Environmental Research & Technology
https://ertjournal.org/index.php
DOI: https://doi.org/10.35208/ert.1587282

RESEARCH ARTICLE

A logistic optimization system inspired by the migration route planning abilities of storks: A new model

Ayşe Meriç YAZICI [1,*]

[1] *Istanbul Gelisim University, International Trade and Business Administration, 34310 Istanbul, Turkiye*

ARTICLE INFO

Article history
Received: 18 November 2024
Revised: 09 February 2025
Accepted: 13 February 2025

Key words:
Logistics optimization, migration behavior of storks, energy efficiency, cost reduction, time management

ABSTRACT

Storks' migration route planning capabilities have long been a focus of attention as a natural phenomenon. This study aims to examine these capabilities and provide a new perspective to the logistics sector. Inspired by the migration behavior of storks, the study presents a new logistics optimization model. The model is designed based on stork migration route planning strategies by combining nature-inspired approaches. By simulating the natural behavior of storks, the model aims to achieve basic logistics goals such as energy saving, cost reduction and effective time management. The stork-inspired logistics model is expected to provide significant advantages in logistics operations. It has the potential to increase energy efficiency, reduce costs, and improve operational efficiency in route planning. In addition, the model takes into account other important factors such as environmental sustainability and social impact. Although further research is needed to evaluate the real-world applicability and effectiveness of this model in logistics operations, it is clear that this approach provides several potential benefits to the sector. Future studies should focus on adapting the model to large-scale enterprises.

Cite this article as: Yazıcı AM. A logistic optimization system inspired by the migration route planning abilities of storks: A new model. Environmental Research and Technology, 2026, 9(1), 25-32.

INTRODUCTION

Storks draw highly efficient routes by taking into account important factors such as energy saving, adaptation to weather conditions and avoiding dangers during their migrations of thousands of kilometers [1]. The migration behaviors of these birds, just like in the logistics sector, travel over long distances by minimizing costs and maximizing efficiency [2]. In the literature, there are successful applications of nature-inspired approaches in the fields of engineering and technology. In particular, techniques such as genetic algorithms and particle swarm optimization have been shown to be effective in solving various optimization problems by imitating the behaviors of biological systems in nature [3,4,5]. The migration route planning abilities of storks are one of the most remarkable and efficient movement strategies in nature. These birds use a complex navigation system that takes into account factors such as energy conservation, adaptation to weather conditions, and avoidance of dangers while performing seasonal migrations over thousands of kilometers [6].

This study offers a new perspective in the field of logistics optimization with solutions inspired by nature. In particular, the migration route planning abilities of storks, their ability to effectively cover large distances and provide energy efficiency can be an important guide in the design of logistics processes. Today's logistics networks require solutions that provide maximum benefit with minimum resources due to limited energy resources and environmental sustainability requirements. Therefore, integrating these successful mechanisms in nature into technology and business processes can increase operational efficiency and minimize environmental impacts. In addition, it has the potential to increase not only efficiency but also the flexibility of logistics processes.

The ability of storks to overcome the difficulties they encounter in migration route planning is also valuable in terms of adapting to rapidly changing global trade conditions. Considering the sustainability dimension, the positive impact of systems to be developed in the logistics sector inspired by such natural mechanisms on the environment is great. The minimization of energy consumption by storks during their long migration journeys is also an inspiring strategy in terms of reducing carbon footprint. In light of all this information, this study aims to present an innovative solution proposal that can contribute to the efforts of the logistics sector to develop more environmentally friendly and sustainable operations by increasing energy efficiency. Thus,

* Corresponding Author: ayazici@gelisim.edu.tr (Ayşe Meriç Yazıcı)

optimization strategies in stork migration routes can form an important basis for new logistics solutions that will provide both economic and ecological benefits. The main research question of the study is "*How can a logistics optimization system inspired by stork migration route planning strategies be applied to existing logistics processes and what are the contributions of this system in terms of cost, time and energy savings?*" In order to answer this question, nature-inspired based strategies such as flock behaviors in nature and migration route planning will be examined and the most suitable model for logistics optimization will be created. In this direction, the aim of the study is to develop a nature-inspired based model for optimizing logistics processes inspired by stork migration route planning abilities and to test the functionality of this model. It is expected that this model, which will be developed by taking inspiration from nature, will be designed to provide cost and energy efficiency especially in international logistics operations. Inspired by the aerodynamic advantages of storks in their migration routes and the effective planning of their routes, a system that can save time and cost in logistics transportation processes is proposed.

