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Article

Development of an indicators system for evaluating the implementation of digital twins in the fuel and energy complex enterprise in the context of the smart energy adaptation

Svetlana Gutman[*], **Evgenii Seredin, Viktoriia Brazovskaia**
Institute of Industrial Management, Economics and Trade, Peter the Great St. Petersburg Polytechnic University, Saint Petersburg 195251, Russia
* **Corresponding author:** Svetlana Gutman, sgutman@spbstu.ru

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Abstract: This article discusses one of the problems of using digital technologies, namely the complexity of assessing the effectiveness of their implementation. Since the use of digital twins at the enterprises of the fuel and energy complex (FEC) has recently become relevant, the authors have chosen the digital twins technology for consideration in this article. For the successful implementation of digital technologies, the authors propose a system of evaluation indicators that will measure the effectiveness of Digital Twins implementation and determine the benefits obtained. The advantages of digital twins include improved management and monitoring, optimization of production processes, prediction of equipment failures, as well as reduced maintenance costs and increased overall efficiency of FEC systems. As a methodological basis for the study, authors use the system of balanced indicators proposed by R. Kaplan and D. Norton, which served as the basis for the development of a set of performance indicators of the fuel and energy complex enterprise with the introduction of digital twins. As a result of the study, a list of indicators for monitoring the effectiveness of digital twins implementation was determined. The study identifies performance indicators for digital twin implementation, with future research aimed at quantitative assessments. The enterprise can implement a digital twin system with a WACC of 10.99%, payback period of 8.06 years, IRR exceeding the discount rate by 9.07%, a 3.5% reduction in harmful emissions, and a 2.5% efficiency increase.

Keywords: balanced scorecard; digital twins; energy sector; fuel and energy enterprise; indicators; smart energy

1. Introduction

Every year more and more often it is said about the need to implement such a concept as a "smart city". The idea of creating a smart city entered our lives in 2008, when IBM developed a scheme for building new cities within the framework of the Smart Planet initiative that could cope with the growing number of people and provide them with a high standard of living (Odendaal, 2021). The idea was instantly picked up by leading IT companies. So, a "smart city" is a city that uses various information and communication technologies (ICT), such as big data analysis, artificial intelligence, machine learning, to improve the quality of citizens' life and optimize the functioning of urban infrastructure (Bhattacharya, 2022). Also, it is the unity of engineering and social infrastructure that increases the intellectual mobility of residents (Akimova, 2020).

Owing to the development of digital production, the new industrial revolution and the spread of the Internet of Things, digital twins have appeared (Berawi, 2022).

The digital twin technology combines a physical object with the digital world and describes a digital model of a cyber physical object or technological process (Zhou et al., 2021).

In the context of smart cities, digital twins play a vital role in simulating and optimizing urban infrastructure, enhancing energy efficiency, and supporting sustainable development goals. Applications in urban planning, traffic management, and environmental monitoring illustrate digital twins capacity to create more resilient and efficient urban environments (Botín-Sanabria et al., 2022).

Depending on the object, different types of digital twins are considered. For example, the digital twin of an organization is a model that describes as accurately as possible the real cause-and-effect relationships between the company's production, economic, financial and organizational indicators (Holopainen et al., 2021). New modeling technologies allow enterprises to use digital twins in their business processes, as well as test new projects in the virtual world, while saving time, resources and money.

Digital twins' technology is extensively used in the automotive sector for vehicle design, manufacturing, and maintenance. Real-time monitoring of vehicle performance, predictive maintenance, and the development of autonomous driving technologies are key applications. These implementations help reduce downtime, improve safety, and enhance the overall lifecycle management of automotive products (Botín-Sanabria et al., 2022).

