Innovative methods and research directions in the field of logistics

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Abstract. By the 21st century, logistics and various supply chains had become key units in the global market and corporate structures. Industry 4.0 has brought developments and implementations to life that have drastically changed and are still changing the practices used in certain areas of logistics. Many new technologies (advanced robotics, additive manufacturing, artificial intelligence (AI), blockchain, drones, Internet of Things (IoT)) have emerged in the digital world, which many companies are using to develop cyber-physical systems in order to increase efficiency, speed, accuracy and the ability to change and steer competition between companies around the world. Planning tasks at the strategic, tactical and operational levels are covered in the areas of production and logistics. The tasks presented here can be identified as extremely complex optimization problems that belong to the np-hard complexity class. These can be addressed in many cases with metaheuristics, and industry also often uses search strategies inspired by biological or physical processes. Metaheuristic algorithms simulate the behavior of a selected phenomenon in a given search area. Algorithms based on various principles can help optimize processes, such as: population-based algorithms, evolutionary methods, behavior-inspired procedures, swarm intelligence methods, etc. New technologies or metaheuristic procedures are also increasingly used in logistics due to the complexity of the tasks. This paper presents theoretical application possibilities of digital transformation, AI and IoT in the field of logistics. The paper provides a further brief overview of the problems surrounding metaheuristics, supported by examples. The article shows the impact of different Industry 4.0 technologies on logistics. There is a shortage of such comprehensive studies, so the article helps provide insight into innovative optimization opportunities in a larger area - the field of logistics. Within this one paper, the impact of new technologies on the field of logistics was collected. A brief description of these will help to identify further directions and deepen the applicability of the new methods in logistics.

1. Introduction

In recent decades, the study and continuous development of various optimization processes has become a defining task and approach in almost every area of the industry. For companies, the rapid development of computing technology, the technologies brought to life by Industry 4.0, and a variety of intelligent solutions offer more and more opportunities to improve, among other things, speed, flexibility, and cost-effective solutions.

The benefits of the global market can best be reaped by companies setting up supply chains in different countries around the world. This process, of course, increases the complexity of the chains,
making it a major challenge for partner companies. It is essential for the proper functioning of global integrations that modern information technology systems are used and utilized in logistics systems and supply chains. [1]

The Fourth Industrial Revolution (Industry 4.0) and the new technologies that have emerged with it have been the focus of attention over the past few decades. Researchers have also been attracted to new techniques (Internet of Things, advanced robotics, artificial intelligence, additive manufacturing, blockchain, drones). A number of studies have addressed their applicability, effects, scalability, and adaptations. Industry 4.0 technologies can also change best practices in logistics processes and supply chains. As a result, the research community of operational management will also have the opportunity to examine the new research issues raised by new technologies and the implications of their application. Under certain conditions, these new technologies have the potential to create economic, social or environmental value, and these conditions can be examined to maximize their value-creating impact on supply chains. [2]

The logistics industry also uses metaheuristics many times, as logistics problems belong to the np-hard complexity class due to their complexity, and one of the best solutions to solve them is these algorithms.

The paper provides a brief overview of Industry 4.0 technologies and their relationship to logistics and discusses the applications of metaheuristics and the problems surrounding them.

2. Technological Advancements in Industry 4.0
This chapter briefly introduces some of the Industry 4.0 technologies and their interfaces with logistics. Due to the diversity and complexity of logistics, numerous optimization tasks and problems arise in this area. Their solution has been a challenge in the past, but Industry 4.0 also offers opportunities to simplify decision-making processes in logistics, manufacturing, warehousing, shipping, or give new perspectives to individual areas or past practices.

One of the biggest demands of manufacturing companies as well as supply chains is to ensure their competitiveness in the global market. This also requires the key features of the Fourth Industrial Revolution: increased efficiency, productivity, flexibility and sustainability. Industry 4.0 technologies also support the development of an intelligent manufacturing environment system. These technologies include a number of methods (Ozemel and Gursev also refer to them as components of I4.0), which may include, but are not limited to: cloud-based systems, IoT platforms, 3D printing, big data analysis, algorithms, heuristics, metaheuristics, intelligent sensors, advanced robotics, etc. [4] [5]

