Available online: https://stat.gov.pl/obszary-tematyczne/nauka-i-technika-spoleczenstwo-informacyjne/spoleczenstwo-informacyjne/wykorzystanie-technologii-informacyjno-komunikacyjnych-w-jednostkach-administracji-publicznej-przedsiebiorstwach-i-gospodarstwach-domowych-w-2020-roku,3,19.html (accessed on 20 March 2021).

Szulc, Wojciech. 2014. *Transformation of Polish Metallurgy into a Free Market Economy*. Works of the Institute of Iron Metallurgy. Monograph. (In Polish: Transformacja polskiego hutnictwa do gospodarki wolnorynkowej. Prace Instytutu Metalurgii Żelaza). Gliwice: IMŻ.

Vernersson, Fredrik, Fredrik Lindblad, and Olof Enerbäck. 2015. Den Smarta Industrin—Industriellt Internet Skapar Möjligheter för Svenska Tillverkande Företag. Report: PwC. Available online: https://www.pwc.se/sv/pdf-reports/den-smarta-industrin.pdf (accessed on 23 September 2021).

Weber, Christian, Jan Königsberger, Laura Kassner, and Bernhard Mitschang. 2017. M2DDM—A maturity model for data-driven manufacturing. *Procedia CIRP* 63: 173–78. [CrossRef]

Wollschlaeger, Martin, Thilo Sauter, and Juergen Jasperneite. 2017. The future of industrial communication: Automation networks in the era of the Internet of Things and Industry 4.0. *IEEE Industrial Electronics Magazine* 11: 17–27. [CrossRef]

Wolniak, Radosław, Sebastian Saniuk, Sandra Grabowska, and Bożena Gajdzik. 2020. Identification of Energy Efficiency Trends in the Context of the Development of Industry 4.0 Using the Polish Steel Sector as an Example. *Energies* 13: 2867. [CrossRef]

WorldSteel Association. n.d. Reports: Steel in Figures from 2002 to 2009 and from 2010 to 2021. Available online: https://www.worldsteel.org/steel-by-topic/statistics/World-Steel-in-Figures.html (accessed on 23 September 2021).

Zeman, Peter. 2017. Industrie und Stahlbau 4.0—Ein paar Gedanken! *Stahlbau* 86: 84–86. [CrossRef]

© 2023 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Unsustainable Development: A Case Study of Urban Planning History and Pandemic Trends in the United States

Warren S. Vaz

1. Introduction

Human population has undergrown explosive growth, going from under a billion in 1800 to almost 8 billion today. Many factors enabled this growth, but it is categorically unsustainable given that it happened in about 10–11 generations. Indeed, thanks to the actions of several governments in the 20th century, many countries have stabilized or even reversed this trend. As technology continues to improve our lives, the amount of resources an individual consumes only continues to increase. Take energy consumption as an example. According to BP's review (BP 2021), global energy consumption has gone from 5653 terawatt-hours in 1800 to 173,340 terawatt-hours in 2019, a factor of over 30. Juxtaposed with a population growth factor of just under 8, it can be concluded that per capita energy consumption has increased and can be projected to continue to increase for a number of reasons. People are using more devices than ever. Modes of transportation are getting faster: high-speed rail, supersonic planes, space travel, etc. The proliferation of the Internet, Big Data, and cryptocurrencies are other powerful factors. Further, huge swaths of the global population are still underdeveloped. This can be expected to further strain the limited resources of the planet as their energy demands catch up to the rest of the developed world.

It is not just the sheer numbers but also the distribution of the growing population that must be studied. There are many ways to categorize population distribution. For this study, the degree of urbanization, i.e., the percentage of urban population, is most relevant. According to the United Nations (United Nations 2018), global population urbanization has gone from 7.3% in 1800 to 54.4% in 2016, and this is projected to be 60% by 2030. While modern cities are reaching unprecedented sizes and pushing the limits of infrastructure, studies conducted in several countries (China (Dong et al. 2018), United Kingdom (Arbabi and Mayfield 2016), United States (Center for Sustainable Systems 2020)) concluded that as the population density increases, per capita energy consumption decreases. Urban centers are definitionally much more densely populated than rural areas. People live closer to work, recreation, and each other, and have to consume less energy to travel. Urban transit adds an additional level of efficiency. Additionally, governing and providing infrastructure and logistical services to such agglomerations is less-energy intensive than if spread over thousands of square kilometers. This does not mean that modern cities are examples of sustainability. City dwellers, in general, tend to consume more resources than their rural counterparts. Car ownership, meat consumption, and the use of multiple appliances are all higher in cities than in rural areas, particularly in developing countries. Torrey (2004) identified several studies that highlighted the patterns of consumption between urban and rural areas. While it is true that cities, in general, are also responsible for a larger portion of wealth generation, they also tend to waste more resources. If cities are not planned correctly, it can lead to unsustainable development that causes inefficient use of resources and unnecessary pollution and waste. Thus, despite the benefits of proximate living, pollution becomes more concentrated, leading to worsening air quality (Wang et al. 2018) and the urban heat island effect (Liu and Zhang 2011). With humanity facing the unprecedented challenge of climate change (IPCC 2019), the time to act to build a more sustainable future is now.

Not all cities are created equal. This study takes a close look at urban development in the United States (US). The US is one of the oldest countries in the world and has the oldest continuously used constitution. The changes in cities from the colonial period through the various pivotal points in US history are examined. Key demographic shifts and their impact, prompted by or spurring changes in public policy and sociological factors, are outlined. The challenges with public policy and funding in a Federal system of government are used to explain how urban planning was impacted. Here, the unsustainable nature of these policies, both in terms of the environment and the economy, is explained. Besides the author's affiliation with the US, there are several reasons why this country provides an instructive and important case study. The US has historically been a world leader, by some measures the only current superpower. It led innovation and invention in several related fields: manufacturing and transportation (road, rail, shipping, air, and space). It is the largest in the world by gross domestic product (GDP), second by total energy consumption, third by population, and fourth by area. It controls and sets trends in several critical sectors. It is regarded as a world leader and tends to lead the way in decision-making and setting policy globally. It has the largest military, and its military spending exceeds the next ten highest countries combined. It also is one of the largest consumer markets in the world, especially for energy, not just by total but also per capita.

The annual primary energy consumption in the US is estimated to be 26,300 terawatt-hours. Numbers differ based on sources. Per capita it is about 80 MWh/y (BP 2021). The only countries with a higher value are small, oil-rich countries such as Bahrain and Qatar. Canada is the notable exception, being right above the US in world rankings. Canada's economy is as developed as the US, but its climate is a lot colder. Indeed, the climate type and economic development are better indicators of energy consumption than the degree of urbanization. In the US, when looking at the energy consumption versus the degree of urbanization on a state level, the correlation coefficient is only 0.31. Figure 1 shows the correlation for 131 countries with available data (US Central Intelligence Agency 2021; International Monetary Fund 2021; The World Bank 2021). The R^2-value between per capita energy consumption and urbanization is 0.2503. For per capita energy consumption and per capita GDP, it increases to 0.3373, indicating a stronger correlation.

This study is meant to serve as a brief review of urban development in the US throughout its history, particularly focusing on its unsustainable nature. The next section provides a brief historical overview to provide context for the observations of Section 3. This section highlights various hallmarks of urban design and planning. The results and issues caused are also discussed with selected examples and case studies from 2021. Section 4 discusses how the COVID-19 pandemic was the catalyst for changing the historical trends. Finally, some perspectives on modern urban planning and solutions to remedy the highlighted issues are provided in the final sections.

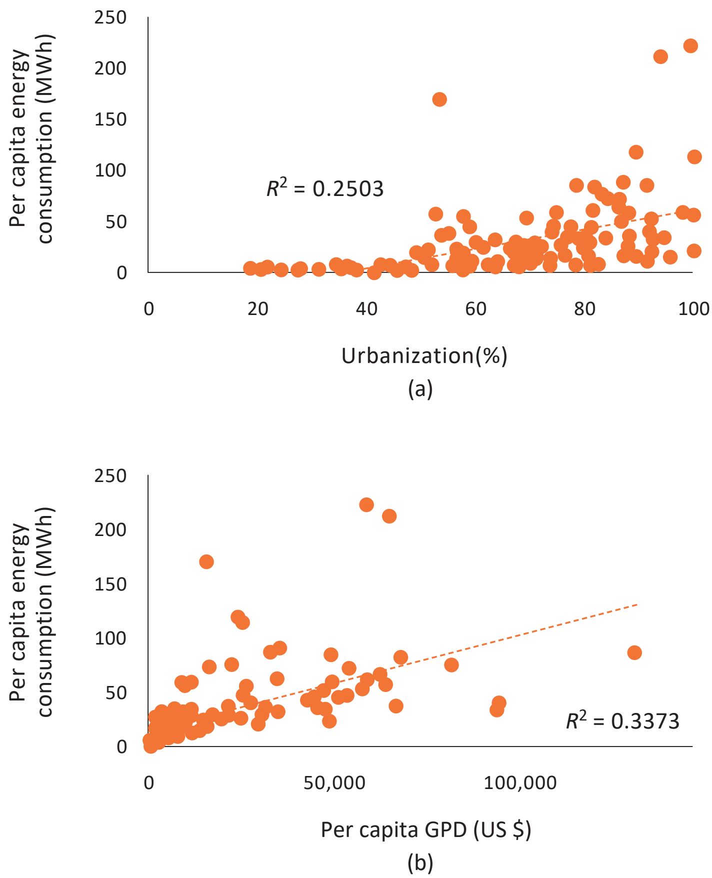


Figure 1. Correlation between per capita energy consumption and (**a**) urbanization; (**b**) per capita GDP. Source: Figure by author, data from US Central Intelligence Agency (2021); International Monetary Fund (2021); The World Bank (2021).

2. Urban Development in the US

2.1. Historical Overview

Urbanization in the US has steadily risen since the country's founding: under 7% in 1790 to around 40% in 1900, rising sharply from about 56% after World War II to about 73% by the 1970s, and climbing steadily to about 82% today (Boustan et al. 2018). The postwar increase is especially notable given that the total population of the country also grew from about 140 million to about 200 million in that same period. To understand the underlying factors, it is important to understand the country's history.

The United States declared its independence from colonial rule in 1776. Like its neighbors, Canada and Mexico, the United States adopted a Federal government with strong state governments. Critical sectors such as transportation are funded and regulated by all levels of government. Concomitantly, in many critical sectors and situations, there is no central authority to provide a unified decision or course of action. In its early years, the US was not globally recognized as a nation for several years. Several established nations still viewed it as a potential colonial acquisition. Most importantly, the entire territory of the first 13 colonies was east of the Appalachian Mountains, north of Florida—about 11% of its extent today. Gradually, several territories were acquired, organized, and formalized as states—territories east of the Mississippi, then the entire Mississippi River basin (Louisiana Purchase), the Oregon Territory, Florida and the Republic of Texas, and Spanish Territories all the way to the Pacific Ocean. Finally, Alaska and Hawaii were added as states in 1959 almost 50 years after Arizona. Several of these regions were, and to some extent still are, very sparsely populated.

Since before the birth of the nation, settlers engaged in importing African natives as slaves to work on large, cash crop plantations—corn, cotton, tobacco, sugar, and rice—in southern states, where the climate and soil enabled such practices. By contrast, the economy of the Northern states was predominantly predicated on agriculture and industry. Innovations in manufacturing and transportation technology—such as the steam engine—propelled the rise of factories and factory workers, with several Northern states abolishing slavery in their territories. Southern fears over the abolishment of slavery in the Union led to the Civil War, which culminated in the permanent abolishment of slavery in the United States in 1863 and the defeat of the Confederacy of Southern States in 1865.

After the war, the conditions in the South degenerated for virtually the entire population. Black Americans, a minority, were now free and full citizens of the Union. However, their White counterparts, some of whom were their former slaveowners, enacted various measures to deny their rights, keep a stranglehold on political power, and restrict their access to education, land ownership, etc. Sharecropping and the Jim Crow Era in the South ensured segregation on the basis of race. Simultaneously, unable to profit from free slave labor, several White landowners, including women, had to work the land themselves—a hardship not previously endured.

Meanwhile, the new territories in the West continued to grow and develop at the expense of the native population, who were continually pushed further west.

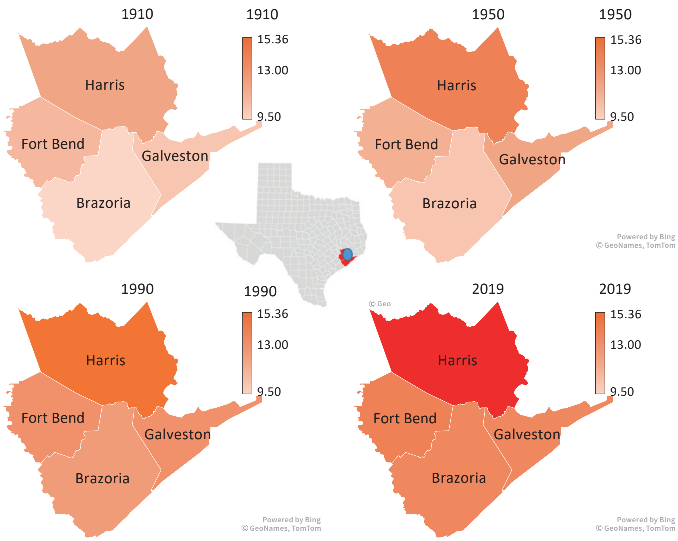
Immigrants, especially Chinese laborers, contributed to the proliferation of the railroad and steam locomotive, which helped to connect the country and spurred the prodigious rise of American industry. The total track length progressed from about 60,000 miles (96,000 km) to about 160,000 miles in the 1890s with the completion of the Transcontinental Railroad. This figure peaked during World War I (254,000 miles) and is about 140,000 miles today (Stover 1999). Some of the most iconic and enduring American companies were founded during the latter half of the 19th century and the early 20th century: Standard Oil (later Marathon, ExxonMobil, BP, and Chevron), General Electric, AT&T, Emerson Electric, Carnegie Steel (later U.S. Steel), Ford, General Motors, etc. The vast majority of these were headquartered and had most of their operations in Northern states.

After World War I, there was a period of booming economic growth in the country. The transportation section grew, with major innovations in aviation, automobile technology, rail (e.g., diesel locomotive), and shipping. Then came the Great Depression, followed by the New Deal, a series of major economic and infrastructure reforms aimed to spur the country out of the Depression. World War II continued to drive the growth of the massive American industrial complex accompanied by a surge in population, the "baby boom". The Interstate System that was signed into law during the war made road travel easier than ever. Continued incidents of racial violence, voter suppression, the rise of the Ku Klux Klan, lynching, segregation, etc., prompted a mass exodus of millions of Black families from the South to the North and West. Coupled with continued immigration, several cities such as Philadelphia, Detroit, Chicago, Cleveland, Baltimore, and New York City saw a huge increase in their population and a change in their demographics. This lasted roughly from 1916 to 1970. On the other hand, after World War II, thousands of veterans left the cold harsh winters of the North and migrated to the Sun Belt states. Cities such as Los Angeles, San Diego, Las Vegas, Dallas, Houston, and Phoenix also grew significantly.

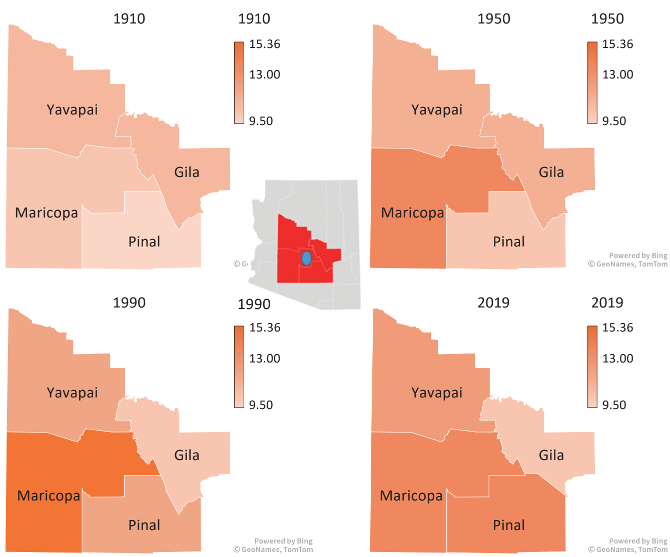
During this period of urbanization, a pattern began to emerge: the gradual movement of large populations from city centers to small satellite towns and communities within close proximity, commonly called suburban development or the suburbs. Spurred by legislation such as the Federal Home Loan Bank Act of 1932 and the National Housing Act of 1934 along with contributions from the Veterans Administration, families were able to buy homes in newly developed areas outside cities. No longer did they need to live in cramped, densely packed apartments in crowded, polluted, and noisy city centers. The United States transitioned from a primary economy (natural resources) to a secondary one (manufacturing). To travel to these well-paying jobs in the cities, workers bought increasingly affordable cars, one of the most important products of this new economy. The total number of miles of paved road continued to increase, especially between cities.

Thus, what happed was that the traditional city centers absorbed the majority of the Black and immigrant population, while most of the middle-class White residents flocked to the suburbs. City centers declined overall despite the new Black residents, because they were, and still are, a minority demographic. Under the National Housing Act, the Federal Housing Authority (FHA) created several guidelines and minimum standards for new housing developments. Unfortunately, it also strongly promoted racial segregation in its guidelines. The design of suburbs focused on car-friendly, wide streets and left out pedestrians. Instead of grid plans, curved and dead-end or cul-de-sac designs were adopted. These were designed to slow cars down and limit traffic through streets but also ensured that cars were necessary to get around. The FHA rated any designs submitted within these guidelines as "good plans" and the rest as "bad plans", making it riskier for developers to pursue. Suburbs grew, their design made walking and public transit inefficient, and existing public transit systems in the city centers fell out of favor and became neglected. The people who depended on these systems the most had little power to influence their improvement. Even if Black families wanted to move out of the city centers, 'redlining' made it impossible for them to secure affordable housing (Lynch et al. 2021). The Fair Housing Act of 1968 put a gradual end to this practice, but the intervening decades had done their damage. Whole generations of minority populations were unable to build wealth via home ownership. Similarly, minorities were also denied access to education and political power with suppression of voting. It was only after the Civil Rights Acts of the 1960s that some of these practices slowly began to decrease. Still, the country is recovering from these effects to this day.

Figure 2 shows the explosive suburban growth for two major cities in the US that have grown the fastest over the last 100 years: Houston, Texas; and Phoenix, Arizona. Note that the population of the counties including and surrounding the city in question is shown based on the best available historical data. The natural logarithmic scale is used to allow for easier discernment of the color scheme. The Houston area grew by a factor of 32 and Phoenix by 69. By comparison, Beijing and Mumbai, two of the largest cities in the world, grew by about 10 and 20, respectively, during the 1910–2020 period. Despite this, inflation-adjusted per capita GDP from 1910–2020 grew by a factor of 29. This phenomenon took place across hundreds of cities in the country. Thus, the United States arrived at the situation in which it is today: declining urban centers surrounded by sprawling suburban development.



(a)



(b)

Figure 2. Growth of urban and suburban regions for (**a**) Houston and (**b**) Phoenix; population in natural logarithm scale corresponding to 13,299 to 4,698,619 for Houston and 9045 to 4,485,414 for Phoenix; blue circle is location of city center in the state (US Census Bureau 2021b). Source: Figure by author.

2.2. Methodology

The approach used is based on the historical context provided. A comprehensive, literature-based argument is used to highlight the characteristics and effects of urban development in the US. Two guiding principles were the influence of Federal policy and economic factors. In addition to satellite map data, Federal (FHA 1956; Code of Federal Regulations 2001) and state (Wisconsin Department of Transportation 2017) traffic planning documents were consulted.

The results are examined from a standpoint of environmental impacts and economic impacts. Accordingly, four categories are examined. How each one influences the other is explained. Given the size of the US, emphasis is placed on common factors that are typical of the urban United States. Case studies from 2021 are used to support the analysis and glean important insights. Similarly, recent developments related to urban development resulting from the COVID-19 pandemic are discussed, along with key legislation that is aimed to stem the ill effects of poor urban planning in the US. The aim is to provide an overview of where the country is headed in the years to come.

3. Unsustainable Development: How Policy Shaped the Present

Armed with some historical perspectives and insights into the critical legislation that steered it, this section highlights why urban development in the suburban US is unsustainable. While urban development is a complex topic, the leading factors are explained here:

-Population density and suburban layout
-Highways, roads, and streets
-Unsustainable finances
-Decaying infrastructure

To demonstrate how one factor leads to the next, certain case studies will be used to provide examples. While the US is a vast and diverse country, traveling from state to state makes for a surprisingly uniform and familiar experience, especially when it comes to modern cities and the interstate system.

3.1. Population Density and Suburban Layout

3.1.1. Land Use—Single-Family Zoning

Even though the US is the third largest nation by population, it is the fourth largest by area, and so it is not surprising that it is listed at 185th out of 250 countries and territories recognized by the United Nations (United Nations 2018) when ranking population density. According to US Census Data (Ruggles et al. 2021), the average household size decreased from 5.79 in 1790 to 2.63 in 2018. Given that the overall population has grown, this implies the number of houses occupied has increased at a much higher rate. Fewer people are living in any given house. However, this alone does not explain the low population density in the country. In the US, the vast majority of housing falls into two types, single-family homes and mid- to high-rise complexes. The term "missing middle" (Wegmann 2020) has been used to define the kinds of housing—duplexes, rowhomes, courtyard apartments, etc.—that used to be more common, especially in older cities before World War II, but are less common now. Zoning policies make it virtually impossible for developers to build anything other than single-family homes in most suburbs. A side effect is that limited land and increasing demand drives up housing prices almost everywhere (Picchi 2021). In cities such as Minneapolis, Minnesota, about 70% of residential land is reserved for single-family housing. In San Jose, California, it is 94%. The average home in the United States grew in size from 1500 sq. ft. in the 1970s to over 2000 sq. ft. nowadays (Friedman and Krawitz 2001). Interestingly, the average lot size has continued to decrease as pressure for suburban housing continues to increase.

3.1.2. Case Study of Kimberly, Wisconsin

To illustrate why American suburbs are huge and sprawling, consider the example in Figure 3. A residential block in the village of Kimberly, Wisconsin is shown. The term "village" is an administrative designation and is used to describe suburbs around large cities, in this case, Appleton, with a metropolitan population of 236,000. Kimberly's population is a mere 6800. The area between Emons Road, Main Street, Calumet Street (major arterial road linking to US Highway 10/Highway 441), and Eisenhower Drive is approximately 200 acres (0.8 km^2). It comprises mostly single-family houses, with a handful of apartment complexes, typically two- or four-unit developments. Note that non-residential buildings are virtually nonexistent. Some restaurants and businesses are located to the southwest. That section is part of the larger highway exit development discussed later. There are about 350 houses. Using the average per household of 2.63, that gives 920 residents. For a conservative estimate, take it as 1000 residents. The population density comes to about 1125/km^2, which is close to the census value of 1143/km^2. For comparison, Manhattan in New York City is 26,821/km^2 and Brussels is 7400/km^2. It is clear that such residential development makes highly inefficient use of land. In the figure, observe the large stretches of open space that are not used. While Americans enjoy their yards, in Figure 3, most of the green space is unusable. It does not belong to the individual homeowner, is not developed for public use, and does not connect to any roads or walking trails. Usually, this space is inhabited by wildlife, but being so close to humans and roads, animals often end up being killed. Plus, it costs time and resources to maintain it: landscaping around the edges, pest control, runoff, etc. There is one park in the middle, but again, it can only be easily accessed by road. The distance from the yellow marker at the end of the cul-de-sac Stillwater Trail is 500 ft (152 m). However, due to the street layout, to avoid walking through private property and undeveloped land, one must walk about 0.5 mi (0.8 km). It is the same situation to access any of the businesses, the main road, or even a neighbor's house. In almost all cases, a five-minute walk is replaced by a car trip.

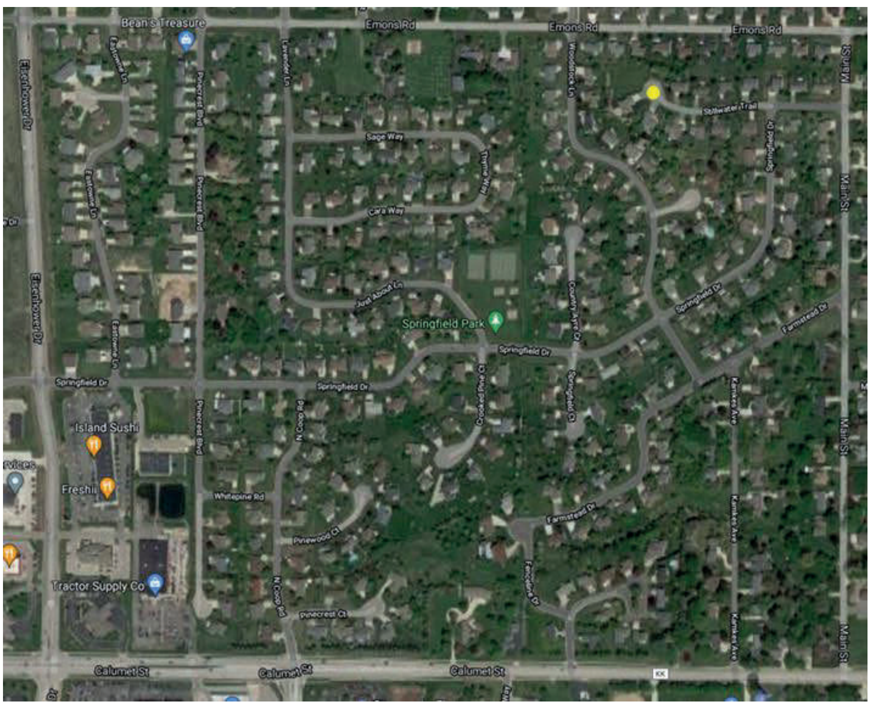


Figure 3. Residential block in Appleton, Wisconsin. Source: Google Maps (2021c)—Kimberly, Wisconsin, @ 44.26, −88.34.