THEORETICAL BACKGROUND

Migration Behavior of Storks

Storks are one of the migratory bird species that migrate thousands of kilometers every year [7]. Storks use extremely complex and optimized routes to save energy, avoid dangers and adapt to weather conditions during their migrations. These migratory movements of storks have developed as an evolutionary strategy for survival, reproduction and adaptation to environmental conditions. Migration processes include regular long-distance journeys between settlement and breeding areas and wintering areas [8]. Migratory behavior of storks is a complex event shaped by environmental factors, internal biological rhythms and social interactions. These birds minimize their energy expenditure using thermal air currents and travel long distances by taking appropriate breaks [9].

Stork migration routes are usually guided by specific geographical landmarks and air currents. During migration, these birds generally prefer to travel over land, avoiding high mountain ranges and large water bodies. This is because migrations over land save energy by taking advantage of thermal air currents [10]. Stopovers during migration are safe areas where birds can rest and recharge. These places are usually areas with rich food resources, such as wetlands and agricultural lands. Factors that storks consider when choosing stopover sites include food abundance, safety, and water resources [2,11]. Stork decision-making processes during migration have been optimized through natural selection. Birds balance energy costs, food resources, and avoiding dangers when determining migration routes. These abilities have developed over millions of years of evolutionary processes [12]. Stork migration behaviors are also characterized by their ability to adapt to changing weather conditions. These birds can adjust their routes and flight timing according to weather and wind conditions. For example, they temporarily stop their migrations in adverse weather conditions and restart them when favorable weather conditions return. Choosing the most efficient routes by taking into account air currents and wind directions increases their energy savings and migration success [2]. They also optimize their flight altitude and speed by considering factors such as air pressure and temperature. These adaptive strategies allow storks to successfully travel long distances.

Ecological and Biological Basis of the Migration Process

The migration behavior of storks is based on ecological and biological needs [13]. Migration is a survival strategy developed by storks to avoid seasonal changes due to reduced food resources or cold climate conditions [14]. Storks winter in warm climate regions and migrate north in the summer to breed in cooler and food-rich regions. These migration routes are generally fixed and storks follow the same paths to breed and winter in the same regions every year. This behavior shows that they follow their migration routes and stopovers with an internal biological clock [15]. From a biological perspective, migration behavior is closely related to storks' metabolism, energy requirements and reproductive cycles [16]. Storks spend a lot of energy during migration and therefore spend a period of intensive feeding to increase their fat stores before migration. It has also been observed that storks have developed a gliding strategy using thermal air currents during migration. This allows them to save energy and cover long distances with less energy expenditure [2].

Energy Efficiency and Conservation

Migrating storks use various strategies to maximize energy efficiency while traveling long distances. These birds use thermal air currents to glide, minimizing the need to flap their wings. Thermal air currents are columns of warm air rising from the ground's surface, and storks use these currents to reach high altitudes. They then glide, traveling long distances with minimal energy expenditure [9]. In addition, storks benefit from aerodynamic advantages by flying in groups during migration. Flying in flocks reduces the energy consumption of each stork and saves energy overall during migration [17].

The strategies developed by storks to increase energy efficiency during migration are not limited to using thermal air currents and flying in groups. These birds also optimize energy management with resting and feeding strategies at different stages of migration. Storks rest and store food at certain stopover points throughout migration, and during this process, they prepare their bodies for long-term flight by providing the necessary energy to their bodies [18]. Important stopover points, especially on the migration route between Africa and Europe, are important during the migration process of storks. These points have strategic importance in terms of having rich food resources and allowing the birds to rest safely [19]. In addition, the metabolic flexibility of storks is another important feature that increases energy conservation during migration. Storks use their body fat stores effectively by minimizing their energy consumption during long-term flights. This process, together with the change in their metabolic rates, enables their bodies to adapt to their energy needs. Thus, they create a balanced structure between their ongoing energy needs and the fulfillment of these needs during migration [20].

The strategies that storks use when choosing their routes also directly affect energy efficiency. Storks generally try to avoid the negative effects of headwinds by following wind currents. Wind speed and direction, in particular, have a great effect on storks' flight efficiency. Studies have shown that storks optimize their flight routes by taking into account the winds during migration, thus saving energy [21]. All of these strategies allow storks to maximize their energy efficiency

during migration, which allows them to successfully travel long distances.

POTENTIAL FOR APPLICATION OF NEW MODEL IN LOGISTICS OPTIMIZATION

Adaptation of Migratory Behavior to Logistics

Storks' migration behaviors exhibit superior abilities in energy efficiency and risk management [22]. Storks' ability to save energy, strategically choose stopovers and adapt to weather conditions while determining migration routes can be directly applied in logistics processes. For example, storks' ability to save energy by using thermal air currents can be a source of inspiration for reducing energy costs in determining logistics routes [23].