In the energy sector of a smart city, digital twins can be used to simulate the operation of energy networks and devices such as solar panels, wind turbines, power plants and electric vehicles (Kumari, 2023). Digital twins allow to optimize the operation of energy systems, predict their behavior and manage them. For example, they can be used to control the load on the power grid, optimize energy distribution and reduce energy consumption. Digital twins can also be used to analyze and predict weather conditions, which makes it possible to more efficiently manage the operation of energy systems using renewable energy sources. Thus, digital twins in the smart city energy sector have an important role in optimizing the operation of energy systems, increasing energy efficiency and reducing the costs of its production and consumption (Yang et al., 2023).

A digital twin is a virtual model of a physical system that uses real-time data for simulation, prediction, and optimization, enhancing management, monitoring, and efficiency. To evaluate its implementation, key indicators include operational efficiency, cost savings, predictive accuracy, environmental impact, return on investment (ROI), and user adoption. These metrics measure improvements in productivity, maintenance cost reductions, predictive maintenance accuracy, emission reductions, financial returns, and ease of use, ensuring a comprehensive assessment of the digital twin's effectiveness (IBM, 2024).

The energy industry is constantly facing new challenges related to digitalization and innovation. One of the key areas of digitalization at fuel and energy complex (FEC) enterprises is the introduction of Digital Twins that improve the efficiency, reliability, and safety of energy production. A set of solutions for automation of production, technological and related processes provide the possibility of transition to automated life cycle management of equipment facilities. At the same time, preferences are given to holistic unified universal and scalable solutions that will allow for any number of objects and divisions of companies to create a single integrated production management system. But at the moment, companies face the difficulty of determining the effectiveness of implementing innovative solutions (Dolganova and Deeva, 2019; Lee et al., 2022).

In this regard, for the successful implementation of digital technologies, it is necessary to develop a system of evaluation indicators that will measure the effectiveness of the Digital Twins implementation and determine the benefits obtained. Therefore, the purpose of this article is to develop a system that will assess the effectiveness of the introduction of Digital Twins in the FEC enterprises. Such a system of indicators will help determine the opportunity for further improvement and make informed decisions on digital transformation.

This study contributes to the field by providing a comprehensive evaluation system for the implementation of digital twins in the fuel and energy complex enterprises. The novelty lies in integrating the balanced scorecard methodology to specifically address the complexities and dynamic nature of digital twin technology in the energy sector. This approach not only helps in better decision-making but also enhances the operational efficiency and sustainability of energy enterprises.

2. Materials and methods

In this study, authors use methods of analysis, synthesis and generalization to process information. As a methodological basis for the study, the system of balanced indicators proposed by Kaplan and Norton (2004) was used, which served as the basis for the development a of performance indicators set of the FEC enterprise with the introduction of digital twins. The Balanced Scorecard (BSC) is an integrated approach that allows, with appropriate adaptation, to explore issues related to the development and implementation of strategies for the development of economic systems at different levels: country, region, municipality, industry, enterprise, etc. The BSC is based on a clear hierarchy of goals, each of which has its own set of key performance indicators (KPIs). We should use BSC to help to execute strategy by showing the cause-and-effect logic between the goals and making them measurable with performance metrics.

The indicators highlighted during the formation of the BSC allow us to move not only to the assessment of the achievement of the strategy's results, but can be used for further modeling of various relationships associated with the implementation of the Smart Energy concept, that is, they can be the basis for building econometric models that evaluate the relationships between various elements of the BSC at various levels of management. Indicators can be used to study the dynamics of the development of a company, industry, region or country when introducing innovative technologies. BSC is able to monitor the achievement of the goals set within the framework of the company's strategy, while several criteria must be met to set effective goals:

- goals should be specific;
- goals should be measurable;
- goals must be achievable;
- goals must be traceable;
- goals should be realistic.

Classical BSC is a system of a company's strategic management based on the measurement and evaluation of its effectiveness by a set of key indicators reflecting both financial and non-financial aspects of the organization's activities. According to the methodological aspects of the BSC formation, the evaluation of the effectiveness of the company's activities includes four projections (components). Accordingly, it is necessary to determine the indicators characterizing the set goals of the company, according to four projections:

- financial component;
- client component;
- internal business processes;
- education and development.