As mentioned before, these suburbs are very unfriendly to pedestrians and cyclists. There are no dedicated lanes for cyclists and no sidewalks in the neighborhood shown. This is a consequence of housing and zoning policy: building around nature rather than integrating nature into the design. Older cities in the US and several other countries integrate green spaces, trees for shade, and other public spaces for leisure or outdoor dining into the neighborhood's design and layout without compromising accessibility. These typically include low- or no-traffic streets and buildings that are multi-use: businesses on the lower levels and residences on the upper levels. All of these are located within a short walk from public transit. This is the basic idea behind the "15-minute city" (Clerici Maestosi et al. 2021).

3.2. Highways, Roads, and Streets

3.2.1. Definitions of Roadway Types

The Interstate System in the US is fairly uniform across the country: two lanes in each direction with entrances and exits having additional dedicated merge lanes. The *highways* (freeways) are mostly straight and flat with virtually no stopping—a huge improvement from the US Highway System that they were meant to replace. There are universal signs for fuel, food, rest stops, etc. The speeds vary from 65 to 75 mph (105 to 120 km/h). These speeds generally drop to 50–60 mph when passing through a city. There is usually a minimum speed as well, 40 mph (64 km/h). By contrast, most *streets* (local roads) passing through residential neighborhoods, such as the ones within the four named borders in Figure 3, have a speed limit of 25 mph (40 km/h). Several of these may not have sidewalks, STOP signs, or even lane markings.

Now consider the *roads* (arterials or collectors) that connect highways to neighborhood streets, such as the four named border roads in Figure 3. These typically vary in speed from 35 to 55 mph (56–88 km/h). These generally have traffic lights, STOP signs, yield signs, or traffic circles (roundabouts). These roads connect highways to streets and are usually lined with non-residential buildings. Not only can traffic execute turns at intersections, but several states have reversible lanes (US Department of Transportation 2020), as shown in Figure 4. These allow either side of the road the right of way. Once in the lane, the driver has to turn left across two lanes of oncoming traffic. For these reasons, they are colloquially called "suicide lanes". The main efficacy is to allow traffic to turn left whenever desired without slowing down the entire road. This also obviates the need to construct a median. The median between interstate highways can be up to 60 ft (18 m) in width and is essentially wasted space. Concrete barriers are also placed within city limits and a reversible lane eliminates the need for such additional material.

Figure 4. Reversible "suicide" lane with yellow lane markings as the centermost lane of US Highway 141. Source: Google Maps (2021e)—Reversible Lane, @ 44.49, −87.97.

3.2.2. Problems with Roads

Roads are inefficient at moving traffic and extremely hostile to cyclists and pedestrians. US intersections prioritize the movement of cars through intersections, meaning pedestrians have to wait a long time and might be tempted to jaywalk. Dedicated cyclist lanes are either absent or within immediate proximity of fast-moving traffic, leading to frequent collisions and fatalities. With cars frequently and unpredictably turning out of or into the road, other drivers have to slow down or completely stop, even with the reversible lane. In addition to being dangerous for cyclists and pedestrians, roads are also dangerous for cars. According to the US Department of Transportation (US Department of Transportation 2020), the average annual rate of traffic crashes per 100 million vehicle miles traveled is as follows: interstates—0.48, arterials—1.1, and local streets—0.78. Arterial roads are by far the worst.

3.2.3. Case Study of Phoenix, Arizona and Appleton, Wisconsin

In Figure 4, on either side of US Highway 141, between the road and the pedestrian sidewalk, green medians are present. These are designed to provide distance between pedestrians and fast-moving traffic, which would be unnecessary on a local street. This is wasted space and adds to the unwalkability of suburbs. To illustrate this, consider Figure 5, a typical suburban intersection—this one is a busy location in Phoenix, Arizona. The intersection has six lanes, three in each direction.

The approximate distance for a pedestrian to make the crossing is 120 ft (36.5 m). The residential portions are, once again, not connected to this intersection in the most direct way, forcing residents to take a meandering route, which encourages them to drive.

Figure 5. Intersection of 43rd Avenue and Thomas Avenue is a residential neighborhood of Phoenix, Arizona. Source: Google Maps (2021d)—Phoenix, Arizona, @ 33.48, −112.15.

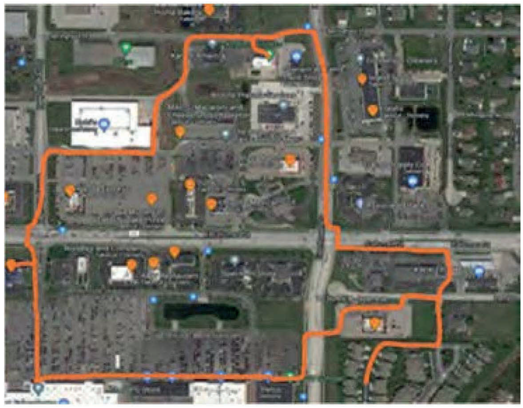
In Figure 6, a busy intersection in Appleton, Wisconsin, is shown. This locality is immediately to the west of the area in Figure 3. A hypothetical walking trip is shown in yellow in Figure 6a. Note the absence of dedicated cycling lanes, forcing cyclists to either share the road with cars or the sidewalk with pedestrians. For someone living in the neighborhood to the bottom-right (Victorian Drive), a walk to the fitness center (Anytime Fitness) in the north necessitates crossing the intersection, which is 148 ft (45 m) because of the number of lanes and medians. Then, the person goes to Kohl's, stops by Culver's for a meal, followed by Walmart, and back home. This simple trip is 1.7 mi (2.74 km) and would take almost 40 min to walk (accounting for stopping at intersections, but not accounting for the actual visits). Just walking from Kohl's to

Walmart is 1284 ft (391 m). Clearly, this is because of the huge parking lots, which dominate the entire business plaza in Figure 6b—in addition to all the unused green space. This is another reason for huge suburb sizes: in addition to single-home lots, useless green space, and wide roads, part of the zoning laws previously mentioned contained guidelines about the minimum parking lot size. This has resulted in oversized lots that are vacant most of the time. Some estimates indicate that 70–80% of downtown parking is vacant (Florida 2018). In Seattle, there are 5.2 spaces per household. In Des Moines, it is 19.4. In New York, with one of the highest transit populations in the country, it is 0.6. The nearest public transit stop in Figure 6, Valley Transit bus service, is at Walmart. Thus, the whole Town of Buchanan, which is to the east of Eisenhower Road, is completely devoid of any public transit. Residents would need to walk a mile to catch a bus to Downtown Appleton. Such development makes walking all but impossible. It must be iterated that, in the US, the Interstate system and collector-feeder system are fairly uniform across the country. While certain historic downtown areas in city centers have one-way and car-free streets, the sheer size of urban sprawl necessitates the design features of roads and parking lots articulated here.

3.3. Unsustainable Development, Unsustainable Finances

3.3.1. Low-Density Development and Suburban Insolvency

The land area of Phoenix is 519 sq. miles (1344 km^2). However, the metropolitan area is listed as 14,600 sq. miles (37,814 km^2), similar to Bhutan. Houston city is 571 sq. miles, but the metropolitan area is 10,062 sq. miles. For comparison, Rome, with a comparable population, is listed at 500 sq. mi (1295 km^2). This is important because the way land is designated by governments directly affects how it is utilized and taxed. Residents within city limits expect certain amenities, infrastructure, utilities, etc. The city is obligated to provide these at the same cost to all. Naturally, if the population density in a given area is very low, then the tax revenue will also be low. However, the cost and energy requirements to build and maintain the same level of service are not the same. It costs significantly more to build roads, dig sewers, lay utility lines, etc., over 14,600 sq. mi than over 500 sq. miles. Maintaining green medians, resurfacing parking lots, patrolling sprawling suburbs, responding to emergencies, etc., exerts a significant financial toll on the limited resources of municipalities, not to mention the planet. A dense, multi-use district brings in much more revenue than a parcel of land such as in Figure 6, where there is one business with 75% of the land dedicated to parking. Figure 4 is no different.



(a)

(b)

Figure 6. Intersection of Calumet Street and Eisenhower Drive in Appleton, Wisconsin: (**a**) hypothetical walking trip in orange; (**b**) parking lots in yellow. Source: Google Maps (2021a)—Calumet Streeta, @ 44.24, −88.34.

The precarious finances of suburban developments can be explained as follows. Due to the Federal nature of government, funding for roads comes from all levels of government. Cities typically provide about a quarter, Federal funds account for another quarter, and the state departments of transportation provide the rest (US Census Bureau 2018). So, cities are incentivized to build new roads because they do not have to pay very much and they generate new tax revenue. However, the cities do have to pay to maintain that infrastructure. At the end of the new road's lifespan, suddenly the city is on the hook for a massive bill. This is typically masked by revenue from new development—recall that US cities such as Houston and Phoenix are recording double digit growth rates. Thus, suburban development becomes a Ponzi Scheme, with the maintenance of old developments being paid for by new developments. If property tax revenue, the main income source for cities, cannot cover road maintenance, sewage systems, water treatment systems, fire and police services, schools, parks and public spaces, etc., the city becomes insolvent.

3.3.2. Effect of Parking Infrastructure

There are numerous examples and case studies of bankrupt cities and municipalities in the US. What is undeniable, is that this low-density, car-centric development comes at a steep cost. Americans, especially in the suburbs, are used to free parking. In New York, the public cost per household for one parking space is USD 6750. In Seattle, it is USD 117,677 and, in Des Moines, it is USD 77,165 (Florida 2018). By legislating parking minimums, local governments are subsidizing parking lots at the taxpayer's expense. The Federal income tax exclusion for commuter parking allows employees to exclude USD 250–255 per month for qualified parking received from their employer from taxable income. Estimates vary, but at 10 spots for every car in the US, the country spends between USD 100 and 374 billion on parking. It is a public subsidy that only serves those who can afford a vehicle. It exerts a health toll by encouraging driving and prohibiting cycling or walking and, by extension, causes more avoidable deaths—not to mention pollution. Moreover, the more people drive, the more they want investment in car infrastructure and that leaves less for public transit.

3.3.3. Examples of Suburban Insolvency

Highways are efficient and safe compared to roads and streets. Streets are necessary. Roads, on the other hand, are dangerous and inefficient—even 45 mph is a relatively high speed, necessitating wider lanes (11–12 feet), longer turn and merge lanes, signaled intersections, etc. This often comes at the cost of other infrastructure. Public Works in Tampa, Florida, for example, created a plan to repair aging infrastructure that would cost USD 3.2 billion over 20 years. Tampa currently spends an eighth of that, about USD 20 million per year. It plans to pay for this by phasing in higher rates over several years and taking on a lot of debt, about half the total expected cost. Notably, just two departments, water and wastewater, already spend USD 28 million on debt payments (City of Tampa 2021). Tampa's geography will be especially taxing on its aging water infrastructure: with an elevation of 48 ft

(14.5 m) above sea level, rising sea levels could prove catastrophic. In the city's history, 68 hurricanes and tropical storms have passed within 60 mi (96.5 km). Most recently, Hurricane Charley caused USD 16 billion in damages in 2004. Given the 80–100-year lifespan of water infrastructure, these expensive repairs could not have been a surprise for the City of Tampa. Further infrastructure-related bankruptcies that are listed for further reading include: Stockton, California; Harrisburg, Pennsylvania; San Bernardino, California; and Desert Hot Springs, California.

3.3.4. Effect of the "Gas Tax"

Another commonly employed measure to remain solvent is to secure a bailout package from the State or Federal government. Americans expect modern, high-service infrastructure, but they are not willing to pay for such infrastructure. Suburbs look nice, but they are unhealthy financially and for the environment. This issue permeates even at the national level. It was mentioned previously that Federal funding accounts for about a quarter of highway funding. This Highway Trust Fund (HTF) is principally funded by fuel tax on gasoline, diesel, and kerosene as well as sales and use taxes for heavy vehicles. In the 1960s and 1970s, over 70% of the construction and maintenance cost of US highways was covered by these driver fees and taxes (Dutzik et al. 2015). The "gas tax" has not been proportionately raised to keep up with inflation and rising costs. From 4 ¢/gallon in 1960, the tax was raised to 9 ¢/gallon in 1983, 14.1 ¢/gallon in 1990, and 18.4 ¢/gallon in 1993, where it has remained. Note that states can levy their own tax, ranging from 14.4 ¢/gallon in Alaska to 86.9 ¢/gallon in California. These do not contribute to the HTF. The gasoline tax, just keeping up with inflation, would be 33 ¢/gallon today. Due to this shortfall, the HTF is projected to have a negative balance by 2022 unless policies change.

Figure 7 shows the breakdown of US freight by mode of transportation. Global shipping is dominated by rail and maritime transport. In the US, however, truck shipping is competitive with rail because of the tremendous subsidies for the auto industry, including depressed fuel prices and taxes. Besides the parking exclusion mentioned above, the sales tax exemption for gasoline purchases in several states is another way the burden of paying for roads is shifted from drivers to all taxpayers. Governments spend more non-user tax dollars on highways than on transit, cycling, and walking combined (Dutzik et al. 2015). Larger vehicles cause more damage to road surfaces. With a load limit of 80,000 lb (36.3 tons), the damage inflicted by a loaded semi-truck compared to a 250 lb cyclist (cycle and cyclist) is about 10 orders of magnitude greater (Dutzik et al. 2015). It is estimated that trucks pay only 50–80% of the costs that they extract from highways via user fees, the rest coming from other drivers and non-user general tax monies. This is how trucking is effectively subsidized and remains competitive in the US.

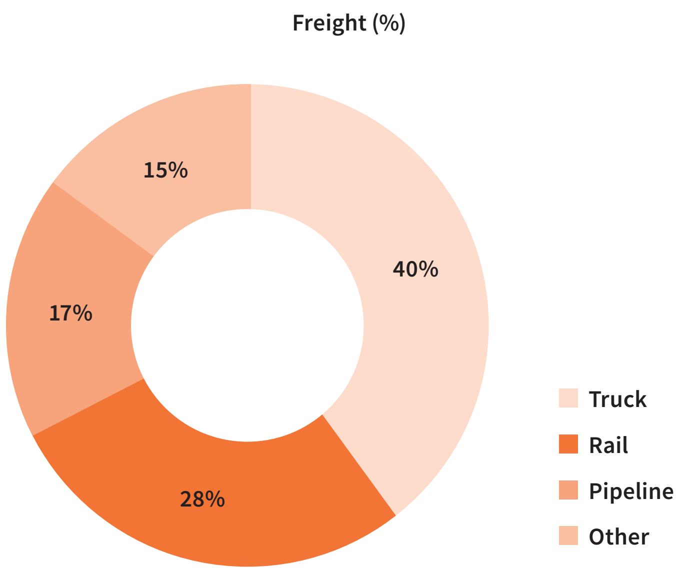


Figure 7. US freight breakdown by mode of transportation. Source: Figure by author, data from US Department of Transportation (2019).

3.3.5. Effects on Social Equality

To come full circle, it is instructive to take a look at the object surrounded by this unsustainable infrastructure: the single-family house. US median home prices have risen from about USD 125,000 in the early 1990s to USD 350,000 in 2021. With mortgage rates lower than ever, borrowing money to buy a house is relatively cheap. Because of high demand and zoning laws, which prohibit multi-family housing or units above a certain height level, developers are disincentivized from building starter houses. Rather, they opt for more expensive homes that afford greater profits. This is not helped by the requirement to set aside land for parking as well. Starter homes have dropped from 40% of new construction to less than 7% (US Census Bureau 2021a). According to Freddie Mac (Federal home Loan Mortgage Corporation), while the homeownership rate in the US hovers around 70%, it is only 43% among Millennials (Freddie Mac 2021). Given that, historically, the most common way to build wealth in the US was owning a home, the current generation is missing out. This does not even address the huge gap between various ethnic and minority groups.

It need not be repeated that the main reason for exclusionary zoning was the desire to keep the suburbs racially segregated.

3.4. Decaying Infrastructure

Politicians and elected leaders have a narrow time horizon. Infrastructure projects require long-term planning. The US had a first-mover advantage, leading the world in rail, telegraph, telephone, airport, electrical grid, and road construction. However, given the complex Federal–state–local funding mix, updating this infrastructure has proven difficult, making it old, unreliable, and prone to failure. Successive administrations are used to plugging holes. Even at the community level, getting funding and approvals requires cooperation between several agencies at different levels, municipalities, residents from multiple communities, etc. Residents seldom support tax increases to pay for infrastructure. People overestimate the value of present conveniences and are more concerned with present pain than future agony (Jacquet et al. 2013). Consensus is often elusive, so action is delayed or deferred. The following recent case studies illustrate these complex forces in action.

3.4.1. Case Study of the Texas ERCOT Grid Failure of 2021

According to the Department of Energy, 70% of the grid's transmission lines and transformers are over 25 years old and the average age of power plants is 30 years (Gerrity and Lantero 2014). Neglect and deferral lead to decay and failure. The most recent and prominent example of this was the failure of the Texas electrical grid in the winter of 2021. Most of the State of Texas (second largest by area and population, about 30 million) is part of the Electric Reliability Council of Texas (ERCOT) Interconnection (Figure 8), which, by design, limited the amount of electricity it could import from neighboring states. Then Winter Storm Uri struck. About 10 million residents were left without electricity for several days. Temperatures were below freezing, breaking records in several places, in a state with little experience dealing with such temperatures. About 111 deaths were recorded (State records only show 14, but some sources cite as high as 705) and about USD 155 billion in economic losses were estimated for the country (Busby et al. 2021). This was primarily because Texas failed to winterize its grid after smaller-scale events in 2011, 2003, and 1989. This was followed up by another close call as recently as June 2021. To date, Texas regulators have not said why 12 GW of generating capacity was offline when demand was dangerously close to the peak of about 70 GW. Residents were asked to reduce consumption to avoid a total blackout.

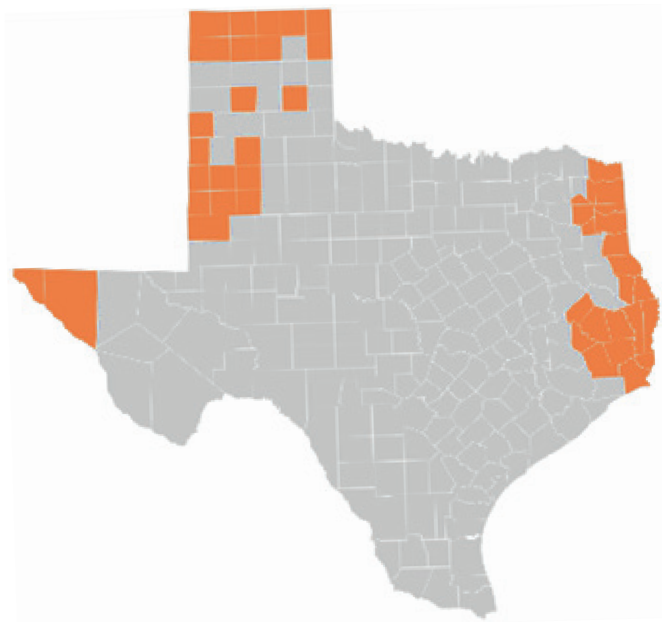


Figure 8. Non-ERCOT counties of Texas (orange). Source: Figure by author.

3.4.2. Case Study of the Hernando de Soto Bridge in Memphis, Tennessee

What can only be described as another close call was the closure of the Hernando de Soto Bridge (Bing Maps 2021). This bridge is a part of Interstate 40 and bridges the Mississippi River as it enters from Arkansas to Memphis, Tennessee, as shown in Figure 9. The bridge is almost 50 years old and carries about 50,000 vehicles per day as it is a major freight corridor. A routine inspection in May 2021 found a one-inch crack across one of the box beams of the main deck. This beam is an arch tie, responsible for withstanding the tension exerted by the truss as it tries to straighten out under the bridge load—this is similar to how a bowstring keeps a bow in tension. The bridge was closed and repaired before opening to traffic in July-August (Burnside 2021). A 2019 inspection was investigated, and drone footage of the bridge revealed significant damage in the area where the crack eventually formed, leading to the inspector responsible being fired.

Figure 9. Hernando de Soto Bridge; inset map of Memphis, Tennessee shows the bridge in a red box. Source: Microsoft product screen shot reprinted with permission from Microsoft Corporation: Bing Maps (2021), @ 35.15, −90.06.

According to a comprehensive study (ARTBA 2021), a third of US bridges, about 220,000, need repair work, with almost 80,000 needing replacement. At the current rate of work, it would take 40 years to complete this. It is impossible to assume that in every single case, critical defects will be found in time for repair. On a related note, Figure 9 (inset) shows another problem with the US highway and road infrastructure. They are designed to move people from the suburbs to the city center. They do not connect neighborhoods in various suburbs to each other very well. Consequently, public transit maps mimic this phenomenon. The main highways through Memphis are I-40, I-55, and I-69. The bypass highway, I-240, circles the city, forming a rough square of 8 mi (12.8 km). I-269 forms an even larger bypass ring through the outer suburbs, as far as Hernando, Mississippi, at 22 mi (35 km). To demonstrate the issue, take Southaven as an example. From Southaven to Downtown Memphis is 13 mi and takes about 13 min. From Southaven to the neighboring suburban town of Olive Branch is 12 mi, but this journey takes 22 min—there is no major highway, just smaller roads. Considering these towns have a combined population of over 90,000, this makes for very inefficient road travel between the two.

3.4.3. Case Study of the Surfside Condominium Collapse

The Surfside condominium collapse happened in Surfside, Florida, about 16 mi (26 km) from Miami. On 24 June 2021, Champlain Towers South (Figure 10), a 12-storey building, partially collapsed (Frisaro and Calvin 2021, p. 40). The official death toll was 98, with several dozens injured and rescued. The building was about 30 years old. As part of its 40-year recertification, inspections as early as 2018 found issues with water seepage in the concrete slab above the parking garage. This likely expedited the corrosion of the reinforcement steel. Since this pool deck slab did not directly support the building, there were likely other factors at play, such as uneven land subsidence putting additional stress on the building's foundations. All these factors were known before the collapse and a USD 15-million plan had been approved before the collapse, but no structural work was being performed at the time of the collapse. As a result of a county-wide audit that followed, multiple buildings were closed off and evacuated due to structural concerns. There have been several other notable public infrastructure failures in the US since 2000 alone. Examples include the breach of the canal levees in New Orleans due to Hurricane Katrina in 2005 and the I-35 Mississippi River Bridge collapse in Minneapolis in 2007.

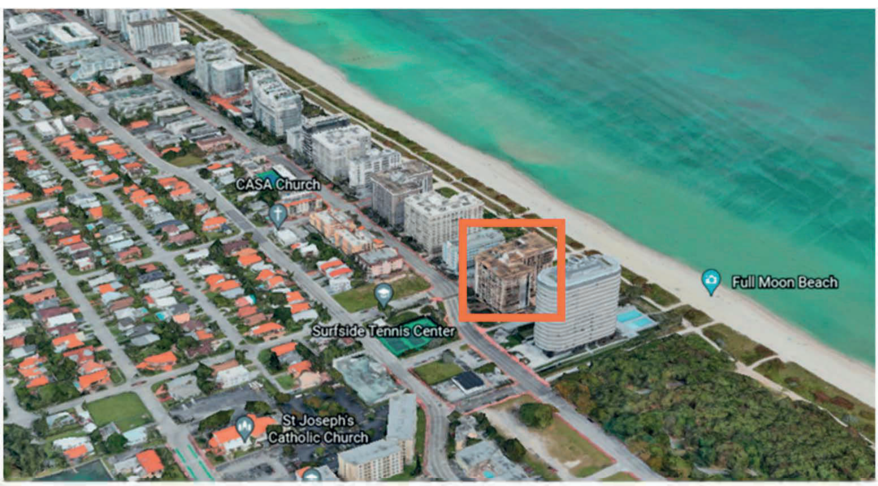


Figure 10. Champlain Towers South (orange box), located in Surfside, Florida. Source: Google Maps (2021b), @ 25.87, −80.12.