In logistics optimization, new models inspired by storks' migration behaviors can provide more efficient and cost-effective solutions in issues such as selection of transportation routes and stopovers. For example, logistics companies can optimize their routes to save energy by analyzing weather and environmental data. Just as storks use thermal currents to choose resting points, stopover points or storage centers can be strategically determined in logistics processes to reduce fuel consumption and energy use of vehicles [24]. In addition, the most efficient routes can be calculated in advance according to weather conditions, traffic density, and environmental conditions using smart algorithms and artificial intelligence. This approach creates a new paradigm that can add both environmental and economic value to the sector by increasing applicability in areas such as supply chain management, cargo transportation and air transportation with the integration of real-time data and artificial intelligence.

Route Planning and Management

The strategies used by storks to determine their migration routes offer new perspectives for route planning and management in the logistics sector. Storks choose the most suitable routes to save energy and avoid dangers. This approach can also be used in logistics to determine the shortest and safest routes. In addition, the fact that storks dynamically adjust their routes according to weather conditions emphasizes the importance of flexible route planning in the logistics sector according to changing traffic and weather conditions [25]. In particular, examining the biological mechanisms of storks in energy saving and adapting to environmental factors can add new dimensions to existing dynamic route planning approaches. Therefore, the contribution of the study lies in the potential to expand applications in the sector and increase sectoral integration opportunities.

Energy-saving methods such as the use of thermal air currents in planning logistics routes can reduce fuel consumption and operational costs. For example, in road transport, fuel consumption can be reduced by transporting during hours and routes with low traffic density [26]. The strategic movements of storks that minimize energy consumption by taking advantage of thermal currents are a source of inspiration in logistics operations beyond energy savings, in terms of adapting to changing environmental conditions and increasing sustainability. This model provides a roadmap for how dynamic adaptation can be achieved in logistics processes, drawing inspiration not only from the implementation of existing strategies, but also from the storks' ability to evaluate environmental data in real time.

Cost Reduction Strategies

Logistics models inspired by the migration behavior of storks can also offer significant advantages in terms of cost reduction strategies [9]. In the logistics sector, strategic positioning of warehouses and distribution centers can reduce operational costs, just as storks optimize their food and resting areas. Positioning warehouses and distribution centers close to main transportation routes and in easily accessible locations will reduce transportation costs. In addition, the environmental impact and cost of logistics operations can be reduced by using energy-efficient vehicles and sustainable fuels [27]. Unlike traditional approaches, this model proposes a method that is not static in the positioning of warehouses and distribution centers, but is continuously optimized according to environmental factors and operational needs. This represents a new perspective that aims to provide superiority in terms of cost, energy efficiency and operational sustainability by taking advantage of not only geographical proximity but also real-time logistics data and variables.

Time Management and Efficiency

The optimal time management and energy efficiency of storks during migration is an example of time management and efficiency in the logistics sector. This strategy can also shorten delivery times and increase efficiency by transporting in the most appropriate time periods in logistics operations [2]. Time management in logistics directly affects delivery times and customer satisfaction. Biomimetic models inspired by the migration behavior of storks can optimize time management in logistics processes. For example, the fastest and most efficient delivery routes can be determined by analyzing traffic and weather conditions using real-time data. These approaches can significantly improve time management and operational efficiency in the logistics sector [28].

Figure 1 shows the logistics optimization system inspired by the migration route planning capabilities of storks.

Inspired by the migration route planning abilities of storks, the logistics optimization system aims to plan the routes, rest and maintenance stops of vehicle fleets in the most efficient way by imitating the natural migration behaviors of storks. Storks' energy saving, risk avoidance and efficient use of natural resources strategies are perfected examples of the evolution process that nature has gone through over millions of years. Inspired by these strategies, the system aims to make logistics processes more sustainable both economically and environmentally. The system also provides a concrete example of how learning from nature can create value in logistics operations.

Each component of the system is designed as a reflection of the natural migration behaviors of storks and works together to optimize logistics processes. This system tries to maximize energy saving, safety and efficiency by optimizing logistics processes with real-time data collection and analysis, advanced route optimization algorithms and user-friendly interface.