To achieve the purpose of this study, it is necessary to adapt these projections taking into account the peculiarities of the fuel and energy complex and reflect the specifics of the implementation of digital twins. Thus, it is necessary to add "innovations" to the "training and development" projection in order to take into account the importance of innovative technologies in the industry. This projection will reflect the development of the company's human capital, as well as the company's interest in introducing innovations. The "client component" projection in this study will reflect the specifics of the functioning of the energy market: since the energy industry is inextricably linked with consumers, it is necessary to take into account the "society" component. Thus, the projection will be called "Society and Market". The Finance projection reflects the financial performance of the company, and internal business processes are elements of tactical management aimed at improving the efficiency of internal processes. The adaptation of the strategic map projections is shown in **Figure 1**.

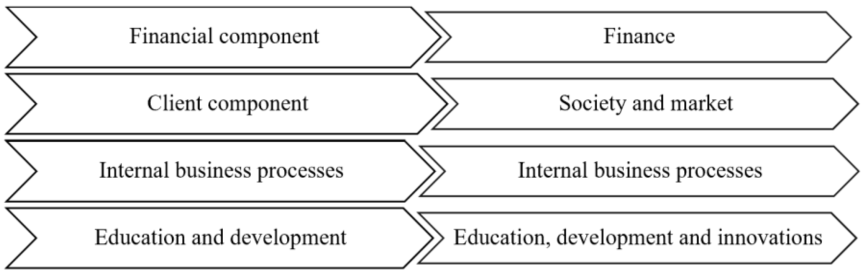

Figure 1. Adaptation of strategic map projections for the purposes of this study (developed by the authors).

3. Results and discussion

3.1. Description of goals for each BSC projection

The initial stage of BSC formation is the development of goals for each projection. The results of goal setting for each BSC projection are presented below.

Three goals were chosen for the Finance projection, taking into account the current state of the enterprise and the values of the organization. The first goal of the Finance projection is to increase profitability. Increasing profitability is the process of increasing the profit and total income of an organization. It is achieved by optimizing business processes, further reducing costs, as well as reducing the number of emergencies. The second goal of the Finance projection is to reduce equipment maintenance costs. The damage caused by accidents at hazardous production facilities includes various components:

- financial losses of the organization operating the facility;
- the costs of eliminating the accident;
- socio-economic damage associated with injuries and loss of life, as well as harm to the environment;
- indirect damage and losses to the state as a result of the loss of labor resources.

During the investigation of an accident, only those aspects of the damage are assessed, data on which are available. The final damage is calculated after the investigation is completed and all necessary data is received. The various components of the damage can be calculated independently of each other. Reduction of repair costs associated with emergency situations is possible by reducing the number of accidents at the enterprise. This is achieved by timely checking the condition of the equipment and increasing the competence of the personnel working with it.

The third goal in the Finance projection is to reduce the cost of one kilowatt-hour (kWh) and one gigacalorie (Gcal). In the production of electricity and heat at the combined heat and power station (CPH), the main share in the cost is fuel, which ranges from 50% to 70%. The cost of fuel is the largest component in the overall cost structure. To reduce the cost of electricity and heat production, a logical step would be to reduce fuel costs. In this process, the introduction of a digital twin can play an important role, helping to optimize fuel use and increase its efficiency.

The fourth goal of the Finance projection is to increase financial stability. The financial stability of the enterprise consists in ensuring a stable ability to pay obligations due to the presence of sufficient equity in the structure of financing sources. Having a sufficient share of equity, the company does not depend on external creditors, which reduces the risk of bankruptcy and ensures financial independence.

The second projection of the BSC is “Society and Market”. The first goal in this projection is to reduce the number of complaints. Customer feedback and dissatisfaction with the quality of the energy provided is a negative factor for the company. However, if an enterprise takes note of all complaints and takes appropriate measures to improve its work and the quality of services provided, then it can count on a bright future.