3.4.4. Discussion

The Texas grid failure was a direct result of decades of state government policy deliberately aiming to isolate most of the state from cooperative interconnects. This is a result of a lack of Federal regulations that would mandate such redundant safety systems—a common theme in various government sectors in the US. The other two case studies, Hernando de Soto and Surfside, are best explained by general neglect of infrastructure, which is pervasive in various cities across the US. As mentioned previously, the time frame of political cycles and general unwillingness of citizens to pay taxes commensurate with the level of infrastructure found in US cities lead to such disastrous outcomes. Recent events have sparked a gradual change in the mindset of policymakers, as is explained in the following section.

4. COVID-19 Pandemic and Future Trends

The 2019 coronavirus disease (COVID-19) pandemic posed unprecedented challenges to the US as a whole. Besides the health and economic tolls, the US was the epicenter of significant political and social unrest as well. The pandemic brought into focus several of the historical issues that have been presented in this article: racial segregation, wealth inequality, and government policy directly affecting infrastructure planning. Compounding these challenges were the unprecedented effects of climate change: extreme drought in the West that continues to this day; severe wildfires in 2020 and 2021; Hurricanes Isaias, Laura, and Sally in 2020; Hurricanes Claudette, Fred, and Ida in 2021; multiple tornadoes; severe weather events; hailstorms in the Midwest and South; multiple heat waves; floods; and extreme freezing events (NOAA 2021). These have caused several deaths, even more injuries, and billions of dollars in damage. Water scarcity continues to stress farmland in several states.

4.1. Migration Trends

There are powerful forces simultaneously driving people to and out of cities. Urbanization has increased by about 0.2% every year since 2010. California and Oregon have had thousands of residents displaced due to fires and ensuing evacuation orders. Louisiana has lost residents living in coastal communities due to rising sea levels. On the other hand, in July 2021 alone, the US Border Patrol reported about 200,000 encounters with migrants at the US–Mexico border. These people migrate for a number of reasons, but climate change was a big factor: Hurricanes Eta and Iota, occurring within days of each other; and the instability of the Dry Corridor, spanning vast areas in Guatemala, El Salvador, Honduras, and Nicaragua. Due to the immigration status of several migrants, exact statistics are hard to obtain. What is clear is that the majority end up in urban areas (McConnell 2008), especially in California, Texas, Arizona, and Florida.

With pandemic lockdowns and working from home being a common refrain in 2020–2021, Americans increasingly moved out of big cities. The fear of social unrest only added to this tendency. There were many factors, but some common ones stand out. The most obvious one was the desire to remain away from population centers during a pandemic driven by an infectious disease. With the closure of campuses, factories, and most of the leisure industry, several individuals moved in with parents or extended families. With millions on furlough or without work, simply being unable to afford expensive housing in and around cities was a major factor. Working from home temporarily or permanently meant people did not have to commute to work, so living close to work was not necessary. Several families sold expensive homes in and around large cities and bought larger homes in cheaper states—to accommodate working from home or just carry out more activities at home, including schooling. About one in five Americans either moved or knew somebody who moved during the pandemic (Cohn 2021). The cities that were the biggest gainers were Sacramento, California; Las Vegas; Phoenix; Austin, Texas; and Atlanta, Georgia. The biggest losers were New York City, New York; San Francisco, California; Los Angeles, California; and Washington, DC (Anderson 2020). This migration has been strangely reminiscent of the Jim Crow Era and Postwar Era: some demographics moving to cities and others away. Recessions typically tend to reduce mobility and vacation spending. However, during the pandemic, expensive vacation destinations saw a huge increase in population. West Palm Beach, Florida, saw an increase of over 62,000 with a 2019 population of just 112,000. Over half of pandemic job losses were in low-wage sectors, so this is not surprising: wealthier individuals moved because they had options.

4.2. Industry Effects

What can be broadly concluded is that the pandemic has continued to disperse the US population, with people investing even more in their homes. These trends have had direct impacts on several related markets—furniture, home improvement, lumber, swimming pools, etc. Another notable trend is the bicycle boom, particularly in the US, where several states had lenient lockdowns and permitted outdoor activities. People also chose to bike to work to avoid crowded public transportation. An approximately 50% increase in cycling traffic was noted in 2020 relative to the same period the year before in New York City. Several metro areas modified traffic patterns and opened more roads to increased numbers of cyclists and pedestrians (Dowell and Hait 2021). In analyzing data from multiple countries such as the US, Canada, Belgium, France, Germany, and the UK, it was found that cycling for recreation and exercise increased while cycling for transportation to work and educational facilities declined. Biking infrastructure was expanded and improved. Simultaneously, car traffic was restricted through various measures such as restricting access to certain streets and reducing speed limits. These were possibly due to the pandemic (Buehler and Pucher 2022). The "bike boom" is predicted to stay, but it is unclear whether it will translate into a long-term transportation alternative. Just a few days into lockdown, March 2020, the average daily travel distance in the US plummeted from 8 km to 1.6 km (Hendrickson and Rilett 2020). Virtually all sectors of transportation declined, from public transit to personal trips to leisure travel. This had a knock-on effect on fuel consumption, air pollution, traffic accidents, etc. Conversely, the demand for transportation and logistics in e-commerce and certain consumer staples surged, sometimes leading to shortages in certain goods. With global supply chains disrupted, the "just-in-time" method of inventory has been questioned going forward.

4.3. Infrastructure Projects and Future Changes

The weak public transit infrastructure in the US has been even more severely tested by diminished ridership during the pandemic. The CARES Act (March 2020) and CRRSAA Act (December 2020) provided USD 25 billion and USD 14 billion, respectively, for public transit. Pandemic protocols such as increased cleaning and disinfecting, physical distancing, and reduced ridership due to working from home are expected to continue to exert financial stress on operating costs, leading to a projected USD 39 billion shortfall through the end of 2023 (APTA 2021). With state and local taxes declining due to overall diminished economic activity and fuel tax revenue also declining due to fewer vehicle miles traveled, public transit budgets face additional challenges from those brought on directly from revenue loss. This is expected to compromise capital spending.

The sea change that was the COVID-19 pandemic has ushered in a new era of change, something that had been building for several years. The City of Minneapolis almost unanimously passed its ambitious Minneapolis 2040 Comprehensive Plan that ends single-family zoning, eliminates citywide parking requirements, and aims to create a more connected urban experience, among several other goals (City of Minneapolis 2018). All this was in response to the rapidly increasing population, increasing pressure on the housing supply, and historical racial disparities. In 2019, the aforementioned Houston is slowly ending mandatory minimums for parking, allowing developers and business owners to decide—this is currently only in a couple of neighborhoods, but it is a start (Brasuell 2019). Currently, states such as California and Massachusetts are considering housing reform, but this issue remains highly divisive.

With lockdowns in place and traditional sources of leisure and entertainment closed or operating with greatly reduced capacity, people spent more time in urban green spaces. The general attitude of the public towards the importance and use of such spaces improved as a result. In several cities, restaurants were allowed to operate with outdoor dining. Even after pandemic restrictions were lifted, some of these changes became permanent. Cities are beginning to increase investment in such spaces, with a view towards equity, as minority communities typically lack access to such spaces. Researchers have proposed models such as Barcelona, the "green block" modeled after the "superblock" (Burrowes and Schilling 2021).

Potentially significant is the Infrastructure Investment and Jobs Act introduced in early June 2021 (IIJA 2021). If successful, it will provide about USD 1 trillion for various infrastructure issues: new safety requirements across all transportation modes, a program to rebuild rural bridges, mitigate climate change and the impacts of the transportation systems including enhancing its resilience, and most relevant to this article, public transit investment—repair and upgrade bus and rail fleets, improve accessibility, reduce inequity, provide service to new communities, and reduce the carbon footprint of transit vehicles. Even before the pandemic, several public transit projects were in progress or set to start: rail link between San Jose and Santa Clara in California; light rail projects in Boston, Los Angeles, San Diego, and Seattle; electric buses in Indianapolis' rapid transit system, etc.

Light vehicle sales continue to reflect the trends discussed earlier in this work: an aging population with the bulk of the wealth concentration, urban sprawl with increasingly expensive homes requiring vehicles to perform even basic tasks. According to Kelly Blue Book sales data, the number of midsize sedans sold in 2020 was about 50% of what it was in 2012. Light vehicle sales constituted 27.3% of all car sales in 2019 (third quarter). This fell to 24.2% a year later and 24.1% in 2021 (first quarter). Thus, the majority of light vehicle sales in the US are crossovers, sports utility vehicles, pickup trucks, and vans. Before the 2008 Financial Crisis, the split was the opposite: about 45% cars and 55% everything else. Luxury vehicles accounted for approximately 14% of all light vehicle sales just before and during the pandemic. Expectedly, the average transaction price of a new vehicle continues to trend upwards: from USD 35.5 thousand in 2016 to USD 42.2 thousand in June 2021. While automakers have relied on efficiency improvements and hybrid technologies to meet fleet-average emissions regulations, several major manufacturers, including General Motors, are planning for all-electric fleets by 2035. The current Federal government has emphasized electrification of the Federal fleet, a good way to lead by example. This means the conversion or replacement of some 645,000 vehicles, comparable to the annual emissions of countries such as Haiti or DR Congo. Once the Federal government takes the lead, state and local governments will follow.

Consumers are already adopting electric vehicles, making it easier for automakers to make the necessary investments.

5. Perspectives on Modern Urban Planning

It is easy to understand the state of urban planning in the US given the historical, political, and technological context. The newest cities, ones developed after World War II, and their suburbs could have been designed differently. However, single-family zoning, redlining, car-friendly layouts, vast parking lots, and inefficient roads produced the environmentally and financially unsustainable suburbs of today. There are many studies that have investigated some of the issues raised in this work. In (Fiack et al. 2021), 22 of the 100 largest US cities' climate adaptation plans were analyzed. At the local level, social equity and climate adaptation were more prominent relative to economic development. Particular concern was shown for marginalized populations. Another study found that zoning does cause inequality and exploding housing costs but indicated that more work is needed to link the co-evolution of zoning across large metro areas and suburbs and how that has shaped demographic changes (Shertzer et al. 2021). A study in Buffalo, New York, specifically looked at pedestrian collisions at intersections with the goal to build a more walkable city. Vulnerable populations were given special focus (Yin and Zhang 2021). Plans to build pandemic-resilient cities in England, Germany, and Italy found that intracity connectivity was more important in disease spread compared to intercity connectivity. City morphology also had an impact, with linear cities being more resilient than grid or radial plans (AbouKorin et al. 2021). The recommendation was to improve the public transit efficiency quickly, before people switched to private vehicles. For a comprehensive treatment of the problems with urban planning in the US in particular, Duany et al. (2010) may be consulted as a starting point.

6. Closing Remarks

The Kardashev Scale is a method to gauge a civilization's technological mastery. The metric used is energy. A Type I civilization is capable of harnessing all the energy available on its planet. Though not perfect, the ability of humanity to harness increasing amounts of energy over time has roughly aligned with technological progress: from wood to coal to petroleum to nuclear. The impact of explosive growth has been so severe that this era of geologic time has even been named the 'Anthropocene Epoch', characterized by increases in population, energy consumption, and GDP (Syvitski et al. 2020). However, the resources for this planet are finite, so efficiency is key to maximizing wellness. Furthermore, humanity has discovered that technological progress must be made whilst keeping the health of the planet in mind.

This study provided a brief historical overview to explain the state of urban planning and urban sprawl in the US. Key features of US cities and suburbs were discussed. These include restrictive zoning laws, car-centric city and suburban design, poorly structured roads, a lack of public transit options, etc. The low population density puts tremendous strain on infrastructure and leads to unsustainable finances for several municipalities. This, in turn, leads to neglected and derelict infrastructure, several examples of which were highlighted. COVID-19 has challenged the status quo and, in many ways, catalyzed future change.

The US has been a pioneer and leader in transportation and several related industries. For a more sustainable and environmentally friendly future, initiatives such as the ones highlighted—relaxing zoning laws, repairing roads and bridges, and investing in clean transportation—will be required. These must go hand in hand with the push for clean energy and social justice. Cities within the US can serve as examples of good urban planning, especially plans from before the proliferation of cars and urban sprawl. Globally, cities such as Copenhagen and Singapore are good examples of smart urban planning: promoting mixed-use housing, cycling and walking, and robust mass transit systems. Finally, urban planners in developing countries with growing populations and industrial centers can learn valuable lessons and avoid repeating the mistakes of the past.

Acknowledgments: The author would like to acknowledge the inspiration, ideas, and examples of Jason Slaughter, host of the YouTube channel on urban planning Not Just Bikes (https://www.youtube.com/c/NotJustBikes).

Funding: This research received no external funding.

Conflicts of Interest: The author declares no conflict of interest.

References

AbouKorin, Salma Antar, Haoying Han, and Mahran Gamal Mahran. 2021. Role of urban planning characteristics in forming pandemic resilient cities—Case study of Covid-19 impacts on European cities within England, Germany and Italy. *Cities* 118: 103324. [CrossRef]

American Public Transportation Association. 2021. *The Impact of the Covid-19 Pandemic on Public Transit Funding Needs in the US*. Washington, DC: EBP US, Inc., January 27.

American Road & Transportation Builders Association. 2021. *Bridge Conditions Report*. Washington, DC: American Road & Transportation Builders Association.

Anderson, Dana. 2020. Austin Is Attracting Twice As Many Out-of-Town Homebuyers As Last Year. *Redfin*. December 21. Available online: https://www.redfin.com/news/october-november-2020-housing-migration-trends/ (accessed on 28 August 2021).

Arbabi, Hadi, and Martin Mayfield. 2016. Urban and Rural—Population and Energy Consumption Dynamics in Local Authorities within England and Wales. *Buildings* 6: 34. [CrossRef]

Bing Maps. 2021. *Hernando de Soto Bridge (Memphis)*. Vexcel Imaging, TomTom Earthstar Geographics SIO, Map Data. Available online: https://www.bing.com/maps (accessed on 20 August 2021).

Boustan, Leah P., Devin Bunten, and Owen Hearey. 2018. Urbanization in American Economic History, 1800–2000. In *The Oxford Handbook of American Economic History*. Edited by Louis P. Cain, Price V. Fishback and Paul W. Rhode. Oxford: Oxford University Press. [CrossRef]

BP. 2021. *bp Statistical Review of World Energy*, 70th ed. Available online: bp.com/energyoutlook (accessed on 3 August 2021).

Brasuell, James. 2019. *Parking Minimums Not Required in a Larger Section of Houston*; Planetizen, July 18. Available online: https://www.planetizen.com/news/2019/07/105304-parking-minimums-not-required-larger-section-houston (accessed on 29 August 2021).

Buehler, Ralph, and John Pucher. 2022. Cycling through the COVID-19 Pandemic to a More Sustainable Transport Future: Evidence from Case Studies of 14 Large Bicycle-Friendly Cities in Europe and North America. *Sustainability* 14: 7293. [CrossRef]

Burnside, Tina. 2021. A vital Memphis bridge shut down since May due to a structural crack will partially open next week. *CNN News*. July 28. Available online: https://www.cnn.com/2021/07/28/us/memphis-hernando-desoto-bridge-partial-reopening/index.html (accessed on 21 August 2021).

Burrowes, Kimberly, and Joseph Schilling. 2021. From Streets to Citizen Spaces: Positioning Parks and Green Spaces in an Equitable COVID-19 Recovery. *Urban Institute*. Available online: https://www.urban.org/sites/default/files/publication/104931/from-streets-to-citizen-spaces_0.pdf (accessed on 3 August 2022).

Busby, Joshua W., Kyri Baker, Morgan D. Bazilian, Alex Q. Gilbert, Emily Grubert, Varun Rai, Joshua D. Rhodes, Sarang Shidore, Caitlin A. Smith, and Michael E. Webber. 2021. Cascading risks: Understanding the 2021 winter blackout in Texas. *Energy Research & Social Science* 77: 102106. [CrossRef]

Center for Sustainable Systems. 2020. *U.S. Cities Factsheet*. Ann Arbor: University of Michigan.

City of Minneapolis. 2018. *Minneapolis 2040 The City's Comprehensive Plan*. December 7. Available online: https://minneapolis2040.com/ (accessed on 29 August 2021).

City of Tampa. 2021. Budget FY2018-FY2021. In *Revenue and Finance*; Budget Division. Available online: https://www.tampa.gov/budget (accessed on 17 August 2021).

Clerici Maestosi, Paola, Maria Beatrice Andreucci, and Paolo Civiero. 2021. Sustainable Urban Areas for 2030 in a Post-COVID-19 Scenario: Focus on Innovative Research and Funding Frameworks to Boost Transition towards 100 Positive Energy Districts and 100 Climate-Neutral Cities. *Energies* 14: 216. [CrossRef]

Code of Federal Regulations. 2001. *Highways* 23: 2001. Available online: https://www.govinfo.gov/content/pkg/CFR-2001-title23-vol1/pdf/CFR-2001-title23-vol1.pdf (accessed on 10 May 2022).

Cohn, D'Vera. 2021. About a fifth of U.S. adults moved due to COVID-19 or know someone who did. *Pew Research Center*. July 6. Available online: https://www.pewresearch.org/fact-tank/2020/07/06/about-a-fifth-of-u-s-adults-moved-due-to-covid-19-or-know-someone-who-did/ (accessed on 28 August 2021).

Dong, Feng, Bolin Yu, Yifei Hua, Shuaiqing Zhang, and Yue Wang. 2018. A Comparative Analysis of Residential Energy Consumption in Urban and Rural China: Determinants and Regional Disparities. *International Journal of Environmental Research Public Health* 15: 2507. [CrossRef] [PubMed]

Dowell, Earlene K.P., and Andrew W. Hait. 2021. Surge in Demand Prompts Bicycle Shortages, Higher Prices. In *US Census Bureau*; June 3. Available online: https://www.census.gov/library/stories/2021/06/consumers-turn-to-biking-for-safe-fun-exercise-during-pandemic.html (accessed on 4 August 2022).

Duany, Andres, Elizabeth Plater-Zyberk, and Jeff Speck. 2010. *Suburban Nation: The Rise of Sprawl and the Decline of the American Dream*. New York: North Point Press.

Dutzik, Tony, Gideon Weissman, and Phineas Baxandall. 2015. Who pays for roads? In *Frontier Group*. Denver: CoPIRG Foundation.

Federal-Aid Highway Act of 1956. 1956, *H.R.10660*, Public Law 627, 94th Cong.

Fiack, Duran, Jeremy Cumberbatch, Michael Sutherland, and Nadine Zerphey. 2021. Sustainable adaptation: Social equity and local climate adaptation planning in U.S. cities. *Cities* 115: 103235. [CrossRef]

Florida, Richard. 2018. Parking Has Eaten American Cities. *Bloomberg CityLab*. July 24. Available online: https://www.bloomberg.com/news/articles/2018-07-24/the-overparked-states-of-america (accessed on 16 August 2021).

Freddie Mac. 2021. Millennials and Housing: Homeownership Demographic Research. In *Marketing Analytics*. Virginia: Market Research and Insights Department, Tysons Corner.

Friedman, Avi, and David Krawitz. 2001. *Peeking Through the Keyhole: The Evolution of North American Homes*. Montreal: McGill-Queen's University Press.

Frisaro, Freida, and Bobby Caina Calvin. 2021. *Surfside Condo Collapse Death Toll Reaches 94; Search Likely to Take Weeks*. NBC 6 South Florida News. July 12. Available online: https://www.nbcmiami.com/news/local/search-in-surfside-condo-collapse-to-take-weeks-death-toll-at-94/2492440/ (accessed on 20 August 2021).

Gerrity, Sarah, and Allison Lantero. 2014. Understanding the Grid. In *US Department of Energy*; November 17. Available online: https://www.energy.gov/articles/infographic-understanding-grid (accessed on 18 August 2021).

Google Maps. 2021a. *Calumet Street*. Maxar Technologies Imagery, USDA Farm Service Agency, Map Data. Available online: https://www.google.com/maps/@44.243989,-88.346232 (accessed on 15 August 2021).

Google Maps. 2021b. *Champlain Towers South*. Map Data, Google. Available online: https://www.google.com/maps/@25.8736427,-80.1232383 (accessed on 20 August 2021).

Google Maps. 2021c. *Kimberly, Wisconsin*. Maxar Technologies Imagery, USDA Farm Service Agency, Map Data. Available online: https://www.google.com/maps/place/Kimberly,+WI/ (accessed on 12 August 2021).

Google Maps. 2021d. *Phoenix, Arizona Intersection (43rd Avenue and Thomas Avenue)*. Map Data, Google. Available online: https://www.google.com/maps/search/thomas+avenue+43rd+avenue/ (accessed on 13 August 2021).

Google Maps. 2021e. *Reversible Lane*. Maxar Technologies Imagery, Airbus/CNES, Map Data. Available online: https://www.google.com/maps/@44.4927765,-87.9760248 (accessed on 15 August 2021).

Hendrickson, Chris, and Laurence R. Rilett. 2020. The Covid-19 Pandemic and Transportation Engineering. *Journal of Transportation Engineering Part A: Systems* 146: 01820001. [CrossRef]

Infrastructure Investment and Jobs Act of 2021. 2021, *H.R.3684*, 117th Cong.

Intergovernmental Panel on Climate Change (IPCC). 2019. *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, Edited by Priyadarshi Shukla, Jim Skea, Eduardo Calvo Buendia, Valerie Masson-Delmotte, Hans-Otto Pörtner, Debra Roberts, Panmao Zhai, Raphael Slade, Sarah Connors, Renee van Diemen and et al. *in press*.

International Monetary Fund. 2021. World Economic Financial Surveys. *World Economic Outlook Database*. Available online: https://www.imf.org/en/Publications/WEO/weo-database/2021/April (accessed on 7 August 2021).

Jacquet, Jennifer, Kristin Hagel, Christoph Hauert, Jochem Marotzke, Torsten Röhl, and Manfred Milinski. 2013. Intra- and intergenerational discounting in the climate game. *Nature Climate Change* 3: 1025–28. [CrossRef]

Liu, Lin, and Yuanzhi Zhang. 2011. Urban Heat Island Analysis Using the Landsat TM Data and ASTER Data: A Case Study in Hong Kong. *Remote Sensing* 3: 1535–52. [CrossRef]

Lynch, Emily E., Lorraine Halinka Malcoe, Sarah E. Laurent, Jason Richardson, Bruce C. Mitchell, and Helen C. S. Meier. 2021. The legacy of structural racism: Associations between historic redlining, current mortgage lending, and health. *SSM—Population Health* 14: 100793. [CrossRef] [PubMed]

McConnell, Eileen Diaz. 2008. The U.S. Destinations of Contemporary Mexican Immigrants. *The International Migration Review* 42: 767–802. [CrossRef]

National Oceanic and Atmospheric Administration. 2021. *Extreme Events*. Available online: https://www.climate.gov/news-features/category/extreme-events (accessed on 25 August 2021).

Picchi, Aimee. 2021. "Wrong direction": Homes now unaffordable in 4 of 10 US counties. *CBS News*. June 24. Available online: https://www.cbsnews.com/news/housing-real-estate-home-buying-affordability/ (accessed on 12 August 2021).

Ruggles, Steven, Sarah Flood, Sophia Foster, Ronald Goeken, Jose Pacas, Megan Schouweiler, and Matthew Sobek. 2021. U.S. Census Data for Social, Economic, and Health Research. In *Integrated Public Use Microdata Series (IPUMS) USA*. Version 11.0 [dataset]. Minneapolis: IPUMS. [CrossRef]

Shertzer, Allison, Tate Twinam, and Randall P. Walsh. 2021. Zoning and segregation in urban economic history. *Regional Science and Urban Economics* 94: 103652. [CrossRef]

Stover, John F. 1999. *The Routledge Historical Atlas of the American Railroads*. New York: Routledge.

Syvitski, Jaia, Colin N. Waters, John Day, John D. Milliman, Colin Summerhayes, Will Steffen, Jan Zalasiewicz, Alejandro Cearreta, Agnieszka Gałuszka, Irka Hajdas, and et al. 2020. Extraordinary human energy consumption and resultant geological impacts beginning around 1950 CE initiated the proposed Anthropocene Epoch. *Communications Earth & Environment—Nature* 32: 1–32. [CrossRef]

The World Bank. 2021. World Development Indications. *Data Catalog*. Available online: https://datacatalog.worldbank.org/dataset/world-development-indicators (accessed on 7 August 2021).

Torrey, Barbara Boyle. 2004. *Urbanization: An Environmental Force to Be Reckoned with*. Available online: https://www.prb.org/resources/urbanization-an-environmental-force-to-be-reckoned-with/ (accessed on 8 August 2021).

United Nations. 2018. World Urbanization Prospects 2018. *Department of Economic and Social Affairs Population Dynamics*. Available online: https://population.un.org/wup (accessed on 3 August 2021).

US Census Bureau. 2018. Annual Survey of State and Local Government Finances, 1977–2018, compiled by the *Urban Institute via State and Local Finance Data: Exploring the Census of Governments*. Available online: https://state-local-finance-data.taxpolicycenter.org/ (accessed on 16 August 2021).

US Census Bureau. 2021a. New Residential Sales. In *Historical Data*. Available online: https://www.census.gov/construction/nrs/historical_data/index.html (accessed on 18 August 2021).

US Census Bureau. 2021b. *Population and Housing Unit Estimates Tables*; archived Data. Available online: https://www.census.gov/programs-surveys/popest.html (accessed on 10 August 2021).