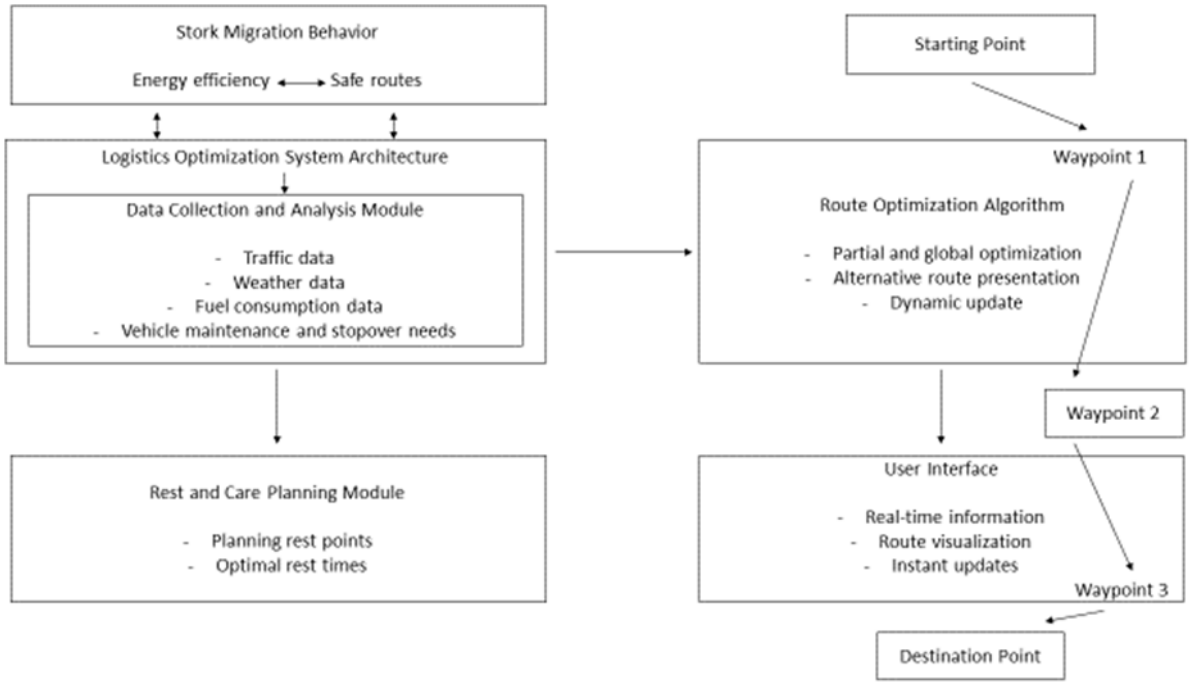

Figure 1. Logistics optimization system inspired by storks' migration route planning abilities. Source: [Authors's own design]

Table 1. Elements of the invention and their importance

Element, No	Element Name	New	Prior Art	Very important for my invention	Function of the Element
1	Logistics Data Analysis and Optimization Algorithms	Yes	Yes	Yes	This element defines data analysis and optimization algorithms specifically designed for logistics operations. These algorithms are important for increasing efficiency and reducing costs.
2	Natural Balance and Adaptation Capabilities	Yes	No	Yes	The invention draws inspiration from natural balance and adaptability, and highlights the ability of logistics operations to adapt to various conditions.
3	Automatic Route Planning and Optimization	Yes	Yes	Yes	The system automatically plans and optimizes routes. This allows for efficient management of logistics operations and cost reduction.
4	Real-Time Data Monitoring and Analysis	Yes	Yes	Yes	This element enables the monitoring and analysis of real-time data from logistics operations. This allows for continuous monitoring and improvement of operations.

Source: own work [Authors's own design]

Analysis of Natural Routes: The system analyzes natural routes by examining the migration routes and planning abilities of storks. This is a process inspired by the impressive navigation abilities of storks in nature. Storks use various strategies to use their energy most efficiently and reach their destinations safely while migrating. Inspired by these strategies, the logistics optimization system will have energy efficiency and safe routes components:

Energy Efficiency: Determines the shortest and fastest routes to optimize fuel consumption of vehicles.

Safe Routes: Chooses safe routes by avoiding traffic congestion and adverse weather conditions.

Logistics Optimization System Architecture: The system consists of a series of algorithms inspired by the ability of storks to plan their migration routes. These algorithms include the following components to optimize logistics processes:

Data Collection and Analysis Module: The system collects and analyzes data from logistics operations. This data includes

factors such as traffic data, weather data, fuel consumption data, and vehicle maintenance and stopover needs.

Route Optimization Algorithm: Using the analyzed data, the system applies specially designed optimization algorithms. These algorithms determine the most suitable routes and delivery plans, while trying to minimize costs and optimize delivery times. The route optimization algorithm determines the best routes using partial and global optimization techniques. This algorithm offers alternative routes and dynamically updates these routes.

Rest and Maintenance Planning Module: Plans strategic stops for vehicle break and maintenance needs. Determines the most suitable rest points and times.