The second goal is to improve the quality of the released energy. The service of electric and thermal consumers is regulated by international and national standards. The quality of thermal energy is understood as the compliance of the thermodynamic parameters of the coolant (the temperature of steam and mains water in the supply pipeline and their pressure), as well as the permissible values of their deviation from the contractual operating conditions of the consumer’s heat-consuming installations. The quality of electrical energy (QEE) is the degree to which the characteristics of electrical energy at a given point in the electrical system correspond to a set of normalized QEE indicators. The quality standards of electrical and thermal energy in the general-purpose power supply system are regulated by industry standards and norms.

The third goal is to reduce harmful emissions. The benefits of reducing harmful emissions include improving the quality of the environment, reducing the impact on human health, reducing possible environmental consequences and risks, as well as increasing the social responsibility of the enterprise. Reducing harmful emissions can also lead to a reduction in the costs of fines and payments for violations of environmental norms and standards, as well as a reduction in resource consumption, which can contribute to saving money for the enterprise.

The third projection of BSC is "Internal business processes". The first goal is to increase the efficiency of CPH by introducing new technologies. Thanks to the introduction of digital technologies, in particular Digital Twins, it is possible to achieve an increase in the efficiency of the station. Increasing efficiency is an important strategy because it allows you to reduce energy consumption, improve economic efficiency and reduce the negative impact on the environment. To achieve high efficiency, various methods can be used, including improving the design and materials, optimizing processes and introducing advanced technologies.

The second goal of the "Business Processes" projection is to reduce the specific fuel consumption for the production of electric and thermal energy. Reducing fuel consumption for the production of the same amount of electricity will significantly reduce costs. New technologies and innovative developments can contribute to reducing costs.

The third goal is to reduce the number of accidents. Accidents at the enterprise occur both due to malfunctions of outdated and worn-out equipment, and due to errors committed by personnel. Repair is a complex of operations aimed at restoring serviceability and operability. To reduce or minimize accidents, it is important to constantly monitor the condition of the equipment, use diagnostic devices and carry out high-quality maintenance. To reduce accidents caused by personnel errors, it is necessary to improve the qualifications and training of employees working with aggregates. Also an effective approach is the introduction of new technologies that allow you to monitor the condition of equipment and prevent possible problems.

The fourth projection is "Training, development and Innovations". The first goal of this projection is to train personnel to work with a digital twin. Training of personnel to work with a digital twin are important steps in its implementation at the enterprise. A digital twin is a virtual model or replica of a real object, process, or system that allows for various analyses, testing, and optimization without directly affecting real objects. When training personnel to work with a digital double, it is necessary to provide them not only with technical knowledge and skills, but also to train them to understand the basic principles and capabilities of this technology.

The second goal is to develop the professional opportunities for employees. The development of the professional potential of employees is an important strategy for ensuring the successful functioning of CPH, reducing accidents and, consequently, the costs of their elimination. This strategy includes a set of activities and programs aimed at improving the knowledge, skills and competencies of employees, as well as their career development. Employees will take various advanced training courses, trainings, retraining courses and other educational events.

The third goal is to increase investments in digitalization-related activities. The benefits of digitalization include increasing efficiency and productivity, reducing costs, improving the quality of services, increasing the speed and accuracy of operations, improving the availability of information, strengthening innovation and developing new business models.

As part of the implementation at CPH, digitalization will allow:

- to conduct predictive analytics;
- optimize business processes;
- reduce fuel consumption;
- to increase the security of the enterprise.

The development of indicators was carried out with the direct participation of experts (interviews were conducted) related to the development of digital counterparts for enterprises of the fuel and energy complex. Specialists of JSC "JET Engineering and Technical Center" provide services for the creation of a digital double on a turnkey basis. The creation of digital doubles involves the complete synchronization of the model and the real object. After testing the collected data, the parameters and criteria were identified, which formed the basis for the development of the proposed system of indicators.