US Central Intelligence Agency. 2021. The World Factbook. In *Field Listing—Urbanization*. Available online: https://www.cia.gov/the-world-factbook/field/urbanization/ (accessed on 7 August 2021).

US Department of Transportation. 2019. *Pocket Guide to Transportation*. Washington DC: Bureau of Transportation Statistics.

US Department of Transportation. 2020. Early Estimates of Motor Vehicle Traffic Fatalities and Fatality Rate by Sub-Categories Through June 2020. In *Traffic Safety Facts: A Brief Statistical Summary*. National Highway Traffic Safety Administration, DOT HS 813 054, Washington, DC: National Center for Statistical Analysis.

Wang, Li, Fengying Zhang, Eva Pilot, Jie Yu, Chengjing Nie, Jennifer Holdaway, Linsheng Yang, Yonghua Li, Wuyi Wang, Sotiris Vardoulakis, and et al. 2018. Taking Action on Air Pollution Control in the Beijing-Tianjin-Hebei (BTH) Region: Progress, Challenges and Opportunities. *Int. J. Environ. Res. Public Health* 15: 306. [CrossRef] [PubMed]

Wegmann, Jake. 2020. Death to Single-Family Zoning . . . and New Life to the Missing Middle. *Journal of the American Planning Association* 86: 113–19. [CrossRef]

Wisconsin Department of Transportation. 2017. *Wisconsin Manual on Uniform Traffic Control Devices*. Madison: Wisconsin Department of Transportation.

Yin, Li, and Hao Zhang. 2021. Building walkable and safe neighborhoods: Assessing the built environment characteristics for pedestrian safety in buffalo, NY. *Journal of Transport & Health* 22: 101129. [CrossRef]

© 2023 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

Enhancing the RPL Protocol Using an Artificial Neural Network for Sustainable IoT Infrastructure

Sonia Kuwelkar and Hassanali G. Virani

1. Introduction

The IoT is a giant communications network connecting billons of devices, such as smart phones, wearable devices, sensors, actuators, and home appliances, over the Internet. It is predicted that by 2025 there will be more than 27 billion IoT connections. The IoT will revolutionize the quality of human life by manifesting a plethora of applications in healthcare, industrial automation (Pister et al. 2009), weather monitoring, smart urban cities (Dohler et al. 2009), home automation (Brandt et al. 2010), logistics, building automation (Martocci et al. 2010), and smart metering (Atzori et al. 2010). The network here comprises of sensors that are battery-operated, use microcontrollers, such as the MSP430, and have limited storage capacity. In contrast to conventional networks, the traffic in these networks can be point-to-point, point-to-multipoint, or multipoint-to-point. The communication network also has several drawbacks, such as instability, low data rates, high packet loss, limited transmission range, frame size limitation, and dynamically varying network topology. Besides these aspects, the links connecting the devices can use a variety of technologies, such as Bluetooth, low-power WiFi, and wired PLC. Another aspect to be considered is that, in large-scale deployments, networks can scale to thousands of nodes. Due to these innumerable constraints on devices and underlying communication technology, the IoT network is characterized as a low-power and lossy network (LLN) (Clausen et al. 2011). All of these unique requirements make the design of an efficient routing protocol a very challenging task (Hui and Culler 2008). One major achievement by the IETF is the 6LoWPAN specification, which specifies how to carry IPv6 datagrams over LLNs (Hui et al. 2012). To devise a routing solution for LLNs, the IETF established the routing over low-power and lossy networks (ROLL) working group and assigned them the task. The working group evaluated existing protocols, such as AODV, DSR, OSPF, and OLSR. They realized that these are inefficient for LLNs with regard to power, latency, overhead, and reliability. As a routing solution, the IETF ROLL working group proposed the IPv6 routing protocol for LLNs (RPL) (Winter et al. 2012). The RPL provides IPv6 connectivity to battery-operated wireless embedded devices that use low-power radios to communicate. The RPL builds upon popular routing protocols, such as CTP and Hydro, used in the WSN domain, but is re-designed and extended to incorporate IPv6. Over a period, the RPL has attained maturity and been standardized as a routing protocol (Syarif et al. 2022). The IP stack of many operating systems, such as Contiki OS, TinyOS, T-Kernel, EyeOS, LiteOS, and RIOT, includes the RPL as a standard routing protocol (Seyfollahi et al. 2022).

As the IoT is going to play a major role in our lives in the near future, it is a must that this infrastructure is efficient in terms of energy, speed, and reliability. Improving the routing process is one essential step in this regard. The routing protocol, the RPL, solves major concerns but has certain gaps which need addressing (Darabkh et al. 2022). The standard RPL version makes a routing decision by considering a single metric, such as hop count. The paths created in this case cannot be optimal ones, since other factors, such as link quality or the energy of nodes, are not considered. This implies that certain design aspects of the RPL require revisions in order to further improve the network performance (Zaatouri et al. 2022). The main aim of this work is to overcome the limitations of single-metric-based routing in the RPL by considering three or four metrics when making the best path decision. A multicriteria decision-making approach must be devised to select the best routes based on multiple routing metrics. This posed a challenge, as traditional computation-intensive hard computing methods would be impossible to implement on IoT nodes that have limited memory and computing ability. Recently, soft computing has risen as a promising approach as it employs approximate models and reasoning, which are comparatively less rigorous. The devices can comfortably accommodate soft computing logic in memory, and microcontrollers, such as the MSP430, can execute it (Charles and Kalavathi 2022). Therefore, we decided to explore the soft computing techniques of fuzzy logic, EA, and ANNs, applying them to improve the RPL. In the initial part of this chapter, a fuzzy logic approach is discussed as a multicriteria decision-making method for choosing the best route based on multiple metrics. Later, the role of evolutionary algorithms, such as genetic algorithms, ant colony optimization, and the firefly algorithm, in enhancing the performance of the RPL is presented here. Finally, a novel version of the RPL, using an artificial neural network, is proposed, which performs better than the existing solutions.

The chapter is organized as follows: In the next section we provide an overview of the RPL. In following sections we discuss the current issues with the RPL and how the RPL has been enhanced by using fuzzy logic, evolutionary algorithms, and artificial neural networks. In the final section we conclude the chapter.

2. RPL Overview

The RPL is a proactive distance-vector-based routing protocol. The network is organized as a destination-oriented directed acyclic graph (DODAG), in which the destination is the root node or LLN border router (LBR). The LBR acts as the gateway for connecting a local network to the Internet. When a network is deployed, the root node initiates the construction of a DODAG (Vasseur et al. 2011). A node can join a DODAG by selecting a preferred parent node. A DODAG is depicted in Figure 1. Each node is assigned a rank, which is directly proportional to the distance from the root node. The LBR has the lowest rank, and the rank increases as we move away from the root. Every parent node will have a rank lower than its children's nodes.

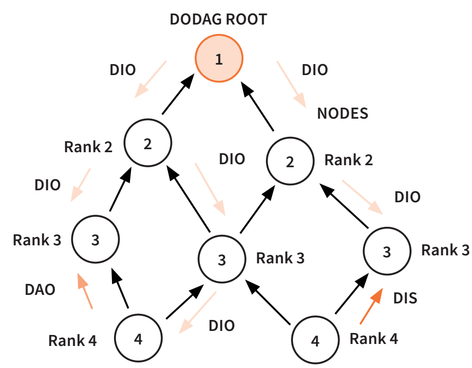


Figure 1. A DODAG and control messages. Source: Reprinted from Kuwelkar and Virani (2021a), used with permission.

In an RPL-based infrastructure, one or more RPL instances can exist, where each instance is identified by a unique ID (RPLInstance_ID). Each instance can have its own set of metrics and routing policy independent of its neighboring instance. Multiple DODAGs can exist within a single RPL instance. In order to distinguish between DODAGs, they are assigned a DODAG ID. Every node can participate in multiple DODAGs. In cases of any inconsistency in the network, the sink can trigger DODAGs to reconstruct themselves. An incremental DODAG Version_Number is assigned to a DODAG by the sink every time it reconstructs itself. The exact version of a particular DODAG can be identified by the tuple of RPLInstance_ID, DODAG_ID, and DODAG Version_Number. To make all of this functional and share routing-sensitive information, the RPL specifies four ICMPv6 control messages. These are as follows:

DODAG information object (DIO): This message contains routing-crucial information, such as objective function, rank, metrics, DODAG ID, trickle timer parameters, and RPL instance ID. This information helps a node to select a parent, identify an RPL instance, and join a DODAG (Tripathi et al. 2010). The DIO message body comprises two parts, a DODAG configuration option and a DAG metric container, where the important information is embedded as shown in Figure 2. DIO messages are essential for constructing upward routes and maintaining a DODAG.

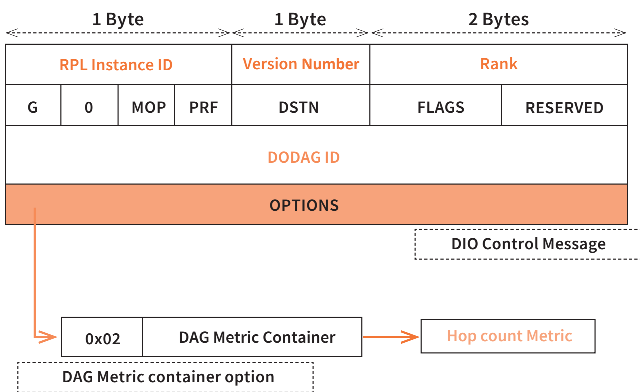


Figure 2. DIO message format. Source: Reprinted from Hassani et al. (2021), used with permission.

Destination advertisement object (DAO): These messages are primarily used to propagate destination information in an upward direction towards the DODAG root. This information in used for construction of downward routes between DODAG root and associated nodes.

DODAG information solicitation (DIS): A node that wants to join a DODAG and has not received a DIO message can use a DIS message to solicit a DIO message from its neighboring nodes.

Destination advertisement object acknowledgement (DAO-ACK): Upon receiving DAO messages, a node can unicast a DAO-ACK to the DAO message sender to acknowledge the receipt of that DAO message.

The root node initiates network formation by broadcasting a DIO message. Whenever a node receives a DIO message, it is able to determine and join the RPL instance, add nodes to its candidate parent list, choose the best parent out of the candidates, and replace a previous parent. The DIO message contains an objective function along with other information. The nodes select the best route by constraining or optimizing certain metrics specified by the objective function. Two objective functions, MRHOF and OF0, are standardized in the RPL. Both of these are briefly described below:

Minimum rank hysteresis objective function (MRHOF): Uses the path cost or expected transmission count (ETX) as a routing metric to select the preferred parent in a DODAG (Gnawali and Levis 2012). The ETX is the number of retransmissions required before a packet is successfully received at the destination. The MRHOF is designed with the aim of preventing frequent changes in the preferred parent. In the MRHOF the path cost of each candidate neighbor is calculated by summing up two components: the value of the neighbor's node or link cost and the selected metric value (e.g., rank) advertised in the metric container. Once the path cost is computed for all of the candidates in the list, the one with the lowest value is selected as the preferred parent node. The MRHOF defines a PARENT_SWITCH_THRESHOLD, which is taken into consideration before a parent switch is made. If the path cost of the new candidate parent exceeds the present parent node by this threshold, only then is the parent switched. This is the hysteresis part of the MRHOF. For example, if a present parent, A, has a link cost of 120 and a rank of 256, then its total cost is 376. Let the PARENT_SWITCH_THRESHOLD be set at 100. Now, if a second candidate node, B, is available, with a path cost of 82 and a rank of 256, then the total cost for this candidate B is 338. In spite of the lower cost, the preferred parent will not be switched to B since the difference in cost between A and B is 38, which is lower than the specified threshold of 100.

Objective function zero (OF0): Depends on the hop count as a metric with which to make routing decisions. A candidate parent with the lowest hop count, which implies a node closest to the root, will be chosen as the preferred parent (Thubert 2012). The node will then compute its rank (Rnode) by adding a scalar Rank_increase to the rank of the selected parent, Rank(parent):

$$\text{Rnode} = \text{Rank(parent)} + \text{Rank\_increase} \tag{1}$$

The rank_increase is computed as follows:

$$\text{Rank\_increase} = (\text{Rf} \times \text{Sp} + \text{Sr}) \times \textit{MinHopRankIncrease} \tag{2}$$

where Rf is the rank factor, Sp is step_of_rank, and Sr is stretch_of_rank. Rf and Sr are normalization factors with default values of 1 and 0, respectively. Sp has a default value of 3 and *MinHopRankIncrease* has a value of 256.

For instance, if a node, A, received a DIO message from a node, B, whose rank is 256, then an RPL implementation with the OF0 will choose B as the parent node; the rank of A will be computed as 1024.

Both of these objective functions have the shortcoming of only considering a single metric for routing decisions (Kuwelkar and Virani 2019). They lack the holistic approach essential for providing QOS. To overcome this, the RPL specification has provided designers with the flexibility to incorporate more metrics into the decision-making process, and we will see in later sections how this can be done.

The devices in IoT infrastructure have severe resource constraints. Hence, to mitigate the control traffic in a network, the DIO messages are transmitted after an interval that increases exponentially, as determined by the trickle algorithm described below:

Trickle algorithm: A trickle timer is used, which runs for a definite interval depending on three configuration parameters:

(a) Imin, the minimum interval size denoted in units of time, such as seconds or milliseconds.
(b) Imax, the maximum interval size specified in terms of the number of doublings of Imin.
(c) k, a redundancy constant which is an integer greater than zero.

Besides these, three other parameters are involved: the current interval size, I, a counter, c, and the time, t, within the current interval. At the start of the execution, the current interval, I, is set to a value in-between the range of [Imin, Imax]. When the interval starts the counter, c, is reset to zero, and the time, t, is set to a random value between [I/2, I]. When trickle receives packets consistently, the counter, c, is incremented monotonically and, at time t, trickle transmits if the value of the counter, c, is less than k (Levis et al. 2011). Each time the interval, I, expires, its value is doubled till it reaches the value of Imax, after which it is maintained constant at Imax. If trickle senses an inconsistent transmission, then it resets the timer by setting I to Imin and starts a new interval.

2.1. Open Issues in the RPL

In the previous section we have seen the key functionalities of the RPL. Now we will discuss some open issues in the RPL which have been reported by researchers working in this domain.

(a) The standard RPL uses an objective function that depends on a single metric, the MRHOF on the ETX and the OF0 on the hop count, to make a routing decision (Kamgueu et al. 2013). The other parameters, such as node energy or delay, are not considered when selecting the best parent. This can lead to a non-optimal node being repeatedly selected as a parent, thus depleting it of its energy. This can adversely affect the network lifetime (Gaddour et al. 2015). These standard objective functions tend to overlook the latency aspect during parent selection. As a result, for applications with real-time data delivery requirements, these standard OFs are proven to be inefficient (Lamaazi and Benamar 2020).

(b) The RPL has an inherent load balancing issue. The number of children nodes assigned to a particular parent can be much higher than that of some other parents. This will exhaust parents' energy and reduce overall network performance. There is no defined scheme in the RPL that regulates the number of children nodes across available parents (Kumar and Hariharan 2020).

(c) The RPL employs the passive link estimation technique, where the number of required retransmissions (ETX) is used to determine link quality (Ancillotti et al. 2014). This is inaccurate as compared to active link monitoring techniques, can converge slowly, and may lead to the RPL choosing long and unreliable links due to incomplete knowledge of neighborhoods (Ancillotti et al. 2017).

(d) The mobile IoT has recently gained popularity, but since the RPL was primarily designed for stationary applications adapting to the dynamic and fluctuating nature of mobile applications is a challenge (Mohammadsalehi et al. 2021). Many researchers have contributed to tuning and providing mobility support for the RPL; however, gaps still exist before it can be made a standard for the mobile IoT (Sanshi and Cd 2019).

(e) In heterogenous networks nodes have diverse hardware specifications, especially regarding their transmission and reception queue buffers (Shirbeigi et al. 2021). The RPL does not differentiate between homogenous and heterogenous networks, which can lead to unbalanced traffic loads and congestion in networks (Shreyas et al. 2019)

(f) In the construction of downward routes, DAO messages play an important role. The RPL does not explicitly specify the timing of DAO transmissions. This may lead to improper employment of the protocol, leading to unproductive results (Ghaleb 2019). In an implementation of the RPL, if a root does not receive DAO messages from all of the intermediate nodes along a path, then it will not be able to determine the source route to that destination.

(g) The RPL is subjected to security attacks, such as neighbor DIS, replay attacks, route table falsification, local repair, DAO inconsistency, version number, rank, worst parent, DIS, routing table overload, and DAG inconsistency (Farzaneh et al. 2020). Several mechanisms are proposed to tackle the security issues in the RPL.

2.2. QOS Requirements for Sustainable Networks

Let us first consider the properties of a sustainable network infrastructure essential for meeting quality of service. The main criteria are as follows:

Energy efficiency: A network is sustainable if it is energy-efficient. Deployed nodes are basically battery-operated. This being the case, minimal energy consumption should happen during network operation and communication to ensure a longer lifetime. Nodes that have higher residual energy must be involved in the construction of routes. Nodes with lower levels of energy should be avoided and not drained further. The routing process should be sensitive to the battery levels of nodes in order to extend the lifetime. For any given network, energy efficiency can be determined by computing residual energy, power consumption (average), and network lifetime (Kechiche et al. 2019)

Reliability: In a network, sensor nodes collect crucial information and transmit it to the sink. A good route should ensure that all of this information reaches the gateway or sink without any loss. The route has to be reliable, with a minimal number of packets getting dropped. The quality of links connecting the nodes in LLNs determines the reliability. It can be determined using link estimators such as the RSSI (received signal strength indicator), number of packets dropped, packet delivery ratio (PDR), and expected number of transmissions for successful delivery (ETX).

Real time: The time a message takes to reach the sink should be as small as possible. For applications which operate in real time, this is a crucial factor. A good route should have low end-to-end delay or latency.

In optimization, we generally observe a trade-off, which means that if we try to improve one factor then some other factor degrades. This makes routing optimization a challenging task. For example, a good reliable route may take more hops, which adversely affects the latency. For sustainable architecture, the main focus is to achieve a balance so that all of the above criteria are met.

Some of the key parameters chosen to determine the efficiency of a network's implementation are as follows:

Packet delivery ratio (PDR): In wireless sensor networks, the sensed data are transmitted continuously to root nodes by individual motes. If data rates are high, then some packets are dropped owing to buffers being full and collisions. The ratio of packets actually received at the root node to the total packets sent is called the packet delivery ratio. The PDR is expressed via the following equation:

$$PDR = \frac{Total\ Packets\ Received}{Total\ Packets\ Sent} \times 100 \quad (3)$$

Power consumption (average) (Pavg): Hundreds of sensor motes deployed within a network consume varying amount of power depending on their activity, placement, topology, and distance from root. The network lifetime is inversely proportional to the average energy consumed by all of the motes. The lower the power consumed, the longer the network lifetime will be. The power consumption, Pavg, is computed by measuring the LPM power, CPU power, transmit power, and listen power, in addition to averaging them for all of the nodes.

Latency: The time it takes for a data packet to travel from the sender node to the receiver sink node is called end-to-end delay or latency. If we average the delays of all of the nodes within a network, we obtain the average latency, as given below:

$$Average\ latency = \frac{Total\ Latency}{Total\ Packets\ Received} \quad (4)$$

The total latency is obtained as follows:

$$Total\ Latency = \sum_{k=1}^{n} (Recv\ time\ (k) - Sent\ time\ (k)) \quad (5)$$

3. Means and Methods of Soft Computing for RPL Enhancement

Soft computing techniques deal with partial truth, uncertainty, imprecision, and approximation to provide solutions to complex real-life problems. The RPL specification is not rigid and allows designers the flexibility to acclimatize according to needs of a particular application within a defined framework. Adopting computationally extensive traditional methods with which to tune the RPL may not be the best alternative, since the devices have severe computing constraints. This makes soft computing a suitable option with which to enhance the RPL.

The term "soft computing" was coined by Dr. Lotfi A. Zadeh in 1980. It consists of a set of algorithms, including fuzzy logic, artificial neural networks, evolutionary algorithms, and expert systems. Soft computing finds applications in control systems, consumer electronics, healthcare, weather forecasting, robotics, stock market prediction, facial pattern recognition, automotive systems, and manufacturing (Ibrahim 2016). In this section we discuss how evolutionary algorithms, fuzzy logic, and artificial neural networks can be applied to improve the RPL.

3.1. RPL Enhancement Using Fuzzy Logic

The concept of fuzzy logic was proposed by Lotfi Zadeh in 1965, and was applied in the control of steam engines by Mamdani in 1974. Fuzzy logic became practically useful in 1990s, where many leading companies started using fuzzy logic to design smart appliances. Fuzzy logic closely represents the reasoning or decision-making ability of a human mind. In contrast to a traditional computer, fuzzy logic deals with a range of possibilities between "TRUE" and "FALSE". A fuzzy logic system is shown in Figure 3.

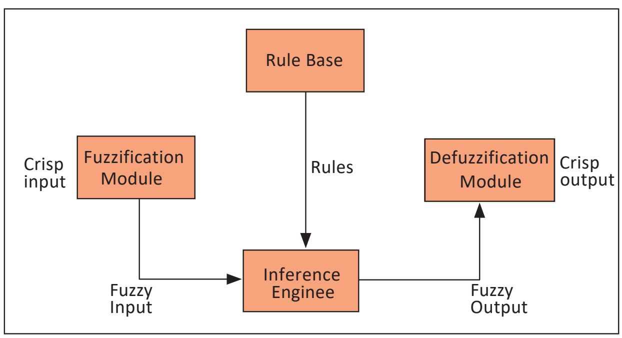


Figure 3. Fuzzy inference system. Source: Reprinted from Kuwelkar and Virani (2021b), used with permission.

The fuzzy logic architecture consists of the following components:

1. Fuzzifier: This unit converts crisp inputs into fuzzy sets. Crisp inputs are defined with linguistic variables and denoted graphically using membership functions. Membership functions depict the degree of membership of an input value in a particular fuzzy set. Some commonly used membership functions are Gaussian, trapezoidal, triangular, sigmoidal, and generalized bell.
2. Rule base: This is an exhaustive collection of all of the rules that govern the decision-making process in the fuzzy inference system. The rules are defined using IF–THEN conditions and operators such as AND, OR, and NOT.

3. Inference engine: This component of the FIS determines the specific set of rules triggered by a given input. The fuzzy output is generated by applying these rules to the input.
4. Defuzzifier: The fuzzy output is transformed into an explicit crisp output during defuzzification. This is the final stage of a fuzzy logic system. Some common defuzzification methods employed are bisector, centroid, smallest of maximum, mean of maximum, largest of maximum, and the weighted average method.

3.1.1. Metrics in the RPL

Earlier, we discussed the limitations of the standard RPL which uses an objective function that depends on a single metric, such as the path cost or hop count, to make routing decisions. To overcome this limitation, several researchers have proposed combining two, three, or more metrics using fuzzy logic to make the preferred parent selection. Some of the metrics which have been used in combination are:

1. Node residual energy (RE or RER): This metric is a measure of the remnant battery level of a sensor node. By considering this metric it is possible to avoid the selection of parents with lower energy levels. This is most desirable in networks with energy efficiency concerns. The residual energy (RE) is given as follows:
$$RE = Eo - Ec \tag{6}$$
2. End-to-end delay or latency: The average time required for a packet to travel from sender to destination is called latency. It is particularly crucial in real-time applications to have a very low delay.
3. Expected transmission count (ETX): The number of retransmissions expected before a data packet is successfully delivered to a sink node is termed the ETX, which is a rough estimate of the link quality. A lower ETX value signifies a reliable and good link. It is given by the following formula:
$$ETX = \frac{1}{df \times dr} \tag{7}$$
where *df* is the probability of the successful delivery of a packet in the forward direction and *dr* is the probability of successfully receiving an acknowledgement.
4. Hop count (HC): This is a measure of the distance between a DODAG root and node in terms of the number of hops. IoT applications that have real-time execution constraints prefer low hop counts for faster processing.
5. RtMetric: Multiple paths exist between a pair of nodes. Depending on the routes chosen by nodes, the congestion level for every route would be different.

Rtmetric is a cost associated with every route within a network. The protocol will use this route metric to select a path with the least congestion (Shreyas et al. 2019).