User Interface: Provides real-time information for drivers and fleet managers. Provides visualization of the route and instant updates.

A list of the elements of the invention in order of importance is shown in Table 1.

INDUSTRIAL APPLICABILITY OF THE INVENTION AND APPLICATION FORM

Data Collection and Analysis

Sensors and IoT Devices: Real-time data is collected with sensors and IoT devices placed in transportation vehicles, warehouses and other logistics points. For example, important data such as instant traffic density, weather or road conditions can be collected thanks to sensors placed on vehicles. This data is processed by advanced analysis software, allowing dynamic creation of routes that minimize energy consumption of transportation vehicles and avoid risks. In addition, IoT devices used in warehouses monitor stock movements and allow adjustments to be made according to demand intensity in route planning. Thus, the role of sensors and IoT devices is not limited to collecting data only, but also serves to transform storks' strategies into real-time application in logistics processes.

OPTIMIZATION ALGORITHMS

Energy Efficiency: Storks' strategies that increase energy efficiency are optimized to minimize fuel consumption of transportation vehicles.

Security and Risk Management: Risk analyses are performed to determine safe routes by avoiding dangerous areas.

Timeliness and Efficiency: Optimization algorithms are used to ensure that transportation processes are carried out on time and effectively.

ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING

Adaptation Ability: AI and machine learning algorithms create flexible logistics routes that can quickly adapt to changing conditions. For example, a distribution company can analyze historical order data and seasonal demand spikes to predict which areas will be congested during certain periods. In addition, weather forecasts and traffic density data can be combined to plan alternative routes in advance, anticipating possible delays or obstacles such as road closures. These models have the potential to reduce operational costs and increase customer satisfaction, especially by making more effective planning in supply chain management.

APPLICATION AND MONITORING

Navigation Systems: Navigation systems integrated into transportation vehicles allow for the tracking of optimized routes.

Real-Time Monitoring: Monitoring systems are used to monitor logistics processes in real time and intervene immediately when necessary.

CONTINUOUS IMPROVEMENT

Feedback and Evaluation: The system is continuously improved by evaluating the feedback and performance data obtained from transportation processes.

Integration of Innovative Technologies: New technological developments and innovations are continuously integrated into the system, providing a competitive advantage.

Deficiencies and Inadequacies in Current Applications

Current logistics systems generally plan on static routes. This can cause difficulties in adapting to variable demand and traffic conditions. Some systems are inadequate in providing flexibility in operations. There is no necessary adaptation ability to cope with unexpected events or changing demands. Logistics systems are also limited in optimizing routes and increasing efficiency. This situation causes extra costs and waste of resources. Although advanced technologies such as quantum computing offer promising potential in this context, it will take time for these technologies to reach large-scale applicability in the logistics sector. The model offers a flexible model that can be optimized with existing technologies and supported by quantum computing in the future during this transition process. In addition, the advantage of the model is that it is inspired by biological systems in nature to simplify complex algorithms and optimize parameters.

Benefits of the Invention

The study also suggests the use of real-time data analysis and machine learning-based algorithms in logistics operations inspired by the migration route planning mechanisms of storks. This system constantly monitors variables such as traffic, weather and demand intensity with sensors and IoT devices, and this data is processed by artificial intelligence algorithms to dynamically determine the most suitable routes. Inspired by the adaptation of biological systems to environmental conditions, the proposed model optimizes the ability to rapidly adapt to changing conditions in logistics operations. In addition, the system optimizes routes, reducing fuel consumption and operational costs while providing maximum efficiency in resource use.

Advantages and Contributions

The idea offers superiority over existing systems in terms of flexibility. It can quickly adapt to changing demands and conditions. The system makes a significant contribution to optimizing routes and managing operations efficiently. Being designed inspired by the migration route planning abilities of storks brings a natural balance and adaptation ability to the system.

CONCLUSION

Today, sustainability and energy efficiency are among the strategic priorities for the logistics sector. Increasing carbon

emissions and environmental impacts have caused companies to rethink their logistics processes. Biomimicry-based solutions can offer a great advantage to logistics companies at this point. Storks' ability to travel long distances by saving energy can create a similar effect in logistics processes, which can contribute to reducing the carbon footprint. In addition, it is inevitable to implement new technologies in order to increase operational efficiency in the logistics sector.

The value of the study lies in its unique approach to integrate a natural phenomenon such as stork migration routes into a logistics optimization solution. This model not only establishes a theoretical connection, but also proposes a solution that can be directly applied to operational processes with real-time data and artificial intelligence-based algorithms. The model aims to solve practical problems such as automatically optimizing logistics routes, adapting to changing weather conditions, traffic density and demand fluctuations. This allows for the creation of a more flexible and efficient logistics infrastructure by overcoming the static structure of existing route systems in the industry.