2.1. Additive Manufacturing (AM)
Additive manufacturing (3D printing) is a revolutionary technology capable of producing objects with complex shapes and internal geometries for which conventional manufacturing methods are not suitable. Its huge advantage is that it does not require a new setting when switching between the production of objects of different shapes and geometries, thus eliminating the shortcomings of conventional manufacturing technologies - in many cases - in terms of flexibility, speed and cost. As a result, the speed of market entry will also increase significantly. These can also reduce the upfront production cost, as no separate production investment is required due to product specifications. It will be possible to fashion products produced in small quantities profitably. How does additive manufacturing affect logistics? AM may be able to change the entire supply chain architecture. It is a possible vision that for some products, instead of an operating strategy for mass production, which may be limited, your mass will be characterized by individual production. This change can be brought to life by AM’s promised speed, quality, flexibility and cost benefits. [6]

Of course, many disadvantages currently limit the wide applicability of AM technologies: different materials require different AM technologies, size, strength, evenness of the product is also a bottleneck. Additionally, the cycle time of AM is usually slower than the cycle time of conventional manufacturing methods, so in some cases considerable time is required for post-processing. Because of these, AM currently performs better than conventional methods with lower production volumes. [2] [6]
2.2. The Internet of Things (IoT)

IoT is one of the latest IT developments, a network that consists of uniquely identifiable endpoints (or "things") that communicate over an IP connection without human intervention. Sensors at the end of the networks are connected to physical devices (such as trucks, freighters, wind turbines, drilling rigs, and smart meters). Efficiency in logistics processes according to Ellis et al. (2015) lies in: The amount of data released from these tools is related to supply chain processes. They provide unprecedented insight into real-time conditions when data is collected and analyzed efficiently and properly. This way, we can get an early warning of problematic situations and take immediate action on recovery. If the response to the signals is timely, the efficiency of the supply chain can rise to a new level. [7]

There are numerous definitions of IoT, many of which have been collected in the paper by Ben-Daya, Hassini, and Bahroun (2017), but in this study we consider what is proposed to define IoT in relation to supply chain management to be authoritative: “The Internet of Things is a network of physical objects that are digitally connected to sense, monitor and interact within a company and between the company and its supply chain enabling agility, visibility, tracking and information sharing to facilitate timely planning, control and coordination of the supply chain processes.” (Ben-Daya, Hassini and Bahroun, 2017) [8]

One of the biggest benefits of IoT is that companies can have accurate data on current inventory levels, including its environment. As a result, they are able to transport a much wider range and volume of data at both the production and logistics levels. Questions may arise as to what types of data are most useful and how best to use the data obtained. This can also be extremely useful information in other areas and for the application of other procedures (e.g. optimization algorithms). [6] Holdowsky et al. (2015) argue that one of the most significant capabilities of the IoT is its ability to generate information in previously unseen conditions where there is no human observation. [9] So IoT can really help to obtain information and data that can be of great help in real-time optimization through in-house but also other (devices, facilities) networks. This will allow to optimize at the system level and find the most effective solution to a particular problem. [10]

Verdouw et al. (2016), for example, suggest the use of IoT to manage the food supply chain, as Internet technologies enable supply chains to dynamically leverage virtualization in operational management processes as well. This virtualization also gives supply chain players the ability to monitor, manage, plan and optimize business processes over the Internet remotely and in real-time, and take immediate action in the event of discrepancies [11]

However, it should also be noted that IoT devices pose significant security and privacy issues (e.g., devices may disrupt other technologies, attack users’ devices or systems, and some IoT devices may remain unattended, thereby exposing them to physical attacks), but the literature on possible solutions is fortunately growing year by year. [12]

2.3. The Blockchain

Companies want to store supply chain data sets more and more, thanks to IoT, in a secure but accessible way. The blockchain is a possible solution for this, which is a distributed and secure general ledger (stores information). The advantage is that it can be accessed, modified or supplemented from anywhere, the data is not stored in a central location, but on a so-called peer-to-peer network. It cannot be modified unilaterally after a new block has been added to the chain. Its distributed nature provides more flexibility than a central database and allows information about the entire history of a product to be stored as it travels throughout the supply chain. The information in the blockchain can be digitized, it can be automatically uploaded from the data of the IoT sensor, for example. The disadvantage may be that the quality of the information is inadequate, not factual, but in an IoT blockchain combination, if the sensor units are accurate, the information in the blockchain will be the same. An important application of the blockchain is also the availability of “smart contracts”. This means that these contracts are automatically activated based on some externally controlled event (e.g. the container arrives at customs, payment can be authorized immediately). [6]
2.4. Artificial Intelligence (AI)