6. Buffer occupancy (BO): Every node within a wireless sensor network may have different rates of packet arrival and transmission. Hence, each node has buffers with which to store and forward packets. Buffer occupancy, BO, denotes the number of packets queued at a buffer for re-transmission.
7. Received signal strength indicator (RSSI): This metric is associated with the RF transceiver signal power. Basically, the RSSI is the strength of a signal over the link between two neighboring nodes. It is an important factor in mobile networks. The nodes use a CC2420 radio chip for communication, which has an in-built RSSI register. By reading this register the RSSI value can be measured. Before the RSSI VALID bit is set, the $RSSI_{VALUE}$ is averaged over a minimum of eight symbol periods and is given through the following:

$$RSSI = RSSI_{VALUE} + RSSI_{OFFSET} \tag{8}$$

where $RSSI_{OFFSET}$ is the front-end gain, computed analytically by manufacturers.
8. Mobility timer (MT): If a radio link within a mobile environment, responsible for forwarding packets to a DODAG root, suddenly becomes unavailable due to the movement of that node, then all of the forwarded packets will be dropped. This problem will persist until a new link is identified or the link failure is detected. A metric, termed mobility timer, MT, is introduced to address this issue. The value of mobility timer is calculated based on the distance between a mobile node and the candidate parent node (CPN), considering the maximum speed that this mobile node can attain (Sanshi and Cd 2019). The approximate distance between a mobile node and the CPN can be computed from the RSSI equation as follows:

$$RSSI = -10\, n \log(D) + C \tag{9}$$

where D is the approximate distance, C represents the fixed constant, and n is the path loss exponent factor. The remaining distance (RD) before losing connectivity with the CPN is calculated by subtracting the approximate distance, D, from the CPN's communication range, CR:

$$RD = CR - D \tag{10}$$

Later, to compute the value of mobility timer, we have to divide the remaining distance, *RD*, by the MN's max speed, *S*:

$$MT = RD/S \tag{11}$$

9. Children number (CN): The number of children affiliated to a particular parent or neighbor node are reflected by this metric. Ideally, the number of children has to be distributed uniformly in order to avoid the saturation or overloading of few parents. Using this metric during routing allows load balancing to be carried out by promoting the selection of a less loaded neighbor as the parent. The CN can be calculated by monitoring the ICMPv6 messages, particularly the DAO and DAO-ACK messages exchanged, to cancel or confirm a candidate parent during the selection process (Kechiche et al. 2019).

3.1.2. Fuzzy Logic to Overcome the Limitation of Single-Metric-Based Objective Functions in the RPL

To enhance the performance of the RPL for a sustainable implementation of the IoT, metrics from the above list can be combined by using fuzzy logic. Many studies have proposed a new, improved objective function for the RPL that employs either two, three, or four metrics to make a routing decision.

In this section, we discuss in detail one such work (Kuwelkar and Virani 2021b), which proposes an improved objective function, OF-FZ, that utilizes four metrics for decision making during routing. The four metrics chosen are the ETX, HC, delay, and RE. The ETX is a measure of reliability, HC and delay are measures for real-time requirements, and RE is linked with energy efficiency. Hence, these four, when included in a routing decision, will guarantee quality of service. They are fed to a fuzzy logic controller to acquire a single output quantity quality assurance (QA) score, which will be used as a criterion for selecting the preferred parent during routing. This process is executed in two stages, as shown in Figure 4.

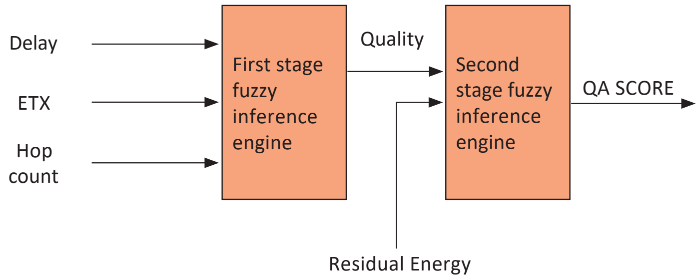


Figure 4. Two-stage fuzzy process. Source: Reprinted from Kuwelkar and Virani (2021b), used with permission.

The following steps are followed in the fuzzy process:

Step 1: Specify the linguistic variables for the inputs to the FIS. The linguistic variables short, average, and long are used to define the ETX input, and the range chosen is one to fifteen. Hop count is defined by using the linguistic fuzzy sets near, average, and far, with a range of one to five. Delay is represented by using the linguistic variables small, average, and high, with a range from 0 to 3000 units. The fuzzy sets used to define the residual energy, RE, are low, medium, and full. The highest energy level is 255. Some very commonly used membership functions with which to quantify the linguistic terms are triangular and trapezoidal. In this case, trapezoidal membership functions are favored for all four inputs—the ETX, HC, delay, and residual energy—as shown below in Figure 5.

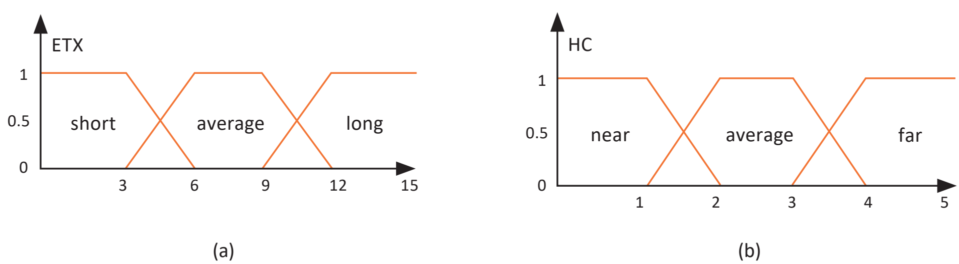


Figure 5. *Cont.*

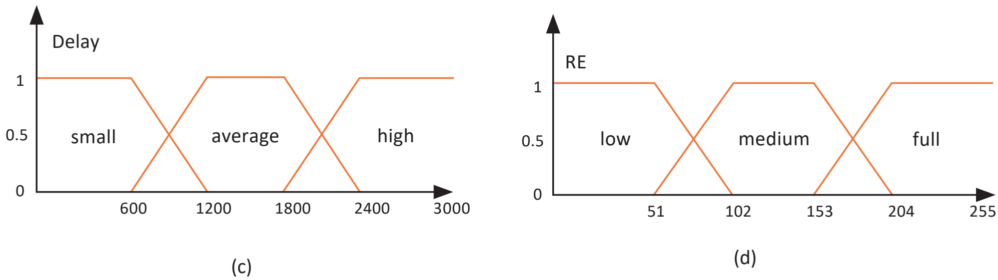


Figure 5. (**a**) ETX, (**b**) HC, (**c**) delay, and (**d**) residual energy membership functions. Source: Reprinted from Kuwelkar and Virani (2021b), used with permission.

The Equations (12)–(14) define the level of membership in the ETX fuzzy sets short, average, and long as follows:

$$\mu\ (short)\,(ETX) = \begin{cases} 0, & ETX > 6 \\ \frac{6-ETX}{6-3}, & 3 \leq ETX \leq 6 \\ 1, & ETX \leq 3 \end{cases} \tag{12}$$

$$(avg)\,(ETX) = \begin{cases} 0, & ETX < 3\ or\ ETX > 12 \\ \frac{ETX-3}{6-3}, & 3 \leq ETX \leq 6 \\ 1, & 6 \leq ETX \leq 9 \\ \frac{12-ETX}{(12-9)}, & 9 \leq ETX \leq 12 \end{cases} \tag{13}$$

$$\mu\ (long)\,(ETX) = \begin{cases} 0, & ETX < 9 \\ \frac{ETX-9}{12-9}, & 9 \leq ETX \leq 12 \\ 1, & ETX > 12 \end{cases} \tag{14}$$

The Equations (15)–(17) define the level of membership in the delay fuzzy sets small, average, and high as follows:

$$\mu\ (small)\,(Delay) = \begin{cases} 0 & ,\ Delay > 1200 \\ \frac{1200-Delay}{1200-600} & ,\ 600 \le Delay \le 1200 \\ 1 & ,\ Delay \le 600 \end{cases} \tag{15}$$

$$\mu\ (avg)\,(Delay) = \begin{cases} 0\ , & Delay < 600\ or\ Delay > 2400 \\ \frac{Delay-600}{1200-600} & ,\ 600 \le Delay \le 1200 \\ 1\ , & 1200 \le Delay \le 1800 \\ \frac{2400-Delay}{2400-1800} & ,\ 1800 \le Delay \le 2400 \end{cases} \tag{16}$$

$$\mu\ (high)\,(Delay) = \begin{cases} 1 & ,\ Delay > 2400 \\ \frac{Delay-1800}{2400-1800} & ,\ 1800 \le Delay \le 2400 \\ 0 & ,\ Delay \le 1800 \end{cases} \tag{17}$$

The equations that determine the levels of membership in the RE and hop count fuzzy sets can be written in a similar manner.

Step 2: Next, a set of rules have to be formed that will define the relationship between inputs and outputs. The FIS database stores these rules. The inputs are combined using AND, OR, and NOT operators, along with IF–THEN conditions, to obtain the rules.

Here, Stage 1 has three fuzzy inputs: hop count (HC), delay, and the ETX. Each one is characterized by three fuzzy sets each; therefore, the Stage 1 rule base will consist of 3^3 = 27 rules. The output of Stage 1 is Quality, and it is comprised of five fuzzy sets, namely very_slow, slow, average, fast, and very_fast. The rules are built using the AND (&&) and OR (| |) operators, in addition to IF–THEN conditions.

Out of the total 27 rules that relate the inputs with the output Quality, some are shown below:

1. If (HC == near) && (ETX == short) && (Delay == small) then (Quality = very fast)

2. If ((HC == average) && (ETX == short) && (Delay == small) then Quality = fast) | | If ((HC == average) && (ETX == short) && (Delay == average) then Quality = fast).
3. If ((HC == near) && (ETX == short) && (Delay == high) then Quality = average) | | If ((HC == average) && (ETX == average) && (Delay == average) then (Quality = average)
4. If ((HC == far) && (ETX == long) && (Delay == average) then Quality = slow) | | If ((HC == far) && (ETX == average) && (Delay == high) then Quality = slow).
5. If (HC == far) && (ETX == long) && (Delay == high) then (Quality = very_slow).

The Quality obtained in Stage 1 is combined with the RE in Stage 2 in order to obtain the output quantity quality assurance score. The linguistic terms for the QA score are very_bad, bad, degraded, average, satisfactory, good, and excellent. Figure 6 shows the membership functions of Quality and the QA score. The QA score is computed using the rules defined as per Table 1.

Table 1. QA score rule table.

Quality/RE	Low	Medium	Full
very_slow	very bad	Bad	average
slow	bad	Degraded	average
average	degraded	Average	satisfactory
fast	average	satisfactory	good
very_fast	average	Good	excellent

Source: Authors' compilation based on their research work.

(a)

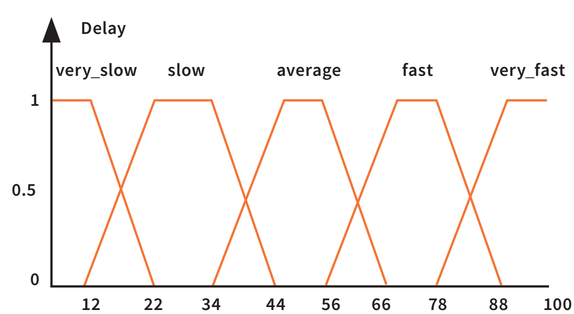


Figure 6. *Cont.*

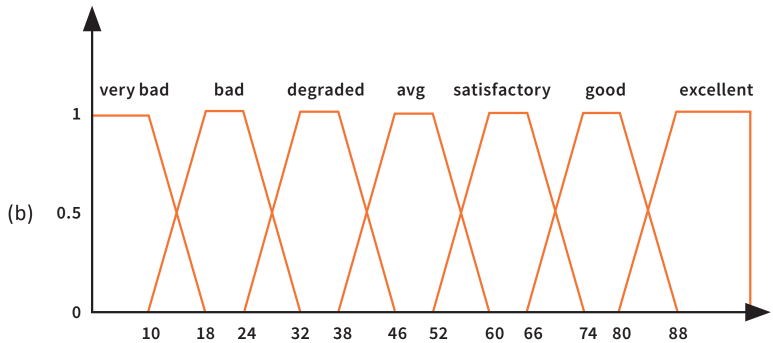


Figure 6. (**a**) Quality and (**b**) QA score membership functions. Source: Reprinted from Kuwelkar and Virani (2021b), used with permission.

The range of the QA score is between 0 and 100. A higher value is an indication of a better-quality parent node. A quality assurance score is computed for each candidate parent in the list by invoking the FIS. When a choice of more than one candidate exists, the one that achieves the higher QA score is selected as the preferred parent.

Step 3: The crisp value for the quality assurance score is computed by defuzzification by using the centroid formula:

$$M = \frac{\sum_{i=1}^{n} Wi \times \mu\ (Wi)}{\sum_{i=1}^{n} \mu\ (Wi)} \tag{18}$$

where M is the crisp value, Wi is the center of gravity of the activated fuzzy set, the number of activated rules is given by n, and μ is the membership value for activated rules computed using max(min) implication. This process works on the Mamdani and Assilian (1975) model.

To understand the fuzzy process working mathematically, consider an example. Let node N1 have two parent choices, P1 and P2, with metric values as shown in Figure 7. Assume a candidate parent, P1, with delay = 1000, the ETX = 2, hop count = 2, and residual energy = 200. Initially, Stage 1 of fuzzification is invoked and Quality is computed. The ETX of 2 belongs to the short fuzzy set, with μ = 1. The delay of 1000 belongs to the small and average sets, with μ = 0.33 and μ = 0.667, respectively. HC = 2 belongs to the average set, with μ = 1. Equations (12)–(17), listed above, are used for computing the μ (membership values). For Quality, four rules are activated, with "fast" and "very_fast" values triggered. From max(min) implication, Rule 1 results in a value of 0.333, the value of Rule 2 is 0.667, that of Rule 3 is zero, and that of Rule 4 is zero. The centroid formula is applied to calculate the crisp value of Quality, Q:

$$Q = \frac{0.333 \text{ x } 72 + 0.667 \text{ x } 72 + 0 \text{ x } 94 + 0 \text{ x } 72}{0.33 + 0.667 + 0 + 0} = 70$$

where 94 and 72 are the centers of gravity for "very_fast" and "fast", respectively. During Stage 2 of fuzzification, a residual energy of 200 belongs in the fuzzy sets "full" and "medium", with values of 0.9216 and 0.078, respectively. The computed quality of 72 in Stage 1 belongs to the fuzzy set "fast", with a value of 1. The QA score is activated by the triggering of two rules with "good" and "satisfactory" values. Using the max(min) implication, Rule 1 results in a value of 0.9216 and Rule 2 has a value of 0.078. Applying the centroid formula, we compute the QA score as follows:

$$QA \; score \; = \frac{0.078 \text{ x } 63 + 0.9216 \text{ x } 77}{0.078 + 0.9216} = 75.9$$

where 77 and 63 are the centers of gravity for the QA score fuzzy sets "good" and "satisfactory", respectively.

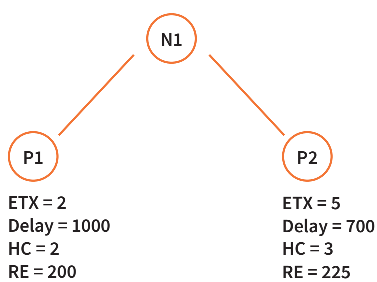


Figure 7. Node with candidate parents. Source: Adapted from Kuwelkar and Virani (2021b), used with permission.

When a node receives a DIO message from a neighboring node, the entry of this neighbor is made in the candidate parent list. The values of the ETX, delay, RE, and hop count for this particular neighbor are extracted from the received DIO message. If more than one candidate is present in the list, then the FIS is invoked and the quality assurance score for all of the candidates is computed. The one with the highest QA score is chosen as the preferred parent node. Suppose for a particular candidate, 1, that the QA score is 78, and that for another candidate, 2, the QA score is 65. Consider that the present parent node had a QA score of 70. This being the case, candidate 1 will be chosen as the new best parent, as it has the highest score among the three. The rank will be computed based on the rank of selected parent. The preceding parent is substituted by the new one and the updated DIO message is broadcasted to its neighbors. This technique gives 9% lower power dissipation, 7% better packet delivery ratios, and 8% lower latency, as shown in Figure 8 where the OF-FZ is the four-metric-based fuzzy improved objective function. The Contiki-OS-based COOJA simulator is used to perform the performance evaluations. The packet rate is set to 5 ppm. The T-mote Sky platform is used in network emulation, and the density is varied from 30 to 100 nodes. A single sink node is used, and the packet length is 128 bytes. In this scenario, the routing process comprising four metrics is thus a holistic approach to ensure quality of service.

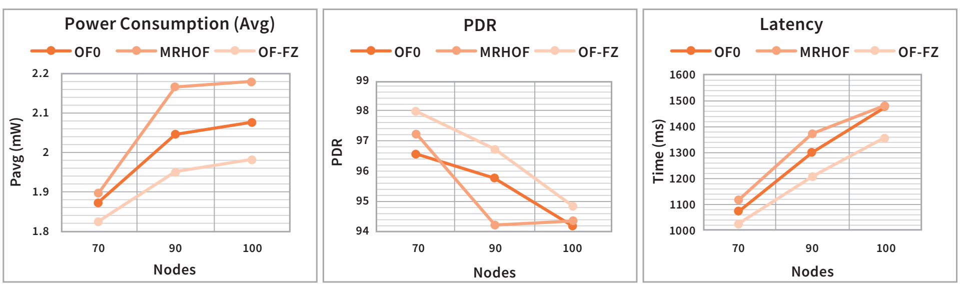


Figure 8. Average power consumption, packet delivery ratio, and latency for the standard RPL and OF-FZ. Source: Reprinted from Kuwelkar and Virani (2021b), used with permission.

3.1.3. Fuzzy Logic to Overcome the Limitation of Mobility in the RPL

The RPL is not optimized for mobile nodes (MNs) and is subject to frequent disconnection in communicating links between mobile nodes. To overcome this issue, an improvement, FL-RPL, is suggested [19], which enhances the reliability and responsiveness of the RPL, thus providing support for mobility. In this work, four metrics, namely the received signal strength indicator (RSSI), residual energy (RE), the ETX, and mobility timer, are chosen as inputs to the fuzzy inference system. Figure 9 shows the membership functions for all four inputs.

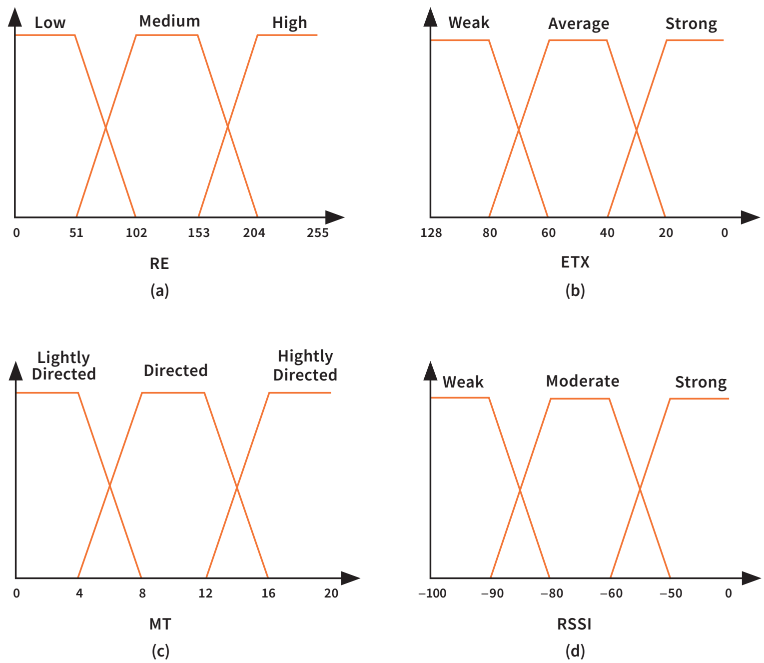


Figure 9. Membership functions of (**a**) RE, (**b**) the ETX, (**c**) MT, and (**d**) RSSI. Source: Reprinted from Sanshi and Cd (2019), used with permission.

The RSSI and mobility timer metrics serve as key factors in providing mobility support to the RPL. The RSSI metric gives an estimate of the signal strength between the node and the candidate parent. Mobility timer indicates the tentative time before a mobile node loses connectivity from a candidate parent. Both of these metrics help mobile nodes in choosing parents that exhibit a strong signal strength and better connectivity for prolonged durations. The FL-RPL works by eliminating weaker parents from the list.

This method uses four fuzzy inputs, and each input is linked with three fuzzy sets; therefore, the rule base consists of $3^4 = 81$ rules. A few rules out of the 81 are defined as follows:

1. IF (MT is lightly directed) and (RE is low) and (ETX is weak) and (RSSI is weak) THEN (confidence score is very_low).
2. IF (MT is directed) and (RE is medium) and (ETX is average) and (RSSI is moderate) THEN (confidence score is moderate).
3. IF (MT is highly directed) and (RE is high) and (ETX is strong) and (RSSI is strong) THEN (confidence score is very_high).

In a similar way, the other rules can be listed by using combinations of different fuzzy sets. The output of the fuzzy inference system after defuzzification is a parameter known as the confidence score. The output has seven fuzzy sets, namely very low, low, moderate low, moderate, moderate high, high, and very high. This score defines the confidence with which a candidate will be selected as the preferred parent. The candidate that results in the highest confidence score will be chosen as the best parent. The confidence score membership function in shown in Figure 10.

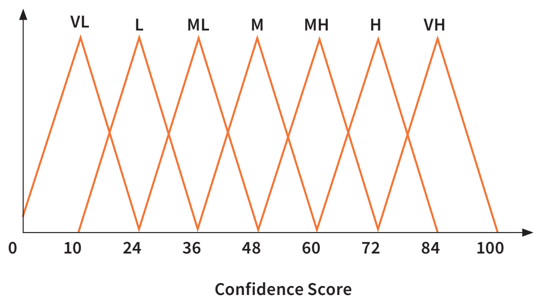


Figure 10. Membership function of the output variable. Source: Reprinted from Sanshi and Cd (2019), used with permission.

The fuzzy inference system is invoked every time a new DIO message is received from a candidate parent or when the freshness timer associated with a chosen parent node expires. The flowchart in Figure 11 shows the parent selection process.

At the start, DIO messages are solicited from neighbors by broadcasting DIS messages in the network. If a DIO message is received from a neighboring node, this neighbor is added as a candidate parent to the list and routing metrics are extracted. The value of the RSSI is obtained, which is then used to compute the approximate value of MT. The freshness timer for this candidate is initialized. If no other candidates are present in the list, then this neighbor is chosen as the preferred parent. Otherwise, the fuzzy inference system is invoked and the confidence score is calculated for all of the candidates. The candidate parent with the highest confidence score is selected as the parent. In cases where a node receives another DIO message from an already-present candidate parent in the list, then the freshness timer values for this CPN are updated. When the current parent node's freshness timer expires, the FIS is invoked and a new parent is selected from among the candidates. Any CPN whose freshness timer expires is omitted from the candidate list.

This improved version of the RPL was tested by using the COOJA simulator in Contiki OS and compared with the standard version. The simulation results clearly confirm that the FL-RPL increases the PDR by 12% and reduces power consumption by 20%. Incorporating metrics such as the RSSI and mobility timer in routing decisions provides the necessary mobility support for the RPL.

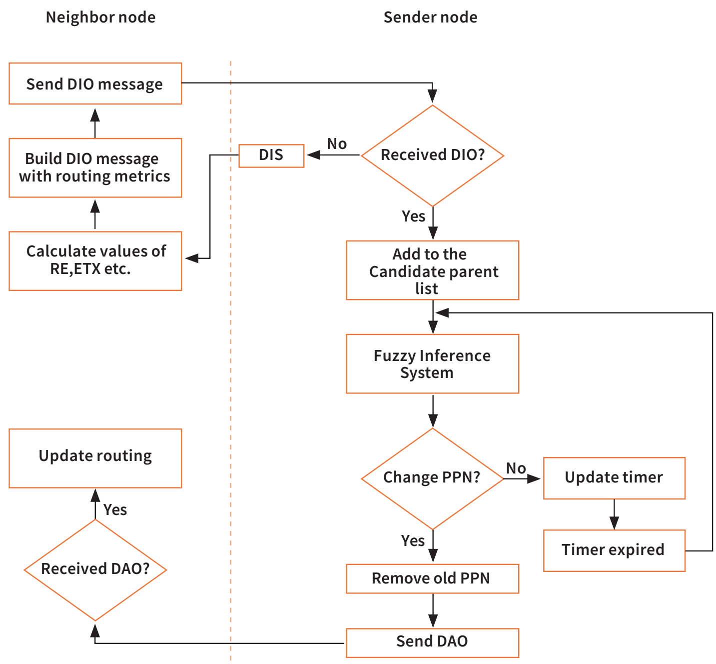


Figure 11. Route construction in the FL-RPL. Source: Reprinted from Sanshi and Cd (2019), used with permission.

3.1.4. Fuzzy-MADM to Overcome the Limitation of Load Balancing and Congestion in the RPL

In IoT networks, a large density of nodes and higher data rates cause congestion. Every node has a buffer associated with it to store and forward packets. If the buffer becomes full then the packets which come in later are dropped. This reduces the packet delivery ratio and affects the network performance. The RPL does not ensure load balancing, so the distribution of children is not uniform among the parent nodes. If a parent, 1, had five children nodes and some other parent, 2, has three children, the chances of the parent 1 buffer becoming full are higher as compared to parent 2. To overcome this issue, a metric called buffer occupancy is utilized in this method (Shreyas et al. 2019) to ensure uniform distribution. It corresponds to the number of packets queued at the buffer of a node for transmission. Another metric used is Rtmetric, which is a measure of the congestion on any particular route. Along with buffer occupancy and Rtmetric, the ETX metric is also used for decision making during routing. It is modeled as a multi attribute decision-making problem (MADM) using a fuzzy weighted sum model (Pahlavani 2010).