The model to be developed in this study is one of the first models to emerge by integrating storks' migration route planning abilities into logistics processes. The fact that storks optimize their routes by taking energy efficiency and environmental conditions into account will be used as a source of inspiration for this model and will enable the development of a new logistics strategy. In addition, the originality of the study is that it does not only present a theoretical study, but also includes a model on how this study can be applied in practice.

The logistics optimization model inspired by the migration route planning abilities of storks offers a number of advantages. First of all, it uses natural algorithms to provide energy efficiency and reduce environmental impact. Inspired by the migration strategies of storks, the logistics optimization model is based on the integration of natural algorithms and risk management strategies aimed at reducing environmental impact with logistics operations. For example, the energy efficiency algorithm works on parameters that provide minimum energy consumption in transportation routes by integrating with real-time weather data. The risk management algorithm determines the safest routes by analyzing traffic density and safety data. These concrete algorithms increase the applicability and benefit of the system and directly contribute to logistics processes in the sector. However, some difficulties may be encountered in the implementation of this new model. In particular, adapting biomimetic approaches to industrial applications can be a complex process. In addition, the model needs to be developed in a way that is compatible with existing technologies and integrated with operational processes. In conclusion, this new logistics optimization model inspired by the migration route planning abilities of storks has significant potential in the industry. This model can increase energy efficiency, reduce costs and make logistics operations more efficient. However, further research and development efforts are required, which could lead to a wider adoption of biomimetic approaches in the logistics sector.

RECOMMENDATIONS

In this study, a new logistics optimization model inspired by the migration route planning abilities of storks is presented. This model has the potential to reduce efficiency and costs in logistics operations by taking the natural behavior of storks as a basis. The migration behavior of storks is a phenomenon that has attracted the attention of scientists and has been the subject of research for years. The strategies used by these birds while planning their long-distance migration routes are seen as an example of natural optimization. The study directly relates to elements such as migration strategies of storks, energy efficiency, risk aversion and adaptation to environmental conditions, and these elements can be embodied in algorithms that optimize the routes of logistics vehicles. These algorithms can be used to provide dynamic route planning that can quickly adapt to changing weather conditions, traffic density and delivery demands, supported by real-time data analysis, artificial intelligence and IoT technologies. Therefore, the applicability of the model will be ensured by integrating algorithms and technologies that mimic the natural behavior of storks into logistics systems, and a biomimetic approach will be adopted rather than a physical connection.

There are several important points to discuss about this new model. First, it should be examined how suitable the model is for real-world logistics operations and to what extent it is applicable. In addition, the performance and efficiency of the model should be evaluated in comparison with existing logistics systems.

The potential advantages of adopting nature-inspired approaches in the logistics sector should also be discussed. This approach can increase environmental sustainability, reduce energy consumption and reduce operational costs. Additionally, models inspired by nature can enable logistics systems to be more flexible and adaptable, responding more effectively to changing market conditions.

Theoretical Findings and Evaluation

The obtained theoretical findings show how the natural behavior of storks can be applied in logistics operations. Stork migration route planning strategies have the potential to be applied in many areas such as determining transportation routes, warehouse layout, delivery timing and use of transportation vehicles in the logistics sector. These strategies can increase energy efficiency, reduce costs and improve operational efficiency. However, translating these theoretical findings into practical application may face some difficulties. In particular, adapting nature-inspired models to industrial applications and integrating them with existing logistics systems can be a complex process. In addition, further experimental studies and field tests are required to determine how effective and applicable this model is in real-world logistics operations.

Contributions and Innovations to the Logistics Sector

Inspired by the migration route planning abilities of storks, this model can increase energy efficiency, reduce costs and improve operational efficiency in the sector. It can also enable sustainable logistics operations by reducing environmental impact. The innovations provided by this model to the logistics sector include increasing flexibility and adaptability. Inspired by the natural strategies of storks, this model can respond more quickly and effectively to changing market conditions. It also encourages innovative approaches in the sector by addressing increasingly important issues such as energy efficiency and environmental sustainability.

LIMITATIONS

There are some limitations to this study. First of all, developing a logistics optimization model inspired by the migration route planning abilities of storks is a complex process and it may take time to translate this model into practical application. In addition, it may be difficult to fully mimic the natural behaviors of storks and adapt these behaviors to logistics operations. However, it should be determined how well the model is suitable for real-world logistics operations and to what extent it is effective. The performance of the model should be evaluated in comparison with existing logistics systems. In addition, further research should be conducted on how the model can be adapted to large-scale logistics networks and how it can be applied on an industrial scale.