It is assumed that digitalization will allow CPH to increase its profitability and environmental friendliness.

3.2. Development of a strategic map

The strategic map serves as a visual representation of the goals and performance indicators. It helps in tracking the progress and impact of digital twin implementation on various aspects such as financial stability, operational efficiency, and environmental sustainability. For instance, by monitoring the reduction in specific fuel consumption and the number of accidents, the strategic map aids in identifying areas needing improvement and ensuring continuous enhancement of processes.

After describing the goals, a strategic map was built to monitor the impact of digital twins' implementation on the activities of the FEC company (**Figure 2**).

Table 1. Goals and indicators of strategic map projections (developed by the authors).

Goal	Indicators	Units of measurement	Period of time for calculations
Finance			
Increase profitability	The amount of income	rubles	Annually
Reduce equipment maintenance costs	Repair costs due to accidents	rubles	Annually
Reduce the first cost of energy	Cost of one kWh	rubles	Annually
	Cost of one Gcal	rubles	Annually
Increase financial stability of FEC	Equity concentration ratio	-	Annually
	The ratio of borrowed and own funds	-	Annually
Society and market			
Reduce the number of complaints	Number of consumer complaints	units	On quarterly basis
Improve the quality of the energy sendout	Voltage frequency deviation	hertz (Hz)	On quarterly basis
Reduce harmful emissions	Emissions of harmful substances per unit of energy produced	g CO_2/kWh	On quarterly basis

Table 1. (*Continued*).

Goal	Indicators	Units of measurement	Period of time for calculations
Internal business-processes			
Increase the efficiency of CPH by introducing new technologies	Average downtime of equipment related to failure or repair	%	Annually
	Energy production efficiency	%	Annually
Reduce the specific fuel consumption for the production of energy	Specific consumption of conventional fuel for the production of electric energy	kg/kWh	Annually
	Specific consumption of conventional fuel for the production of thermal energy	kg/Gcal	Annually
Reduce the number of accidents	Number of accidents	incident count	Annually
Training, development and Innovations			
Training of personnel to work with a digital twin	The number of people who have completed training on the simulator	number	Annually
Develop the professional opportunities for employees	Number of completed trainings and training courses per employee	units	Annually
Increase investments in digitalization-related activities	Invested funds	thousands rubles	Annually

Table 1 presents the described goals with the corresponding indicators.