A typical fuzzy multi attribute decision-making (MADM) problem consists of m possible alternatives, *A1, A2, . . . , Am*, which must be examined with respect to n attributes, *C1, C2, . . . , Cn.* The attribute weights or weighting factors are denoted by *w1, w2, . . . , wn*. In a fuzzy MADM problem the key feature is a decision matrix, *D*:

$$D = \begin{bmatrix} y11 & \cdots & y1n \\ \vdots & \ddots & \vdots \\ ym1 & \cdots & ymn \end{bmatrix} \tag{19}$$

where *yij* represents the assessment of the alternative *Ai* under the attribute *Cj*. It can be an approximate number, interval, crisp number, or linguistic words.

Consider that P = {pi, i = 1, 2, 3, . . . , n} is a finite set of parents for a node. The set of metrics for each parent is denoted by R = {rj, j = 1, 2, 3}. In this technique, Rtmetric, the ETX, and buffer occupancy are chosen as the routing metrics. Rtmetric gives an indication of the congestion on a route and BO is a measure of the buffer space availability at a parent. Including these two along with the ETX makes the routing process congestion aware and provides a uniform distribution of children nodes. In the weighted sum model weights are associated with the metrics, which is represented by a weight vector: W = {wj, j = 1, 2, 3}.

The decision matrix, A_{WSM}, is a representation for MADM parent selection. In this case, a (N $\times$ 3) matrix, *M*, is selected to represent the metrics. Each element, Vj(ai), represents the value of the jth routing metric for the ith parent for all i = (1, 2, 3, . . . , N) and j = (1, 2, 3). The matrix, M, is represented as follows:

$$M = \begin{bmatrix} V_1\left(a_1\right) V_2\left(a_1\right) V_3\left(a_1\right) \\ V_1\left(a_2\right) V_2\left(a_2\right) V_3\left(a_2\right) \\ V_1\left(a_n\right) V_{2(a_n)} V_3\left(a_n\right) \end{bmatrix} \tag{20}$$

The matrix, *M*, is multiplied with the weight vector matrix, *W*, to obtain the decision matrix, A_{WSM}:

$$A\text{WSM} = M \times W \tag{21}$$

$$AWSM = \begin{bmatrix} V_1\,(a_1)\; V_2\,(a_1)\; V_3\,(a_1) \\ V_1\,(a_2)\; V_2\,(a_2)\; V_3\,(a_2) \\ V_1\,(a_n)\; V_{2(a_n)} V_3\,(a_n) \end{bmatrix} \times \;\; W \tag{22}$$

For an individual parent, Pi, the A_{WSM} will be computed as follows:

$$AWSM(i) = ETX(i) \times W_{ETX} + BO(i) \times W_{BO} + rtMetric(i) \times W_{rtMetric} \tag{23}$$

The ETX, BO, and Rtmetric values are obtained for all of the candidate parents in the list from the DIO message. Using the decision matrix and weight matrix, the AWSM values are calculated for all of the candidates. As the ETX is a measure of link quality, the lower the value the better the candidate. A low BO value indicates better space availability at the candidate buffer. Additionally, a candidate with a low Rtmetric value signifies a less congested route. The above being the case, among the available candidates the one with the lowest value of the AWSM is selected as the best parent for routing. This method provides improvements in packet delivery to the tune of 5% as compared to the standard RPL. The networks were tested in the COOJA simulator with data rates of six packets/sec. An application with payload of 30 bytes is executing on each node. The UDP transport layer protocol was used. A buffer size of eight packets was set at each node.

Figure 12 shows the networks constructed using the standard RPL and this improved version of the RPL. It can be seen that the network employing the improved RPL has a more uniform distribution of children nodes.

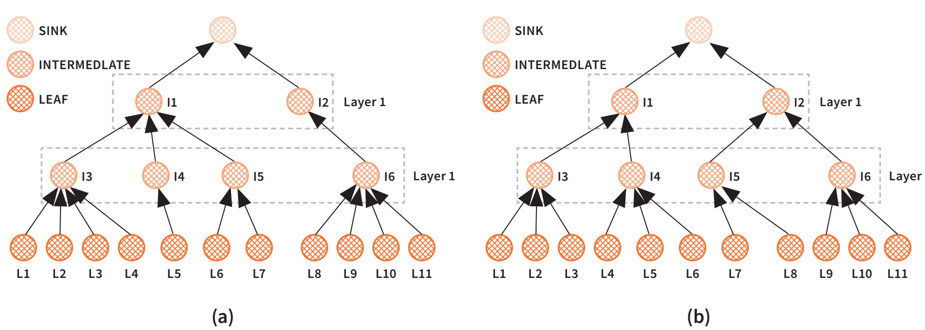


Figure 12. Networks constructed using (**a**) the standard RPL and (**b**) the improved version of the RPL. Source: Reprinted from Shreyas et al. (2019), used with permission.

Several other works use a fuzzy logic model to include more than one metric during routing and overcome the limitation of a single metric. In one study, the authors (Farzaneh et al. 2020) proposed a novel method with which to detect intrusion in the RPL. Fuzzy logic is used to include three metrics, namely residual energy, distance, and the expected transmission count (ETX). This method effectively detects local repair attacks with high rates of true positive and low rates of false positives. In Kechiche et al. (2019), the authors propose an opportunistic fuzzy-logic-based objective function. A novel metric, known as children number, is derived by using a fuzzy logic approach to combine the conventional expected transmission count (ETX) and hop count (HC) metrics. Lamaazi and Benamar (2018), have proposed OF-EC, a novel objective function that combines three metrics, namely energy consumption, the ETX, and hop count, using fuzzy logic and provides a composition metric based on which routing decisions are taken. Using OF-EC, RPL implementation shows improvements in terms of the network convergence time, energy consumption, latency, routing overhead, packet delivery ratio, and network lifetime. Gaddour et al. (2014), in their work have developed a holistic objective function, OF-FL, that combines hop count, end-to-end delay, link quality, and energy by using fuzzy logic. Simulations are carried out that compare the performance of OF-FL with standard RPL objective functions for network sizes up to 100 nodes. A better network lifetime, PDR, and lower frequency of parent change is achieved. Kamgueu et al. (2013), proposed combining three routing metrics—the ETX, delay, and energy—by using fuzzy logic to determine the Quality of candidate parents. This is the pioneer work that suggested the use of fuzzy logic for improving the RPL since 2013.

3.2. RPL Enhancement Using Evolutionary Algorithms

"Evolutionary algorithms" (EAs) constitute a collection of methods developed to solve optimization problems. They adapt Darwinian principles to automate problem solving. Evolutionary algorithms are metaheuristic optimization algorithms based on populations and inspired by natural evolution (Slowik and Kwasnicka 2020). The main components of EAs are populations of individuals, a problem-specific objective function or fitness function for optimization, and operations. Evolutionary algorithms include particle swarm optimization (Yang and Karamanoglu 2013), genetic algorithms, ant colony optimization (Sahani and Kumar 2013), differential evolution, and the firefly optimization algorithm. EAs have characteristics of flexibility and robustness with which to capture global solutions for complex optimization problems. The term evolutionary computation (EC) was recently adopted to epitomize the whole family of evolutionary algorithms. In this section, we provide an overview of how these evolutionary algorithms can be applied to improve the functionality of RPL implementations.

3.2.1. RPL Enhancement Using Genetic Algorithms

John Holland, University of Michigan, proposed genetic algorithms in 1960, but they only gained popularity in the 1990s. Genetic algorithms are used for solving both constrained and unconstrained optimization problems by using the concept of natural selection and biological evolution. GAs recurrently modify a population of individual solutions. At every step, the GA selects individuals from the current population as parents by using a fitness function. The selected parents will reproduce the offspring of the next generation. The population evolves towards an optimum solution over successive generations. Genetic algorithms can be applied to solve a variety of optimization problems that cannot be solved with standard algorithms, including problems in which the objective function is nondifferentiable, stochastic, discontinuous, or highly nonlinear. It can be widely used in the image processing, stock market prediction, function optimization, and machine learning application areas. Genetic algorithms use three types of operations at each step to create next-generation populations from current ones:

(a) Selection, to select the parents for reproduction based on a fitness function.
(b) Crossover, to combine two parents, thus forming offspring for the next generation.
(c) Mutation, where random changes are made to individual parents to obtain children.

In this work (Cao and Wu 2018), the authors have introduced a chaotic genetic algorithm (CGA) by introducing the mechanism of chaotic optimization into a genetic algorithm. The basic steps in a CGA are consistent with a simple GA; that is, start with a random initial population, perform a fitness calculation, select parents, perform crossover, and mutation. The inclusion of chaotic optimization effectively improves the selection of the initial population and control parameters, thus reducing the randomness of a genetic algorithm. Chaotic selection, crossover, and mutation help to constructively improve the local optimization and convergence of a GA. In a CGA, the ergodicity of a chaotic algorithm allows for a larger search sample space. The initial sensitivity of chaotic optimization helps in avoiding local optimization, thus finding an optimal global solution. Chaotic optimization algorithms utilize chaotic maps, such as a logistic map, to generate pseudo-random numbers that are mapped as the design variables for global optimization (Yang et al. 2014). A CGA was proven to be a better option in solving optimization problems as compared to a simple genetic algorithm. A CGA is applied to improve the performance of the RPL.

As we have seen in previous sections, more than one metric can be combined, and based on this composition metric the best parent decisions are made. Generally, in techniques that use weighting factors for routing metrics to obtain a composition metric, once the weights are allotted they are static and cannot be modified during runtime; however, an implementation that tunes the weights dynamically, as per network behavior and needs, would be a better option. A CGA can be applied to search for the optimum solution for the weighting factors of routing metrics during runtime. This improved version of the RPL, which applies a CGA to search for optimal weighting factors in a composition metric for evaluating candidate parents, is termed RPL-CGA.

This version of the RPL combines five metrics, as listed below:

1. *g1*(*i*): This is the ratio of the queue length in the buffer of the ith candidate, ($Q_L(i)$), to the maximum packet queue length, (Q_{Lmax}). It helps in network load balancing by avoiding parents that have less buffer space. The following equation represents *g1*(*i*):

$$g1\left(i\right) = \frac{QL\left(i\right)}{QLmax} \tag{24}$$

2. *g2*(*i*): *EED*(*i*) represents the end-to-end delay when a node is transmitting data to a root via a candidate parent, i. For (i = 1, 2, 3, . . . , n) parents, the *EED*(*i*) for all routes via different parents is determined. EEDmax is the maximum delay obtained for a route via some parent, X. The candidate with the lowest EED will be preferred as the parent. The weight factor *g2*(*i*) is the ratio of *EED*(*i*) for candidate *i* to the maximum EED, as given by following equation:

$$g2\left(i\right) = \frac{EED\left(i\right)}{EEDmax} \tag{25}$$

3. *g3*(*i*): This factor represents the ratio of residual energy (RER) for a candidate parent, i, where i = 1, 2, . . . , n. *Ecurrent*(*i*) and *Einitial*(*i*) represent the current energy of candidate parent i and the initial energy at deployment, respectively. To prolong the network lifetime it is desirable to select the candidate with higher residual energy as the preferred parent. *g3*(*i*), or RER, is given by the following equation:

$$g3\left(i\right) = 1 - \frac{Ecurrent\left(i\right)}{Einitial\left(i\right)} \tag{26}$$

4. *g4*(*i*): This is the ratio of the hop count for a particular candidate, i, to the maximum hop count between a candidate parent and root, given by the following equation:

$$g4\,(i) = \frac{HC\,(i)}{HCmax} \tag{27}$$

5. *g5*(*i*): The *ETX*(*i*) for (i = 1, 2, . . . , n) represents the expected number of retransmissions from a node to the root via a candidate parent, i. Suppose that, among the n candidate parents, a route via candidate X takes the maximum ETX; this value is then denoted as ETXmax. *g5*(*i*) is the ratio of the ETX(i) for a candidate parent, i, to the *ETXmax*, given below:

$$g5\,(i) = \frac{ETX\,(i)}{ETXmax} \tag{28}$$

The above five metrics are combined by using weighting factors to form a composition metric, *CM*. The weighting factors a1, a2, a3, a4, and a5 are used to adjust the impact of each routing metric. The function *F*(*i*)*CM*, shown below, defines the composition metric formed by individual routing metrics and weighting factors:

$$F\,(i)\,\mathrm{CM} = \sum\nolimits_{j=1}^{5} \mathrm{aj\ gj\ (I)}, \qquad for\ i = 1,\ 2,\ 3, \ldots,\ n \tag{29}$$

$$\text{Such that } \sum\nolimits_{j=1}^{5} a\mathrm{j} = 1 \text{ and } 0 \le a\mathrm{j} \le 1$$

The objective function for RPL-CGA is defined as the minimum function of the composition metric, *CM*:

$$\text{OFRPL-CGA} = \min\,(\mathrm{F(i)CM}) = \min\left(\sum\nolimits_{j=1}^{5} \mathrm{aj\ gj\ (i)}, \quad for\ i = 1,\ 2,\ 3, \ldots,\ n\right)$$

If we have *n* candidate parents and RPL-CGA employs five metrics, QL, EED, RER, HC, and the ETX, then the jth routing metric for the ith individual candidate can be denoted as *xij*, where i = 1, 2, . . . , n and j = 1, 2, 3, 4, 5. The sample set of each routing metric for each parent can be written as a matrix called the initial decision matrix:

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ x_{21} & x_{22} & x_{23} & x_{24} & x_{25} \end{bmatrix} \tag{30}$$

Using the weighting factor *aj* for every *jth* metric, the comprehensive evaluate function values, *F*(*i*), of each candidate parent can be obtained as shown below, A being the weighting factor matrix:

$$F = A\,X \tag{30a}$$

$$F\,(i) = \sum_{j=1}^{5} aj\; x\mathrm{ij}\;,\; for\;\; (i = 1, 2, 3, \ldots,\; n)\;\; and\; (j = 1, 2, 3, 4, 5) \tag{30b}$$

The candidate, *i*, with the minimum value of *F*(*i*) is chosen as the best parent. The values of the weighting factors, aj, could be obtained using multi attribute optimization algorithms, but in this work a chaotic genetic algorithm is applied to search for the optimal solution for weighting factors. In RPL-CGA, the initial population genes of weighting factors are obtained through a chaotic system. In successive steps, the population is improved through the selection of superior individuals, crossover, mutation, and chaos perturbation. Once the stopping criterion is met, the algorithm stops. At this stage, the population individuals with the maximum fitness value are the final weighting factors for the routing metrics.

The detailed steps in RPL-CGA are listed below:

Step 1: Initialization

During initialization, the parameters to be used in RPL-CGA are determined, such as the maximum number of iterations, *k*, population size, *w*, mutation probability, *Pm*, and crossover probability, *Pc*.

Step 2: Deciding the Fitness Function

In genetic algorithms the fitness function plays a crucial role in selecting the population individuals for reproduction at each step. It helps in assessing the quality of population individuals. Generally, individuals with the highest fitness values are chosen as parents for determining the next generation so that better offspring is obtained and weaker ones eliminated. This is consistent with the Darwinian theory of survival of the fittest.

In RPL-CGA the fitness function is dependent on the comprehensive evaluation function, *F*(*i*). The fitness function is defined as follows:

$$Fitness\;\;(a) = \frac{1}{1 + F\,(i)}\;\; for\;\; i = 1, 2, 3, \ldots,\; n \tag{31}$$

$$\max Fitness\,(a)\,, under\; constraints \sum_{j=1}^{5} a\mathrm{j} = 1\; and\; 0 \le a\mathrm{j}\; \le 1$$

The comprehensive function, $F(i)$, depends on the weighting factors, aj. Therefore, the variation in weighting factors will affect the fitness function. The optimal weighting factors can be determined by evaluating the maximum value of the fitness function under given constraints. At the end of a CGA, the population individual with the maximum fitness will be the optimal solution of the weighting factors.

Step 3: Generation of Initial Population Using a Chaotic System

Including the chaotic system results in better initial population values, better sequence randomness, and wider traversing of state points in a chaotic region. This work uses a representative logistic map to generate chaos perturbation vectors and initial population genes. The state equation for a chaotic system is shown in the equation below:

$$\tau_{z+1} = \eta\ \tau_z\ (1 - \tau_z),\ z = 0, 1, 2, \cdots, 0 < \tau_0 < 1, 0 \leq \eta \leq 4 \tag{32}$$

where η is the control parameter. The system goes into a chaotic state when $\eta > 3.57$ and $\tau \neq 0.25, 0.5, 0.75$, and the iteration provides results comparable to random numbers [0, 1]. In the initial population, w individuals are selected and m genes are assigned to each individual. This means that w * m population genes are chosen from the chaotic sequence generated. Each individual gene represents the weighting factor of each routing metric. In this case, m = 5 since RPL-CGA uses five routing metrics. The individual genes should meet the constraints specified above for aj. The individual population can be written as hij (i = 1, 2, 3, ..., w and j = 1, 2, 3, . . . , m).

Step 4: Selection of Superior Individuals

In RPL-CGA, once the population individuals are generated the fitness is calculated for every hi. The fitness function values, Fitness(hi), are arranged in descending order, and the topmost 15%, with higher fitness values, are taken to the next generation directly. No operations, such as crossover or mutation, are applied to them. The remaining 85% of the population for the next generation is obtained by applying the crossover and mutation operations of a genetic algorithm.

Step 5: Addition of Chaotic Perturbation

RPL-CGA adds chaotic perturbation to population individuals, with the purpose of avoiding local convergence, reducing evolution algebra, and finding optimal solutions very quickly. The chaotic perturbation is applied to only 85% of the individuals with lower fitness, according to Equation (33):

$$h' = (1 - \alpha)\, h + \alpha h'' \tag{33}$$

where h' is the new population individuals generated after adding chaotic perturbation, h is the 85% individuals generated in Step 4, h'' is an m-dimension chaotic perturbation vector selected from the chaotic series, and $\alpha \in [0, 1]$ is an adjustment factor.

Step 6: Deciding the Stopping Criterion

The RPL-CGA algorithm stops if the number of iterations reaches 100 or if the following condition is met:

$$\text{Fitness(a)max - Fitness(a)avg} \leq \epsilon \tag{34}$$

where *Fitness(a)max* is the maximum fitness value and *Fitness(a)avg* is the average of all of the values. ϵ = 0.00001 is a small positive constant. At the end of a CGA, the population individuals with the maximum fitness values will be the optimal weighting factors used in a comprehensive evaluation function, F(i), to determine the best parent among all of the candidates. The flowchart in Figure 13 shows the detailed steps followed in a CGA for computing the weighting factors.

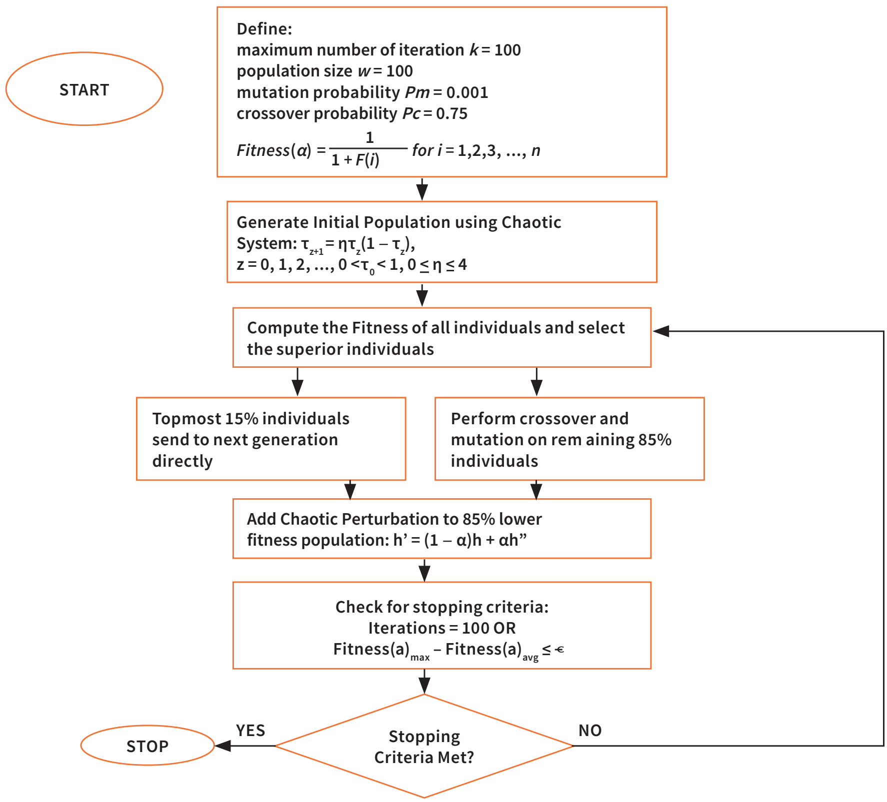


Figure 13. Flowchart of a CGA for computing the weighting factors of a comprehensive evaluation function. Source: Figure by authors.

Network simulations using OPNET show that RPL-CGA performs much better with regard to power efficiency, packet delivery success ratio, network lifetime, and delay. The graphs below, in Figure 14, indicate the superior behavior of RPL-CGA over other implementations for a simulation time of 3000 s. Chaotic Genetic Algorithm, being a computationally intensive algorithm, would require a comparatively powerful microcontroller on the motes to be deployed with a bigger memory size, which is a drawback compared to fuzzy-based implementation.

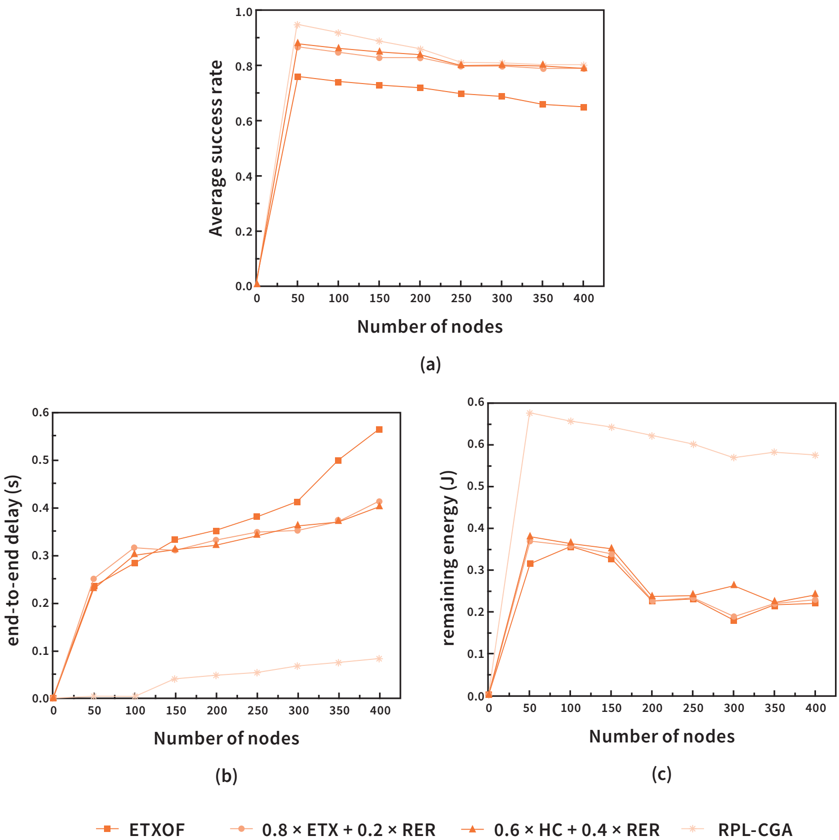


Figure 14. (**a**) Packet delivery success rate, (**b**) delay, and (**c**) average remaining energy for RPL-CGA and other implementations. Source: Reprinted from Cao and Wu (2018), used with permission.

3.2.2. RPL Enhancement Using the Firefly Algorithm

Yang (2009), proposed the firefly algorithm in 2007–2008; it is a biologically inspired metaheuristic optimization algorithm. Studies have shown that the firefly algorithm can outperform the genetic and particle swarm optimization algorithms. It has a better success rate and efficiency for solving NP-hard problems. This algorithm is inspired by the natural behavior of fireflies. In fireflies, the flashing light is produced through a bioluminescence process. The flashing light helps in communication, allowing fireflies to attract mating partners or potential prey, and possibly acts as a defensive cautionary mechanism. The flashing rhythm, flashing rate, and amount of time form part of the signaling system that attracts mates.

Light intensity at a distance, y, from the light source obeys the inverse square law, which means that light intensity decreases with an increase in the distance from the source. This makes fireflies visible for only a limited distance at night, maybe a few hundred meters, which is sufficient for fireflies to communicate. The flashing light is formulated in such a way that it can be associated with the objective function to be optimized in any optimization problem. The following assumptions are made in the firefly algorithm:

(1) All fireflies are unisex, so regardless of gender fireflies will be attracted to other fireflies.
(2) Attractiveness between two fireflies is proportional to their brightness, meaning that the less bright one will move towards the brighter one. If a firefly cannot find a brighter one then it will move randomly.
(3) The landscape of the objective function governs or determines the brightness of a firefly.