RECOMMENDATIONS FOR FUTURE WORK

A number of recommendations can be made for future work. First of all, the model needs to be validated with more experimental studies and field tests. This is important to determine how effective the model is in real-world logistics operations. In addition, further research should be conducted on how the model can be adapted to larger-scale logistics networks and how it can be applied on an industrial scale. In addition, new algorithms and optimization techniques need to be developed to improve the performance of the model. It is important to develop new approaches that will address more complex logistics scenarios and provide more accurate and efficient solutions. In addition, the model needs to be expanded to take into account other important factors such as environmental sustainability and social impact. Finally, it should be considered that this model, inspired by the migration route planning abilities of storks, can be part of a broader biomimetic approach by also taking inspiration from the behavior of other animal species. This could allow for the development of more innovative and effective solutions in logistics optimization.

DATA AVAILABILITY STATEMENT

The author confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

USE OF AI FOR WRITING ASSISTANCE

Not declared.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1]. J.S. Kirby, A.J. Stattersfield, S.H. Butchart, M.I. Evans, R.F. Grimmett, V.R. Jones, J. O'Sullivan, G.M. Tucker, and I. Newton, "Key conservation issues for migratory land-and waterbird species on the world's major flyways". Bird Conservation International, Vol. 18 (S1), pp.49-73, 2008. https://doi.org/10.1017/S0959270908000439

[2]. T. Alerstam, "Optimal bird migration revisited", Journal of Ornithology, Vol. 152 (Suppl 1), pp.5-23, 2011. DOI 10.1007/s10336-011-0694-1

[3]. S. Binitha, and S.S. Sathya, "A survey of bio inspired optimization algorithms", International journal of soft computing and engineering, Vol. 2 (2), pp.137-151, 2012.

[4]. A.K. Kar, "Bio inspired computing–a review of algorithms and scope of applications", Expert Systems with Applications, Vol. 59, pp.20-32, 2016. https://doi.org/10.1016/j.eswa.2016.04.018

[5]. S. Darvishpoor, A. Darvishpour, M. Escarcega, and M. Hassanalian, "Nature-inspired algorithms from oceans to space: A comprehensive review of heuristic and meta-heuristic optimization algorithms and their potential applications in drones". Drones, Vol. 7 (7), p.427, 2023. https://doi.org/10.3390/drones7070427

[6]. E. Nourani, and N.M. Yamaguchi, "The effects of atmospheric currents on the migratory behavior of soaring birds: a review", Ornithological Science, Vol. 16 (1), pp.5-15, 2017. https://doi.org/10.2326/osj.16.5

[7]. A. Flack, M. Nagy, W. Fiedler, I.D. Couzin, and M. Wikelski, "From local collective behavior to global migratory patterns in white storks", Science, Vol. 360 (6391), pp.911-914, 2018. DOI:10.1126/science.aap7781

[8]. D. Chevallier, Y. Handrich, J.Y. Georges, F. Baillon, P. Brossault, A. Aurouet, Y.L. Maho, and S. Massemin, "Influence of weather conditions on the flight of migrating black storks", Proceedings of the Royal Society B: Biological Sciences, Vol. 277 (1695), pp.2755-2764, 2010. https://doi.org/10.1098/rspb.2010.0422

[9]. P. Berthold, "Bird migration: a general survey", Oxford University Press, 2001.

[10]. T.A. Miller, R.P. Brooks, M.J. Lanzone, D. Brandes, J. Cooper, J.A. Tremblay, J. Wilhelm, A. Duerr, and T.E. Katzner, "Limitations and mechanisms influencing the migratory performance of soaring birds", Ibis, Vol. 158 (1), pp.116-134, 2016. https://doi.org/10.1111/ibi.12331

[11]. N.J. Bayly, K.V. Rosenberg, W.E. Easton, C. Gomez, J.A.Y. Carlisle, D.N. Ewert, A. Drake, and L. Goodrich, "Major stopover regions and migratory bottlenecks for Nearctic-Neotropical landbirds within the Neotropics: a review", Bird Conservation International, Vol. 28 (1), pp.1-26, 2018. https://doi.org/10.1017/S0959270917000296

[12]. V. Salewski, and B. Bruderer, "The evolution of bird migration—a synthesis", Naturwissenschaften, Vol. 94, pp.268-279, 2007. DOI: 10.1007/s00114-006-0186-y