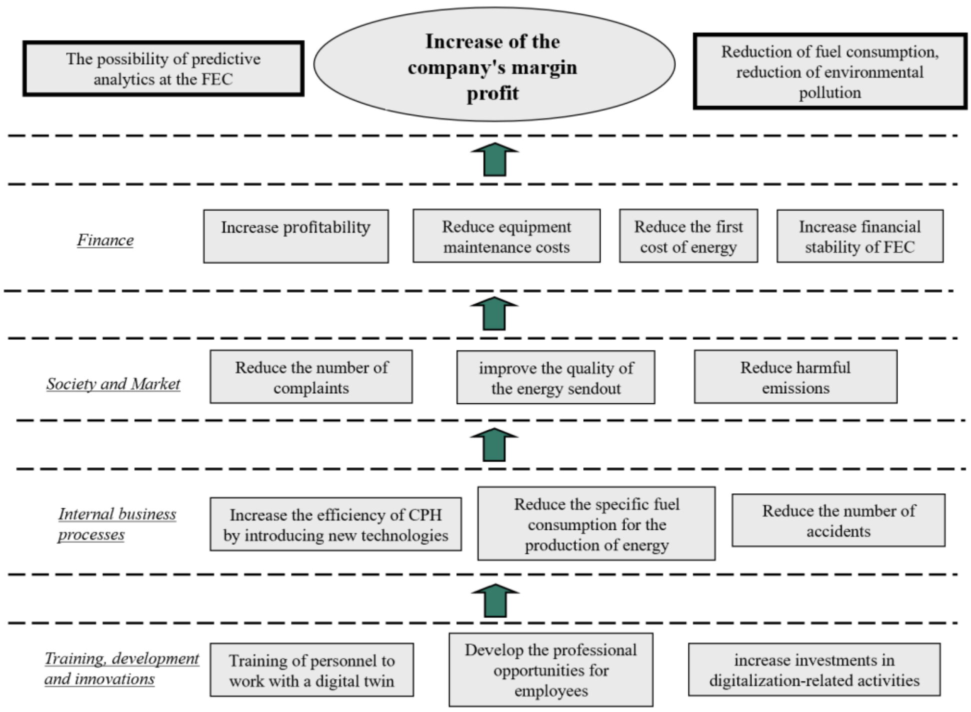

Figure 2. Strategic map (developed by the authors).

Thus, we have gradually obtained a strategic map of the introduction of a digital twin at an industrial enterprise, and also identified the necessary targets, with the help of monitoring of which the effect of the introduction of digital technologies will be clearly visible. To increase the positive effect, it is necessary to regularly monitor these indicators and develop programs to improve them.

Creating a digital twin is a difficult task, involving serious financial costs, where it is necessary to carefully evaluate the results, primarily economic, and compare them with the costs (Pan and Zhang, 2021). Economic effects within the framework of the implementation of projects on the introduction of twin technology are manifested in the effective distribution and use of financial, logistical, human resources and they are achieved in several directions at once (Golovina et al., 2020). Digital counterparts in the energy sector increase productivity and efficiency. The development and dissemination of the introduction of smart energy will contribute to the further emergence of new opportunities to improve the efficiency of FEC enterprises.

The goals of the study are structured according to the SMART criteria, ensuring specificity, measurability, achievability, relevance, and timeliness. The primary objective is to increase profitability through operational efficiencies and cost savings, tracked by monitoring income levels and cost reductions, with a target realization within the next fiscal year. Additionally, maintenance costs will be reduced by employing predictive maintenance technologies, measured by maintenance expenditure and cost per kWh, with an 18-month target for achieving these reductions.

Further goals include improving energy efficiency by optimizing processes, measured through specific fuel consumption and energy output, with an aim to achieve this within two years using existing technologies. Enhancing safety and reliability involves tracking accidents and system reliability metrics, targeting improvement within one year through advanced monitoring and safety protocols. Lastly, promoting environmental sustainability focuses on reducing emissions per unit of energy produced, targeting a three-year timeframe using clean technologies and process optimizations. These SMART goals ensure clear, realistic, and time-bound objectives that can be effectively monitored and achieved.

4. Conclusion

The implementation of indicators system for evaluating the utilization efficiency of Digital Twins at the FEC enterprise also allows the following conclusions.

1) The indicator system provides a more accurate and objective measurement of the results of the introduction of Digital Twins, which helps management to make informed decisions and optimize management processes.

2) The analysis of data collected through Digital Twins allows us to identify areas of inefficient use of resources, such as energy, fuel, time and labor resources. This allows you to optimize costs and increase the efficiency of resource use.

3) Digital Twins allow more accurate modeling and simulation of processes at the FEC enterprise, which helps to identify potential problems and errors even at the design and planning stage. This allows you to improve the quality of production and prevent possible failures and accidents.

4) Digital Twins provide the opportunity to conduct virtual training and simulations, which allows you to train personnel and develop security strategies at the FEC enterprise. This helps to reduce risks and increase safety at work.

5) Owing to Digital Twins, it is possible to actively monitor the condition of equipment, predict possible failures and take measures to prevent downtime. This helps to reduce downtime and increase the availability and reliability of the FEC enterprise.