The algorithm steps can be summarized as follows:

1. The objective function is defined as follows: $f(x)$, $x = (x1, x2, \ldots, x\mathrm{d})$.
2. An initial random population, Xi, of fireflies is generated.
3. Compute light intensity, $Ii \propto f(xi)$, at xi.
4. Update each firefly position with the position update equation:

$$x_i = x_i + \beta_0{}^{-\gamma r^2_{ij}} \left(x_j - x_i\right) + \alpha \left(rand - \frac{1}{2}\right) \tag{35}$$

where r_{ij} is the cartesian distance between two fireflies, i and j, at x_i and x_j, respectively, and is given as follows:

$$r_{ij} = \|x_i - x_j\| = \sqrt{\sum_{k=1}^{d} \left(x_{ik} - x_{jk}\right)^2} \tag{36}$$

βo is the attractiveness constant, γ is the absorption constant, and α is the randomization parameter. Generally, $\beta o = 1$ and $\alpha \in [0, 1]$.

5. Perform greedy selection by using the fitness function.
6. Check if the termination criteria are fulfilled, otherwise go back to Step 3.

In this method, the firefly optimization algorithm is applied to select the best parent for forwarding the data to the root in an RPL network (Sennan et al. 2021). This proposed version is termed EEOPS-RPL. Here, the ETX and residual energy (RER) metrics are chosen as the attractiveness parameters, while the distance between nodes is chosen as the movement parameter, to select the optimal parent in a DODAG. EEOPS-RPL provides faster convergence and a longer network lifetime.

All of the nodes in the network are considered to be fireflies. The fitness function or objective function is chosen as follows:

$$F(i) = w_1 \text{ x } RER(y_i) + w_2 \text{ x } ETX(y_i) \quad (37)$$

where *w1* and *w2* are the weights chosen for RER and the ETX.

The steps followed in EEOPS-RPL are shown in the flowchart of Figure 15. The performance of EEOPS-RPL was studied under different network scenarios by using the COOJA simulator. The WISMote sensor node was used in the simulations in a random distribution. The initial energy of each node was set at 1000 J. A network area of 100 m × 100 m was considered. The number of nodes was taken as 30, with a network coverage of 50 m. A data packet of a size of 127 bytes was chosen. The data rate was set to 1 pkt/min. The following parameter values were used: $\beta o = 1$, $\alpha = 0.3$, $\gamma = 1$, and MinHopRankIncrease = 256. There was improvement in the packet transmission ratio and network lifetime by 5% and 10%, respectively, in comparison to others.

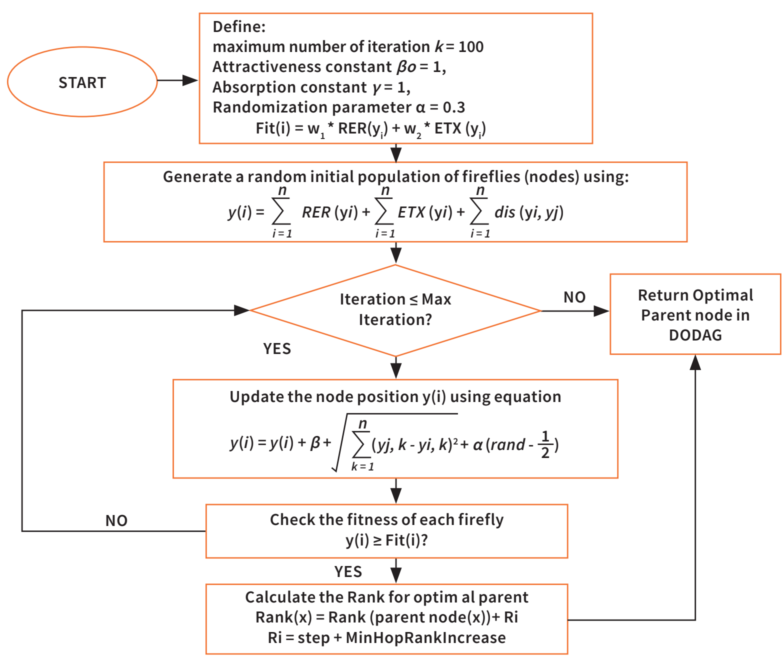


Figure 15. Operation flow of EEOPS-RPL. Source: Figure by authors.

3.2.3. RPL Enhancement Using the Ant Colony Optimization Algorithm

The ant colony optimization protocol is a metaheuristic, probabilistic technique for finding optimal paths or solving optimization problems in computer science or operations research. It belongs to the family of swarm intelligence algorithms and uses the pheromone-based communication technique of biological ants. It was proposed initially by Marco Dorigo in 1992, where the algorithm was seeking to find the optimal path in a graph, mimicking an ant's behavior of searching for the shortest path between their colony and a food source. The application of the ant colony optimization algorithm is explored in RPL networks for optimal parent selection. Here, the researchers have proposed an improvised E-RPL based on the ACO (Preeth et al. 2020).

In this method, the ETX, residual energy (RER), children number, and rank value metrics are used. The ETX and rank value are considered pheromone factors. The RER and children number are taken as heuristic factors. The child–parent relationship is taken as a pheromone evaporation factor. The pheromone, heuristic factors, and evaporation factor are combined to form an objective function by using weights. The pheromone factor is defined for a node as *PH(i)*, given by the following equation:

$$PH = x\left(\frac{1}{Rank\ value\,(\mathrm{i})}\right) \tag{38}$$

where *ETX(i-j)* is the ETX value of a link between nodes i and j.

A term, $E_{\mathrm{PH(i)}}$, is introduced to represent the evaporation factor, and it is governed by the parent–child relationship. Initially, when there is no relationship between nodes *i* and *j*, $E_{PH(i)}$ = 0. The first time node j is selected as the parent a value of 0.1 is assigned. Every subsequent time this node, j, is selected as the parent, the value of $E_{PH(i)}$ is incremented by 0.1. The equation is shown below:

$$\mathrm{EPH}\,(\mathrm{i}) = \begin{cases} 0, E\mathrm{PH}\,(\mathrm{i}) > 1 \\ E\mathrm{PH}\,(\mathrm{i}) + 0.1, E\mathrm{PH}\,(\mathrm{i}) > 0.1 \\ 0.1, otherwise \end{cases} \tag{39}$$

The minimum residual energy of any link between a DIO message receiver and a DODAG root is termed MRE_{ij}. The next important metric taken into account is the children count for any node j, denoted as CC_j. Too many children nodes can result in collision and packet dropping. *CCj* is a measure of children count and the probability of packet loss due to collisions:

$$\text{CCj} = \frac{Children\ Count}{Total\ Number\ of\ neighbors} \tag{40}$$

Two subobjective functions are defined for a parent node, *EIPNj* and *EEPNj*, which correspond to efficiency and effectivity, respectively. *EIPNj* is the product of *PH(i)* and $E_{PH(i)}$, and *EEPNj* is proportional to *MRE* and *CCj*:

$$EIPNj = PH\,(i) \times \text{EPH}\,(\text{i}) \tag{41}$$

$$EEPNj = \left(1 - \frac{1}{MRE\text{ij}}\right) \times \left(1 - \frac{1}{\text{CCj}}\right) \tag{42}$$

The ant colony optimization algorithm evaluates the fitness for a particular parent by using the following objective function:

$$F\daleth tnss_j = \left\{ \frac{(\alpha \times EIPN_j) \times (\beta \times EEPN_j)}{AvG\left((\alpha \times EIPN_j) \times (\beta \times EEPN_j)\right)} \right\} \tag{43}$$

where α and β are the weights used to combine the two subjective functions, *EIPNj* and *EEPNj*.

This method gives an energy-efficient and reliable implementation. There is significant improvement in the packet delivery ratio to the tune of 35% over standard implementations; however, due to the computations involved it experiences a slightly higher delay then the standard and may not be ideal for real-time applications. The flowchart is shown below in Figure 16. In addition to the ACO algorithm, the authors have used a coverage-based dynamic trickle algorithm that works on the concentric corona mechanism. It utilizes node density information within DIO messages to determine the transmission duration of DIO messages, thus reducing routing overhead considerably without affecting the network coverage. This technique achieves faster network convergence as compared to the standard RPL.

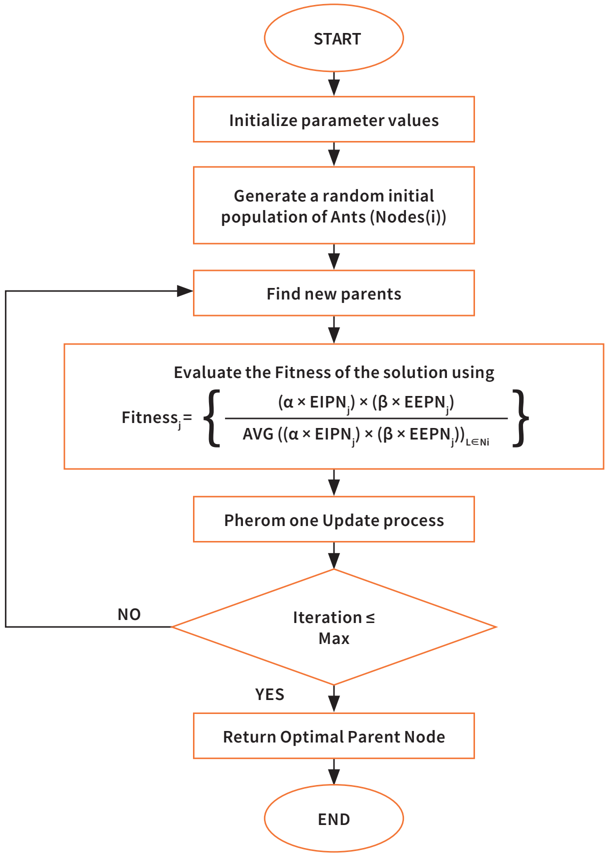


Figure 16. Operation flow of E-RPL by using the ACO algorithm. Source: Figure by authors.

3.3. RPL Enhancement Using Neural Networks

Neural networks are computational models inspired by the human brain. They consist of a network of neurons connected by synaptic weights and configured to perform a specific task. ANNs can be applied to solve problems in the domains of classification, regression, optimization, and clustering. A training algorithm is used to determine the optimal value of weights and reduce error to a minimum. Some of the very popular applications of ANNs include image recognition, stock market prediction, speech and pattern recognition, handwriting analysis, medical diagnosis, text translation, and social media platforms.

The application of neural networks in communication protocols is explored in this section. This section describes the role of ANNs in improving the routing protocol, RPL, used in low-power and lossy networks. A novel objective function, based on neural networks, is proposed for parent selection and routing decisions in RPL implementations. A multilayer perceptron feedforward network is designed, which will be applied to determine the optimal parent for a node within a DODAG.

The hop count (HC), ETX, residual energy (RER), and end-to-end delay metrics are chosen as the criteria for selecting the optimum parent. These four metrics are fed as inputs to the feedforward neural network. The design consists of three layers of neurons. In layer1 there are 10 neurons, layer2 constitutes 5 neurons, and layer3 is a single-output neuron. This is a typical example of a network for performing regression. The network computes the SCORE for each candidate parent depending on the values of the ETX, HC, RER, and delay. This network is trained using a database with 42,67,199 sample values, where the dataset was split 70% and 30% for training and validation. The gradient-descent-based Delta learning algorithm was used for training the network. This network provides an accuracy of 96%. The network is shown below in Figure 17, and the scatter plot of actual vs. predicted is shown in Figure 18a.

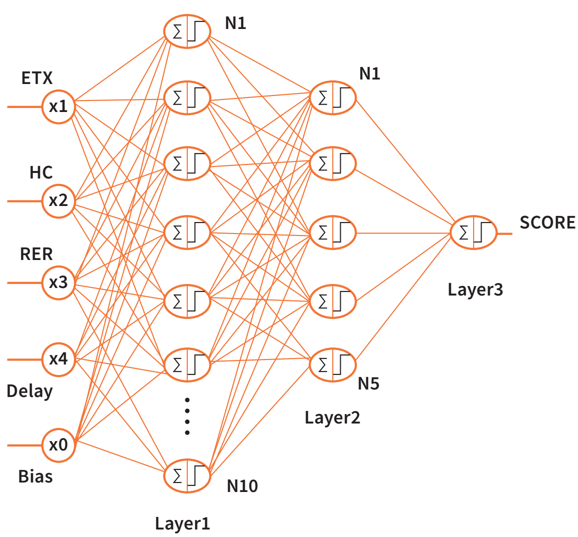


Figure 17. Neural network for selecting the parent in an RPL network. Source: Adapted from Kuwelkar and Virani (2023), used with permission.

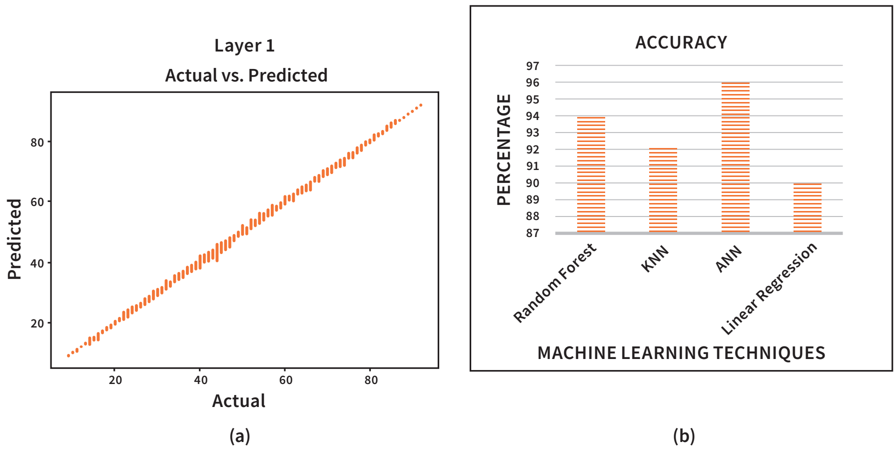


Figure 18. (**a**) Actual vs. predicted scatter plot for the trained NN. (**b**) Accuracy of various machine learning techniques vs. ANNs. Source: Adapted from Kuwelkar and Virani (2023), used with permission.

The design and training of the neural network was performed by using tools such as Google Collab and Jupyter Notebook. Several other neural network configurations with different numbers of layers and neurons were tried and tested; however, the one shown above displayed better accuracy and practicality of implementation in Contiki OS. This neural network was compared against other machine-learning-based regression techniques, such as random forest regressor, K-nearest neighbor, and linear regression, which were trained by using the same dataset. Artificial neural networks had the highest accuracy as compared to the other methods. The accuracy graph is shown in Figure 18b.

The steps involved in best parent selection and routing using ANN-based RPL implementation are as follows:

1. The values of the ETX, HC, RER, and delay metrics are extracted from the received DIO message.
2. Add the DIO sender node as a candidate to the candidate parent list.
3. If more than one parent exists in the list, then invoke the neural network.
4. Compute the scores for all of the candidate parents.
5. Select the candidate with the highest score and compare it to the score of the existing parent.
6. If the candidate's score is more than the score of the present parent, then select this candidate as the new best parent.

7. Compute the rank of the node based on the rank of the new selected parent by using the rank equation.
8. Send the DAO and DIO messages after the expiry of respective timers.

This novel ANN-based objective function must be incorporated into operating systems meant for IoT motes. Contiki is one such OS build for the wireless low-power sensor motes used in Internet of things applications. Contiki OS has a built-in TCP/IP stack and multitasking flexibility. The memory requirement is around 30 KB of ROM and 10 KB of RAM. The RPL is standardized as the routing protocol in Contiki. The neural network functionality is incorporated into Contiki OS and simulations are performed by using the in-built network simulator COOJA (Kuwelkar and Virani 2023).

The network view in Contiki OS COOJA simulator is shown in Figure 19.

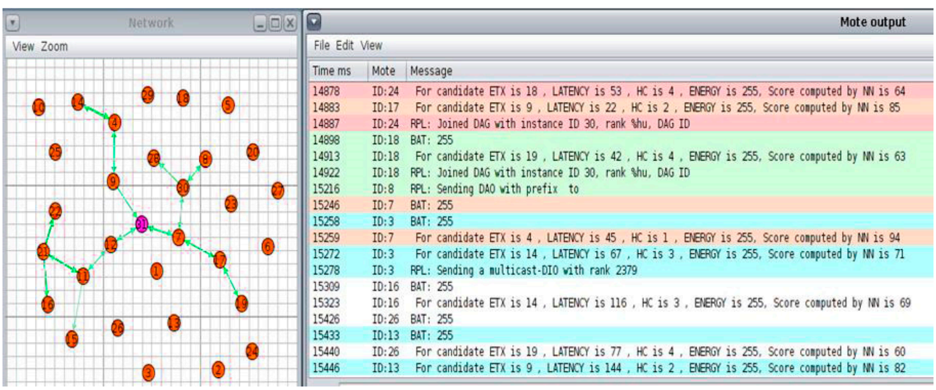


Figure 19. Network view of ANN-based RPL implementation in the COOJA simulator. Source: Adapted from Kuwelkar and Virani (2023), used with permission.

The test logs generated during the simulation in COOJA can be used to extract the values of power consumption, packet delivery ratio, delay, and control overhead by writing PERL or Python scripts. The proposed ANN-based objective function is evaluated against the standard RPL by varying the node density from 30 to 100. A single sink node is used. Packets of a length of 128 bytes are transmitted at a rate of 5 p/min. The parameters used during simulation are shown below in Table 2.

Table 2. Parameters used during simulation.

Simulator	Contiki OS 2.7-COOJA
Network area	300 m x 300 m
Transmission range	30 m
Network density	70, 90, and 100 static nodes
MAC layer	Contiki MAC
Number of sink nodes	1
Deployment type	Random Topology
Packet transmission rate	Five packets per min
Emulated nodes	Zolertia Z1 motes
Transmission ratio	100%
Simulation time	20 min

Source: Authors' compilation based on their research work.

The simulations are performed and graphs are plotted for latency, PDR, average power consumption, and control overhead, as shown in Figure 20. ANN-RPL uses the RER metric, hence avoiding the use of candidates with lower RER as parents. This preserves node energy and improves overall efficiency. It reduces power consumption to the tune of 11%. The delay and HC metrics ensure that candidates with lower delays and shorter routes are chosen as parents, hence ensuring faster packet delivery. The delay in ANN-RPL is lower by 17% as compared to MRHOF. The ETX metric ensures better reliability and hence improves packet delivery. The PDR of ANN-RPL is higher by 3%. In the RPL, the DAO messages are generated after the expiration of the DelayDAO timer. In the standard RPL, the expiration of this timer happens at regular intervals, leading to excess DAO messages circulating in the network. In this work the DelayDAO timer expiration is triggered upon the selection of a new parent node. This ensures that DAO messages are only generated when crucial routing updates must be sent, and avoids unwanted overhead. The DIO messages, which carry the crucial routing information, are generated upon the expiration of the Trickle timer. This timer expires at predefined fixed intervals and after a change in the parent node. Together, DIO and DAO messages ensure that updated routing information is circulated within the network. This leads to a significant amount of reduction in control overhead due to the mechanism adopted in transmitting DAO and DIO messages. Traffic reduction to the tune of 48% is achieved. This novel ANN-RPL technique is proven to be substantially better than the standard RPL.

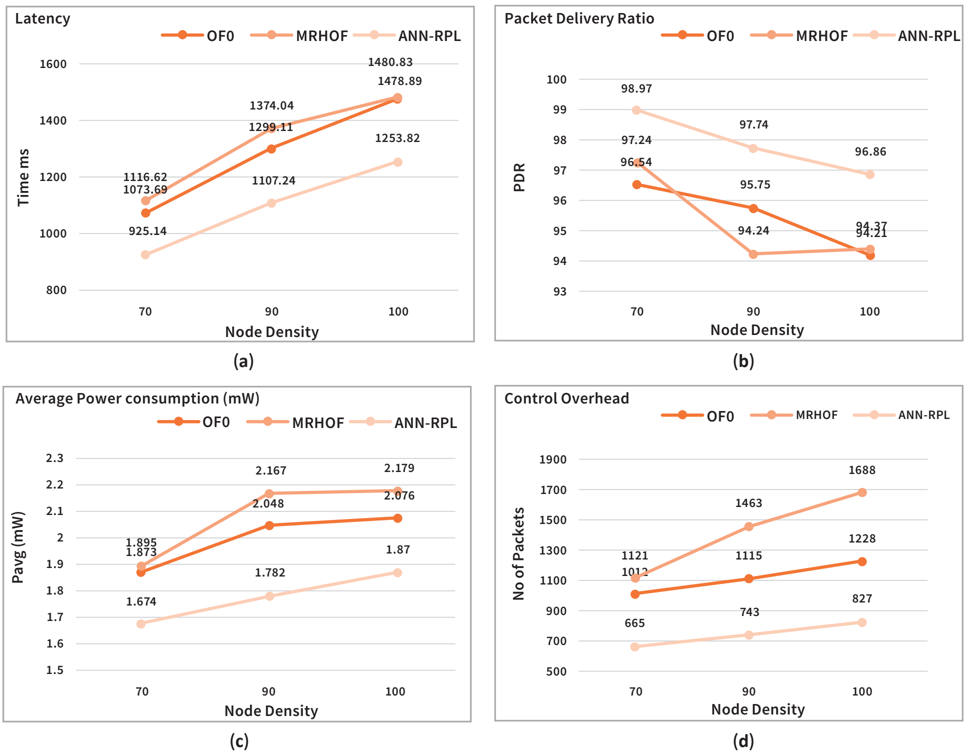
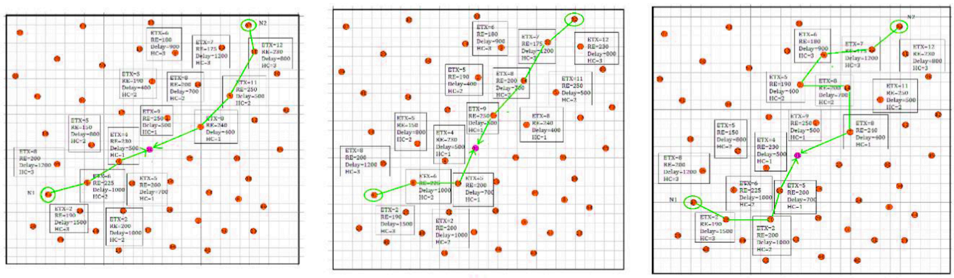


Figure 20. Plots of (**a**) latency, (**b**) PDR, (**c**) Pavg, and (**d**) traffic overhead for ANN-RPL, OF0, and MRHOF. Source: Adapted from Kuwelkar and Virani (2023), used with permission.

Figure 21 shows the paths chosen from two nodes, N1 and N2, towards the sink node in an RPL instance when the network is operating using the objective function of ANN-RPL as compared to the standard OF0 and MRHOF. ANN-RPL chooses optimal parents that have higher energy levels and lower delays, contrary to what is seen with OF0 and MRHOF. For node N2 there are two neighbors in the vicinity, with the following metric values: P1 (ETX = 12, RE = 230, Delay = 800 and HC = 3) and P2 (ETX = 7, RE = 175, Delay = 1200 and HC = 3). ANN-RPL yields a quality score of 80 for neighbor P1 and 66 for P2. Since the score of P1 is higher, ANN-RPL choses P1 as the parent for the route towards the sink, whereas OF0 and MRHOF choose P2. As P2 has lower energy and higher delay then P1, it is evident that the performances of OF0 and MHROF networks will be poorer.



(a) (b) (c)

Figure 21. Route chosen in RPL networks from sender to sink in (**a**) ANN-RPL, (**b**) OF0, and (**c**) MRHOF. Source: Figure by authors.

3.3.1. Comparison Analysis of ANN-RPL with Other RPL Implementations

The performance of the novel ANN-RPL objective function is compared with other work performed previously. The graphs plotted in Figure 22 show the values of ANN-RPL for PDR, latency, power consumption, and control overhead in addition to other implementations, such as RPL-HC, RPL-ETX, RPL-CGA, HOFESA, EEOPS-RPL, E-RPL, and DN-RPL.

ANN-RPL has a higher PDR as compared to the standard RPL, chaotic genetic algorithm, firefly optimization algorithm, and ant colony optimization algorithm. ANN-RPL reduces the number of control overhead in the network, thus ensuring less traffic and congestion in network. This ensures a higher successful packet delivery rate. DN-RPL (Kharche and Pawar 2020) has deep nets in the neural network, which provide slightly higher packet delivery but affect the delay. The HOFESA (Hassani et al. 2021) implementation is an empirical stability aware technique that avoids frequent parent changes to maintain network stability. It provides a trivially higher PDR then ANN-RPL but has higher power consumption.