[13]. C. López-Calderón, V. Martín-Vélez, J. Blas, U. Höfle, M.I. Sánchez, A. Flack, W. Fiedler, M. Wikelski, and A.J. Green, "White stork movements reveal the ecological connectivity between landfills and different habitats", Movement Ecology, Vol. 11 (1), p.18, 2023. https://doi.org/10.1186/s40462-023-00380-7

[14]. B. Martín, A. Onrubia, and M. Ferrer, "Migration timing responses to climate change differ between adult and juvenile white storks across Western Europe", Climate Research, Vol. 69 (1), pp.9-23, 2016. DOI: https://doi.org/10.3354/cr01390

[15]. D. Vaitkuviene, M. Dagys, G. Bartkeviciene, and D. Romanovskaja, "The effect of weather variables on the White Stork (Ciconia ciconia) spring migration phenology", Ornis Fennica, Vol. 92 (1), pp.43-52, 2015. https://doi.org/10.51812/of.133867

[16]. J.M. Cornelius, T. Boswell, S. Jenni-Eiermann, C.W. Breuner, and M. Ramenofsky, "Contributions of

endocrinology to the migration life history of birds", General and Comparative Endocrinology, Vol. 190, pp.47-60, 2013. https://doi.org/10.1016/j.ygcen.2013.03.027

[17]. A. Hedenström, "Migration by soaring or flapping flight in birds: the relative importance of energy cost and speed", Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences, Vol. 342 (1302), pp. 353-361, 1993. https://doi.org/10.1098/rstb.1993.0164

[18]. S. Massemin-Challet, J.P. Gendner, S. Samtmann, L. Pichegru, A. Wulgue, Y. and Y. Le Maho, "The effect of migration strategy and food availability on White Stork Ciconia ciconia breeding success", Ibis, Vol. 148 (3), pp. 503-508, 2006. https://doi.org/10.1111/j.1474-919X.2006.00550.x

[19]. J. Arizaga, J. Resano-Mayor, D. Villanúa, D. Alonso, J.M. Barbarin, A. Herrero, J.M. Lekuona, and R. Rodríguez, "Importance of artificial stopover sites through avian migration flyways: A landfill-based assessment with the White Stork Ciconia ciconia", Ibis, Vol. 160 (3), pp.542-553, 2018. https://doi.org/10.1111/ibi.12566

[20]. C.J. Pennycuick, "Modelling the flying bird", Elsevier, 2008.

[21]. S. Åkesson, and A. Hedenström, "How migrants get there: migratory performance and orientation", BioScience, Vol. 57 (2), pp.123-133, 2007.

[22]. R. Harel, O. Duriez, O. Spiegel, J. Fluhr, N. Horvitz, W.M. Getz, W. Bouten, F. Sarrazin, O. Hatzofe, and R. Nathan, "Decision-making by a soaring bird: time, energy and risk considerations at different spatio-temporal scales", Philosophical Transactions of the Royal Society B: Biological Sciences, Vol. 371 (1704), 20150397, 2016. https://doi.org/10.1098/rstb.2015.0397

[23]. F. Oloo, K. Safi, and J. Aryal, "Predicting migratory corridors of white storks, ciconia ciconia, to enhance sustainable wind energy planning: a data-driven agent-based model", Sustainability, Vol. 10 (5), p.1470, 2018. https://doi.org/10.3390/su10051470

[24]. Q. Liu, "Logistics Distribution Route Optimization in Artificial Intelligence and Internet of Things Environment", Decision Making: Applications in Management and Engineering, Vol. 7 (2), pp.221-239, 2024. https://doi.org/10.31181/dmame7220241072

[25]. T. Alerstam, "Conflicting evidence about long-distance animal navigation", Science, Vol. 313 (5788), pp.791-794, 2006. DOI: 10.1126/science.1129048

[26]. K. Behnke, and M.F.W.H.A. Janssen, "Boundary conditions for traceability in food supply chains using blockchain technology", International Journal of Information Management, Vol. 52, 101969, 2020. https://doi.org/10.1016/j.ijinfomgt.2019.05.025

[27]. V. Pajić, M. Andrejić, M. Jolović, and M. Kilibarda, "Strategic warehouse location selection in business logistics: A novel approach using imf SWARA–MARCOS—A case study of a Serbian logistics service provider", Mathematics, Vol. 12 (5), p.776, 2024. https://doi.org/10.3390/math12050776

[28]. A.S. Umair, W. Zhang, Z. Han, and S.H.U. Haq, "Impact of logistics management on customer satisfaction: A case of retail stores of Islamabad and Rawalpindi", American Journal of Industrial and Business Management, Vol. 9 (8), pp.1723-1752, 2019. DOI: 10.4236/ajibm.2019.98113