In general, the developed system of indicators for evaluating the introduction of Digital Twins at the FEC enterprise allows to increase efficiency, optimize resources, improve production quality, ensure safety and reduce downtime, which leads to improved results and competitiveness of the enterprise.

Further research will help assess the impact of the use of digital twins on environmental performance and energy efficiency of the FEC, as well as consider the use of machine learning and artificial intelligence methods to analyze data obtained from digital twins. This can help in automating decision-making processes and conducting predictive analytics.

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References

Akimova O. E., Volkov S. K., Hryseva A. A., (2020). The concept of “Smart city”: evolution, elements and form of implementation. Theoretical economics, 6(66), 55-63

Berawi, M. A. (2022). Fostering Smart City Development to Enhance Quality of Life. International Journal of Technology, 13(3), 454. https://doi.org/10.14716/ijtech.v13i3.5733

Bhattacharya, S., Somayaji, S. R. K., Gadekallu, T. R., et al. (2020). A review on deep learning for future smart cities. Internet Technology Letters, 5(1). https://doi.org/10.1002/itl2.187

Botín-Sanabria, D. M., Mihaita, A. S., Peimbert-García, R. E., et al. (2022). Digital Twin Technology Challenges and Applications: A Comprehensive Review. Remote Sensing, 14(6), 1335. https://doi.org/10.3390/rs14061335

Dolganova, O., & Deeva, E. (2019). Company readiness for digital transformations: problems and diagnosis. Business Informatics, 13(2), 59–72. https://doi.org/10.17323/1998-0663.2019.2.59.72

Golovina, T., Polyanin, A., Adamenko, A., et al. (2020). Digital Twins as a New Paradigm of an Industrial Enterprise. International Journal of Technology, 11(6), 1115. https://doi.org/10.14716/ijtech.v11i6.4427

Holopainen, M., Ukko, J., Saunila, M., et al. (2021). The digital twin combined with real-time performance measurement in lean manufacturing. Real-Time Simulation for Sustainable Production, 165–176. https://doi.org/10.4324/9781003054214-17

IBM. (2024). What Is a Digital Twin? Available online: https://www.ibm.com/topics/what-is-a-digital-twin (accessed on 27 May 2024)

Kaplan, R. S., Norton, D. P. (2004). Strategy Maps: Converting Intangible Assets into Tangible Outcomes. Harvard Business Press: Boston, Massachusetts

Kumari, N., Sharma, A., Tran, B., et al. (2023). A Comprehensive Review of Digital Twin Technology for Grid-Connected Microgrid Systems: State of the Art, Potential and Challenges Faced. Energies, 16(14), 5525. https://doi.org/10.3390/en16145525

Lee, K. L., Romzi, P. N., Hanaysha, J. R., et al. (2022). Investigating the impact of benefits and challenges of IOT adoption on supply chain performance and organizational performance: An empirical study in Malaysia. Uncertain Supply Chain Management, 10(2), 537–550. https://doi.org/10.5267/j.uscm.2021.11.009

Odendaal, N. (2020). Everyday urbanisms and the importance of place: Exploring the elements of the emancipatory smart city. Urban Studies, 58(3), 639–654. https://doi.org/10.1177/0042098020970970

Pan, Y., & Zhang, L. (2021). Roles of artificial intelligence in construction engineering and management: A critical review and future trends. Automation in Construction, 122, 103517. https://doi.org/10.1016/j.autcon.2020.103517

Yang, H., Zhang, S., Zeng, J., et al. (2023). Future of sustainable renewable-based energy systems in smart city industry: Interruptible load scheduling perspective. Solar Energy, 263, 111866. https://doi.org/10.1016/j.solener.2023.111866

Zhou, X., Xu, X., Liang, W., et al. (2022). Intelligent Small Object Detection for Digital Twin in Smart Manufacturing with Industrial Cyber-Physical Systems. IEEE Transactions on Industrial Informatics, 18(2), 1377–1386. https://doi.org/10.1109/tii.2021.3061419