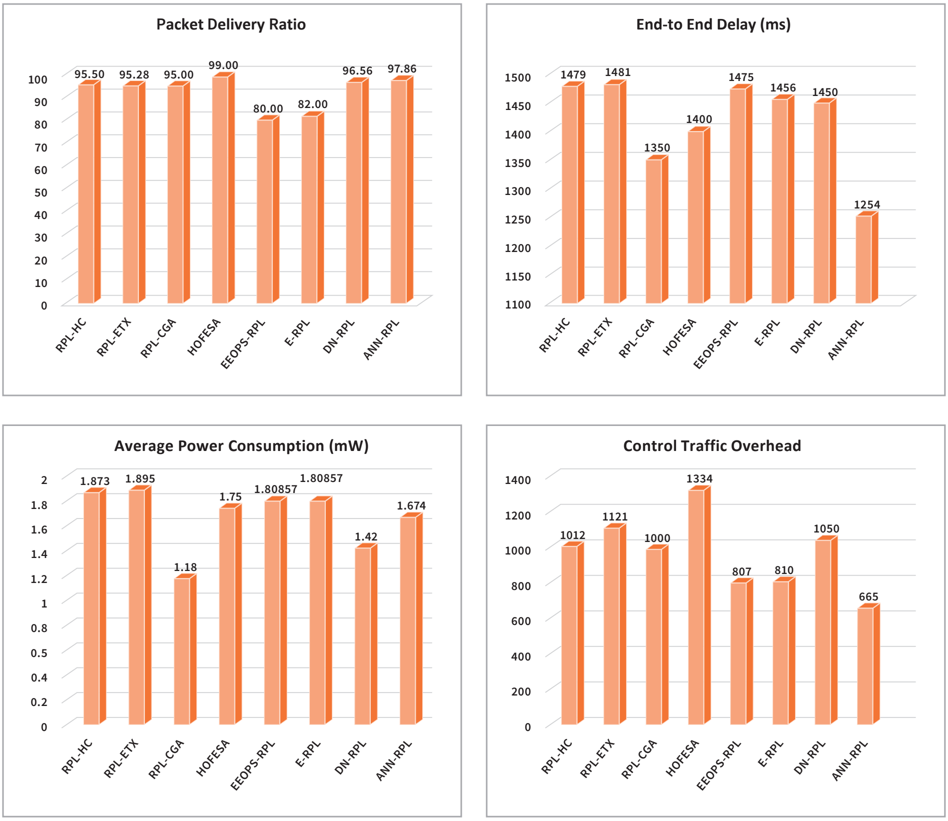


Figure 22. ANN-RPL vs. other works in terms of PDR, latency, power consumption, and control overhead. Source: Adapted from Kuwelkar and Virani (2023), used with permission.

ANN-RPL has lower power consumption as compared to most other implementations, with the exception of genetic algorithm techniques and deep-neural-net-based optimization. In deep nets more hidden layers are added to allow better performance. This assists in achieving lower power consumption in DN-RPL, but with the tradeoff of higher delays. RPL-CGA considers queue length, RER, HC, the ETX, and delay. The computation time in a CGA is significant due to the chaotic mechanism. The optimization in RPL-CGA is more focused for energy as compared to delay.

ANN-RPL uses the delay metric to make a routing decision; hence, it chooses paths with the lowest distance and delay to the root. This provides a significant reduction in latency as compared to all of the other techniques, whereas RPL-HC, RPL-ETX, EEOPS-RPL, E-RPL, and DN-RPL do not consider the delay metric when making routing decisions.

ANN-RPL has the least control overhead compared to all of the other techniques. DAO message generation depends on a DelayDAO timer. In ANN-RPL, DAO messages are triggered only when a new parent is selected. The messages are unicast to the parent node only. This avoids any excess DAO messages in the network and considerably reduces DAO message overhead. Control traffic overhead has a direct or indirect impact on the resource consumption of the network. Less traffic leads to lower congestion in the network and improves the performance further.

If we compare ANN-RPL with the fuzzy-based RPL, then it scores better. In fuzzy logic a range of values within a fuzzy set are assigned the same value and are evaluated without distinction. For instance, a candidate with RER values of 110 and 150 will have equal scores, since they will figure in the same fuzzy set; however, in this NN scheme a candidate with an RER value of 150 will clearly have a higher weightage over one with a value of 110. This technique has more sensitivity and responsivity to the metric values, thus performing better. Table 3, below, shows the percentage improvement in the performance of ANN-RPL with as compared to other works.

Table 3. Performance comparison of ANN-RPL with other works.

RPL Implementation	PDR	% Improvement in PDR for ANN-RPL	Pavg	% Improvement in Pavg for ANN-RPL	End-to-End Delay	% Improvement in Latency for ANN_RPL	Control Overhead	% Improvement in Traffic for ANN-RPL
RPL-HC	95.5	2.47%	1.873	10.62%	1478.89	15.22%	1012	34.29%
RPL-ETX	95.28	2.70%	1.895	11.66%	1480.83	15.33%	1121	40.68%
RPL-CGA	95	3.01%	1.18	−41.86%	1350	7.12%	1000	33.50%
HOFESA	99	−1.17%	1.75	4.34%	1400	10.44%	1334	50.15%
EEOPS-RPL	80	22.32%	1.8085	7.44%	1475	15.00%	807	17.60%
E-RPL	82	19.34%	1.8	7.00%	1456	13.89%	810	17.90%
DN-RPL	96.56	1.33%	1.42	−15.17%	1450	13.53%	1050	36.67%
OF-FZ	96.523	1.38%	1.823	8.17%	1353.82	7.39%	629	−5.72%
ANN-RPL	97.856	-	1.674	-	1253.82	-	665	-

Source: Authors' compilation based on their research work.

The evolutionary-algorithm-based RPL implementations require more computing time due to the large number of iterations involved in the algorithms. On average, the delay is seen to be around 0.4 min. Additionally, they need more powerful microcontrollers with a larger memory space. This considerably increases the deployment cost. These factors provide ANN-RPL with leverage over these

EA-based schemes. ANN-RPL has much lower computation time since it only involves a series of addition and multiplication operations at the three layers of neurons. The delay is approximately 1.2 s and sizably lower than the EA-based RPL. It can work well on most commercially available microcontrollers, such as the MSP430. This extended and improved RPL version is suitable for the various applications of the WSN and IoT domains. Table 4 below summarizes the various approaches with which to improve the RPL by using soft learning techniques.

Table 4. Summary of works.

Paper	Proposed Solution	Objective Function Metrics	Findings
FL-RPL	Fuzzy optimized FL-RPL metric to provide mobility support for the RPL	Mobility timer, the ETX, energy, and the RSSI	Mobile nodes achieve 95% PDR with an average power consumption of 2.26 mW
CAUF	Multi attribute decision-making method for parent selection. Fuzzy weighted sum model adopted. Congestion-aware algorithm	Buffer occupancy (BO), the expected transmission count (ETX), and RtMetric	4.5% packets less dropped and 15% more throughput
IDS-RPL	Three-metric combination using fuzzy logic for intrusion detection	Distance, residual energy (RE), and the ETX	Improved detection of local repair attacks
OPP-FL	Three-metric combination using fuzzy logic	The ETX, hop count (HC), and children number	Better PDR and less delay
FUZZY	Three-metric combination using fuzzy logic	The ETX, delay, and energy (fuzzy)	Better network lifetime. Node battery levels retained around 69% to 78% towards the end
OF-EC	Three-metric combination using fuzzy logic	HC, the ETX, and energy consumption	Improvement in energy consumption, network convergence tine, PDR, latency, overhead, and Network Lifetime
OF-FL	Four-metric combination using fuzzy logic	Energy, hop count, end-to-end delay, and link quality	Improvement in the packet delivery ratio, network lifetime, hop count, and smaller number of frequent parent changes

Table 4. *Cont.*

Paper	Proposed Solution	Objective Function Metrics	Findings
OF-FZ	Four-metric combination using fuzzy logic	RER, the ETX, HC, and latency	Reduction of 9% in energy consumption, 7% better PDR, 8% lower latency, and 45% lower traffic overhead then the standard RPL
RPL-CGA	Genetic algorithm for optimizing weighting factors in composition metric	Queue length, delay, RER, HC, and the ETX	Improvement in the PDR, energy efficiency, and lower delays
EEOPS-RPL	Firefly algorithm for optimization	RER, the ETX, and distance	5% better PDR and 10% higher network lifetime
E-RPL	Ant colony optimization	Children count, RER, the ETX, rank value	Better PDR to the tune of 35% over standard implementations; however, due to the computations involved it experiences slightly higher delay then the standard RPL
DN-RPL	Deep neural nets	Energy, the ETX, location of nodes	Better energy, lower delay, and better SINR
RPL-FZ	Three-metric combination using fuzzy logic	RER, delay, and the ETX	Improvement in the PDR, energy efficiency, and lower delay
RPL-OC	Four-metric combination using operator calculus	Energy, the RSSI, delay, and hop count	Improvement in energy consumption and delay
MFO-RPL	Secure scheme for the RPL based on moth–flame Optimization	Distance	Optimizes the routing process and rank attack detection in the RPL
FL-HELR-OF	Four-metric combination using Fuzzy Logic	Hop count, energy consumption, latency, and the RSSI	Better PDR, lower latency, and less control overhead
HOFESA	Hybrid objective function with empirical stability aware technique	Hop count, the RSSI, and node energy consumption	Avoids frequent parent changes to maintain network stability
ANN-RPL	Multilayer feedforward neural network	The ETX, delay, HC, and RER	Reduction of 11% in energy consumption, 8% better PDR, 14% lower latency, and 48% lower traffic overhead as compared to the standard RPL

Source: Authors' compilation based on their research work.

4. Discussion and Conclusions

This chapter has explored two revolutionizing technologies of the future: the IoT and soft computing. The popularity of the Internet of things has grown by many bounds over the decade. With the advancements in sensor technologies, embedded systems, and communication technology, such as 5G, the IoT will pervade our lives in the coming years. To ensure sustainability in such networks, the routing operation plays a crucial role and needs to be optimized. Overall, routing affects energy efficiency, end-to-end delay, packet delivery, network lifetime, and reliability.

The domain of wireless sensor networks and ADHOC networks has matured, and a number of routing protocols exist, such as AODV, OLSR, LEACH, and OSPF. IoT networks are characterized as low-power as well as lossy, and are designed to adopt IPv6 addressing. Due to these factors, existing protocols were proven to be unsuitable with regard to power, latency, overhead, and reliability. To overcome this limitation, the IETF standardized the 6LoWPAN specification, which specifies how to carry IPv6 datagrams over LLNs. As a routing solution, the IETF ROLL working group proposed the IPv6 routing protocol for LLNs (RPL). The RPL provides IPv6 addressing to low-power wireless embedded devices for WSN and IoT applications.

Over a period, the RPL has attained maturity and been standardized as a routing protocol. Although the RPL was able to resolve major routing issues in LLNs, there were still certain limitations that needed addressing. Several researchers have contributed to effectively improving the RPL over the years. In this chapter we have reviewed these works, with a primary focus on the soft computing techniques adopted for enhancing the RPL.

The application of fuzzy logic in order to overcome the limitations of single-metric-based objective function, support for mobility, load balancing, and congestion in the RPL is explained in detail. The application of evolutionary algorithms, such as genetic algorithms, the firefly algorithm, and ant colony optimization, to augment the performance of the RPL is described. These methods provide better results in terms of energy efficiency, packet delivery, delay, and lifetime over the standard RPL, thus paving the way for sustainable IoT infrastructure. In the latter part, a novel technique using a multilayer feedforward neural network was proposed for RPL improvisation. This technique lowers energy consumption by 12%, improves the PDR by 3%, lowers delay by 17%, and reduces control overhead by 48% as compared to standard RPL implementations. Some of these proposed methods have been tested on real-life motes, such as WISMote, T-mote Sky, and the Zolertia Z1 platform.

Acknowledgments: We are grateful to the Director, Directorate of Technical Education, Goa, India and Principal, Goa College of Engineering for constant support rendered during the research work.

Author Contributions: Conceptualization, S.K. and H.G.V.; methodology and software, S.K.; validation, H.G.V.; formal analysis, investigation, resources, data curation, writing—original draft preparation, S.K.; writing—review and editing, H.G.V.; project administration, H.G.V.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

Atzori, Luigi, Antonio Iera, and Giacomo Morabito. 2010. The internet of things: A survey. *Computer Networks* 54: 2787–2805. [CrossRef]

Ancillotti, Emilio, Carlo Vallati, Raffaele Bruno, and Enzo Mingozzi. 2017. A reinforcement learning-based link quality estimation strategy for RPL and its impact on topology management. *Computer Communications* 112: 1–13. [CrossRef]

Ancillotti, Emilio, Raffaele Bruno, and Marco Conti. 2014. Reliable data delivery with the IETF routing protocol for low-power and lossy networks. *IEEE Transactions on Industrial Informatics* 10: 1864–77. [CrossRef]

Brandt, Anders, Jakob Buron, and Giorgio Porcu. 2010. *Home Automation Routing Requirements in Low-Power and Lossy Networks*. Internet Eng Task Force Standard No. rfc5826.

Cao, Yanan, and Muqing Wu. 2018. A novel RPL algorithm based on chaotic genetic algorithm. *Sensors* 18: 3647. [CrossRef]

Charles, A. S. Joseph, and P. Kalavathi. 2022. A reliable link quality-based RPL routing for Internet of Things. *Soft Computing* 26: 123–35. [CrossRef]

Clausen, Thomas, Ulrich Herberg, and Matthias Philipp. 2011. A critical evaluation of the IPv6 routing protocol for low power and lossy networks (RPL). Paper presented at 2011 IEEE 7th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Shanghai, China, October 10–12; pp. 365–72.

Darabkh, Khalid A., Muna Al-Akhras, Khalifeh AlaF, Iyad F. Jafar, and Fahed Jubair. 2022. An innovative RPL objective function for broad range of IoT domains utilizing fuzzy logic and multiple metrics. *Expert Systems with Applications* 205: 117593. [CrossRef]

Dohler, Mischa, Thomas Watteyne, Tim Winter, and Dominique Barthel. 2009. *Routing Requirements for Urban Low-Power and Lossy Networks*. Internet Eng Task Force Standard No. rfc5548.

Farzaneh, Behnam, Mohammad Koosha, Elahe Boochanpour, and Emad Alizadeh. 2020. A new method for intrusion detection on RPL routing protocol using fuzzy logic. Paper presented at 2020 6th International Conference on Web Research (ICWR), Tehran, Iran, April 22–23; pp. 245–50.

Gaddour, Olfa, Anis Koubâa, Nouha Baccour, and Mohamed Abid. 2014. OF-FL: QoS-aware fuzzy logic objective function for the RPL routing protocol. Paper presented at 2014 12th International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), Hammamet, Tunisia, May 12–16; pp. 365–72.

Gaddour, Olfa, Anis Koubâa, and Mohamed Abid. 2015. Quality-of-service aware routing for static and mobile IPv6-based low-power and lossy sensor networks using RPL. *Ad Hoc Networks* 33: 233–56. [CrossRef]

Ghaleb, Baraq. 2019. Efficient Routing Primitives for Low-Power and Lossy Networks in Internet of Things. Ph.D. dissertation, Edinburgh Napier University, Edinburgh, UK, August 29.

Gnawali, Omprakash, and Philip Levis. 2012. *The Minimum Rank with Hysteresis Objective Function*. Internet Eng Task Force Standard No. rfc6719.

Hassani, Abdelhadi Eloudrhiri, Aicha Sahel, Abdelmajid Badri, and El Mourabit Ilham. 2021. A hybrid objective function with empirical stability aware to improve RPL for IoT applications. *International Journal of Electrical and Computer Engineering (IJECE)* 11: 2350–59. [CrossRef]

Hui, Jonathan W., and David E. Culler. 2008. Extending IP to low-power, wireless personal area networks. *IEEE Internet Computing* 12: 37–45. [CrossRef]

Hui, J., J. P. Vasseur, D. Culler, and V. Manral. 2012. *An ipv6 routing header for source routes with the routing protocol for low-power and lossy networks (rpl).* Internet Eng Task Force Standard rfc6554.

Ibrahim, Dogan. 2016. An overview of soft computing. *Procedia Computer Science* 102: 34–38. [CrossRef]

Kamgueu, Patrick Olivier, Emmanuel Nataf, Thomas Ndie Djotio, and Olivier Festor. 2013. Energy-based Metric for the Routing Protocol in Low-power and Lossy Network. Paper presented at SENSORNETS 2013: 2nd International Conference on Sensor Networks, Barcelona, Spain, February 19–21; pp. 145–48.

Kechiche, Ines, Ines Bousnina, and Abdelaziz Samet. 2019. A novel opportunistic fuzzy logic based objective function for the routing protocol for low-power and lossy networks. Paper presented at 2019 15th International Wireless Communications & Mobile Computing Conference (IWCMC), Tangier, Morocco, June 24–28; pp. 698–703.

Kharche, Shubhangi, and Sanjay Pawar. 2020. Optimizing network lifetime and QoS in 6LoWPANs using deep neural networks. *Computers & Electrical Engineering* 87: 106775.

Kumar, Ajay, and Narayanan Hariharan. 2020. DCRL-RPL: Dual context-based routing and load balancing in RPL for IoT Networks. *IET Communications* 14: 1869–82. [CrossRef]

Kuwelkar, Sonia, and Hassanali Virani. 2019. Performance analysis of the objective functions in IPv6 routing protocol for LLN's used in IOT applications. Paper presented at 2019 IEEE Pune Section International Conference (PuneCon), Pune, India, December 18–20; pp. 1–5.

Kuwelkar, Sonia, and Hassanali Virani. 2021a. Design of an efficient RPL objective function for internet of things applications. *International Journal of Advanced Computer Science and Applications* 12: 228–35. [CrossRef]

Kuwelkar, Sonia, and Hassanali Virani. 2021b. OF-FZ: An Optimized Objective Function for the Ipv6 Routing Protocol for LLNs. *IETE Journal of Research, Taylor & Francis*, 1–19. [CrossRef]

Kuwelkar, Sonia, and Hassanali Virani. 2023. RPL Protocol Enhancement using Artificial Neural Network (ANN) for IoT Applications. Paper presented at 2023 International Conference on Intelligent Data Communication Technologies and Internet of Things (IDCIoT), Bengaluru, India, January 5–7; pp. 52–58.

Lamaazi, Hanane, and Nabil Benamar. 2020. A comprehensive survey on enhancements and limitations of the RPL protocol: A focus on the objective function. *Ad Hoc Networks* 96: 102001. [CrossRef]

Lamaazi, Hanane, and Nabil Benamar. 2018. OF-EC: A novel energy consumption aware objective function for RPL based on fuzzy logic. *Journal of Network and Computer Applications* 117: 42–58. [CrossRef]

Levis, P., T. Clausen, J. Hui, O. Gnawali, and J. Ko. 2011. *The Trickle Algorithm*. Internet Eng. Task Force Standard RFC6206.

Mamdani, Ebrahim H., and Sedrak Assilian. 1975. An experiment in linguistic synthesis with a fuzzy logic controller. *International Journal of Man-Machine Studies* 7: 1–13. [CrossRef]

Martocci, Jerry, Pieter De Mil, Nicolas Riou, and Wouter Vermeylen. 2010. *Building Automation Routing Requirements in Low-Power and Lossy Networks*. Internet Eng. Task Force Standard No. rfc5867.

Mohammadsalehi, Aliasghar, Bardia Safaei, Amir Mahdi Hosseini Monazzah, Lars Bauer, Jörg Henkel, and Alireza Ejlali. 2021. ARMOR: A reliable and mobility-aware RPL for mobile Internet of Things infrastructures. *IEEE Internet of Things Journal* 9: 1503–16. [CrossRef]

Pahlavani, Ali. 2010. A new fuzzy MADM approach and its application to project selection problem. *International Journal of Computational Intelligence Systems* 3: 103–14.

Pister, Kris, Pascal Thubert, Sicco Dwars, and Tom Phinney. 2009. *Industrial Routing Requirements in Low-Power and Lossy Networks*. Internet Eng. Task Force Standard No. rfc5673.

Preeth, SK Sathya Lakshmi, R. Dhanalakshmi, Rajagopal Kumar, and Sangar Si. 2020. Efficient parent selection for RPL using ACO and coverage based dynamic trickle techniques. *Journal of Ambient Intelligence and Humanized Computing* 11: 4377–91. [CrossRef]

Sahani, Sanjay Kumar, and K. Kumar. 2013. Multi-routing in wireless sensor networks using an ant colony optimization (ACO). *International Journal of Computer Networking, Wireless and Mobile Communications* 3: 87–98.

Sanshi, Shridhar, and Jaidhar Cd. 2019. Fuzzy optimised routing metric with mobility support for RPL. 2019. *IET Communications* 13: 1253–61. [CrossRef]

Sennan, Sankar, Ramasubbareddy Somula, Ashish K. Luhach, Ganesh Gopal Deverajan, Waleed Alnumay, N. Z. Jhanjhi, Uttam Ghosh, and Pradip Sharma. 2021. Energy efficient optimal parent selection based routing protocol for Internet of Things using firefly optimization algorithm. *Transactions on Emerging Telecommunications Technologies* 32: e4171. [CrossRef]

Seyfollahi, Ali, Meysam Moodi, and Ali Ghaffari. 2022. MFO-RPL: A secure RPL-based routing protocol utilizing moth-flame optimizer for the IoT applications. *Computer Standards & Interfaces* 82: 103622.

Shirbeigi, Maryam, Bardia Safaei, Aliasghar Mohammadsalehi, Amir Mahdi Hosseini Monazzah, Jörg Henkel, and Alireza Ejlali. 2021. A cluster-based and drop-aware extension of RPL to provide reliability in IoT applications. Paper presented at 2021 IEEE International Systems Conference (SysCon), Vancouver, BC, Canada, April 15; pp. 1–7.

Shreyas, J., Hemant Singh, Jatin Bhutani, Sanjay Pandit, N. N. Srinidhi, and Dilip Kumar SM. 2019. Congestion aware algorithm using fuzzy logic to find an optimal routing path for IoT networks. Paper presented at 2019 International Conference on Computational Intelligence and Knowledge Economy (ICCIKE), Dubai, United Arab Emirates, December 11–12; IEEE, pp. 141–45.

Slowik, Adam, and Halina Kwasnicka. 2020. Evolutionary algorithms and their applications to engineering problems. *Neural Computing and Applications* 32: 12363–79. [CrossRef]

Syarif, Abdusy, Mohamed-el-Amine Brahmia, Jean-François Dollinger, Abdelhafid Abouaissa, and Lhassane Idoumghar. 2022. RPL-OC: Extension of RPL protocol for LLN networks based on the operator calculus approach. Paper presented at Proceedings of Sixth International Congress on Information and Communication Technology: ICICT 2021, London, UK, February 25–26; Singapore: Springer, Volume 1, pp. 47–58.

Thubert, Pascal. 2012. *Objective Function zero for the Routing Protocol for Low-Power and Lossy Networks (RPL)*. No. rfc6552.

Tripathi, Joydeep, Jaudelice Cavalcante de Oliveira, and Jean-Philippe Vasseur. 2010. A performance evaluation study of rpl: Routing protocol for low power and lossy networks. Paper presented at the 2010 IEEE 44th Annual Conference on Information Sciences and Systems (CISS), Princeton, NJ, USA, March 17–19; pp. 1–6.

Vasseur, Jp, Navneet Agarwal, Jonathan Hui, Zach Shelby, Paul Bertrand, and Cedric Chauvenet. 2011. RPL: The IP routing protocol designed for low power and lossy networks. *Internet Protocol for Smart Objects (IPSO) Alliance* 36: 1–20.

Winter, Tim, Pascal Thubert, Anders Brandt, Jonathan Hui, Richard Kelsey, Philip Levis, Kris Pister, Rene Struik, Jean-Philippe Vasseur, and Roger Alexander. 2012. *RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks*. Internet Engineering Task Force Standard No. rfc6550.

Yang, Xin-She. 2009. Firefly algorithms for multimodal optimization. In *Stochastic Algorithms: Foundations and Applications: 5th International Symposium, SAGA 2009, Sapporo, Japan, October 26–28, Proceedings 5*. Berlin and Heidelberg: Springer, pp. 169–78.

Yang, Xin-She, and Mehmet Karamanoglu. 2013. Swarm intelligence and bio-inspired computation: An overview. *Swarm Intelligence and Bio-Inspired Computation*, 3–23. [CrossRef]

Yang, Dixiong, Zhenjun Liu, and Jilei Zhou. 2014. Chaos optimization algorithms based on chaotic maps with different probability distribution and search speed for global optimization. *Communications in Nonlinear Science and Numerical Simulation* 19: 1229–46. [CrossRef]

Zaatouri, Ibtissem, Nouha Alyaoui, Awatef Benfradj Guiloufi, Francoise Sailhan, and Abdennaceur Kachouri. 2022. Design and Performance Analysis of Objective Functions for RPL Routing Protocol. *Wireless Personal Communications* 124: 2677–97. [CrossRef]

© 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland
Tel. +41 61 683 77 34
Fax +41 61 302 89 18
www.mdpi.com

MDPI Books Editorial Office
E-mail: books@mdpi.com
www.mdpi.com/books

MDPI
St. Alban-Anlage 66
4052 Basel
Switzerland

Tel: +41 61 683 77 34
Fax: +41 61 302 89 18

www.mdpi.com

ISBN 978-3-03897-869-5