The term artificial intelligence nowadays means much more than human intelligence when it comes to the automation of thinking in terms of games (e.g., chess), proving mathematical theorems, making a diagnosis, or translating text. With a wealth of intelligent solutions, decision support software, optimization programs, and the rapid development of IT technologies, AI’s algorithms are also capable of solving increasingly complex tasks, helping professionals work. Like Industry 4.0, AI does not have a single specific, exact definition, it is used in summary to indicate that it is not a person but a computer that is involved in problem solving. Machine learning, expert systems, neural networks, metaheuristics, IoT alone or together robotics, increase the efficiency and applicability of artificial intelligence. [6]

According to the paper by Vemuri et al. (2021), the application of AI contributes to the development of all undertakings. Its use also has an impact on the business environment, enhances the speed and productivity of business operations, raises the standard of monitoring, develops talent management skills, and expands the capabilities of the business organization. [13]

As a result of Industry 4.0 technologies, the use of digitization, IoT, and AI is becoming increasingly important in supply chains. The field of logistics is of great importance to the global market, which is why the term Logistics 4.0 summarizes the possibilities for optimizing logistics chains and networks using intelligent technologies. The goal of Logistics 4.0 is to adapt the flow of materials and information to the requirements of Industry 4.0 technologies, thereby increasing the efficiency of the entire supply chain. [14]

Toorajipour et al. (2021) carried out a comprehensive analysis of, inter alia, AI techniques in the field of logistics and supply chain. The following have been identified: field logistics: Automated planning, Artificial neural networks, Data mining, Agent-based/multi-agent systems, Simulated annealing, Robot programming, General forms of AI, Heuristics; field supply chain: Artificial neural networks, Agent-based/multi-agent systems, FL/modelling, General forms of AI, Physarum model, Swarm intelligence, Bayesian networks, Data mining, Stochastic simulation, Support vector machines. [15]

It can be seen, therefore, that AI’s growing raison d’être in logistics and supply chains is gaining ground and emerging as a competitive advantage for its users.

2.5. Advanced Robotics

Manufacturing automation and robotics used in factories are already a widespread and increasingly sophisticated technology. Basically, they have been used to reduce the cost of expensive labor, improve quality (the robot will not get tired or become inattentive), or increase safety (e.g., the environment is dangerous to humans, the material, etc.). Due to its rapid development, it can have a major impact on factories, agricultural production, many services and even distribution logistics. The great advancement of sensor technology and artificial intelligence enables can enable a new generation of robotic technologies that can work accurately, precisely and safely, and together with human workers. The latter raises a number of questions regarding the design and management of such systems. Its disadvantage is that its acquisition and installation can be time-consuming and can only be carried out by suitable, highly qualified professionals. Therefore, in many cases, installation can be expensive, costing several times the purchase price of the robot.

The latest and perhaps most exciting development in robotics - where there are also major advances - is the automation of vehicles or the increasing use of drones. For example, they can be used to survey remote locations, monitor certain devices, spray crops, or deliver smaller products. Robotic delivery options can have a significant impact on supply chain design, however this still requires the different robot technologies to improve their cost, flexibility, speed, or even quality. [6]

3. Metaheuristics

Key corporate goals include continuously improving optimization procedures to reduce computation times, inventory costs, and lead times, increase customer satisfaction, and enable companies to make
higher profits. In the areas of supply chains as well as production and logistics, metaheuristic procedures are increasingly used due to the complexity of processes and tasks.

Countless metaheuristic algorithms are noted in the literature, and more and more new methods are emerging in this field every year. Not to mention that for many problems, the best solution can be achieved by using multiple metaheuristics together (hybrid versions), so the number of methods used is much larger than the existing single algorithms. [3] [16]

Metaheuristics can be grouped according to several aspects, Talbi (2009) and Liao and Li (2020) similarly divided them into single-solution based metaheuristics (e.g. Iterated Local Search, Greedy Randomized Adaptive Search Procedure, Local Search, Simulated Annealing, Tabu Search, etc.) and population-based metaheuristics (e.g., Evolutionary Algorithms, Swarm Intelligence, Artificial Immune System, etc.). [17] [18] According to Maier et al. (2019) population-based evolutionary algorithms are one of the main and most popular classes of metaheuristics. [19]

There are numerous advantages to using metaheuristics, but according to Swan et. al, one of the biggest advantages is that „the underlying search logic can be applied to any problem which can be decomposed into a few elementary aspects, namely solution representation, solution quality evaluation and some notion of locality.” (Swan et. al, 2022, p.394) [16]

3.1. Problems surrounding the discipline of metaheuristics
As part of my doctoral research, I have examined a number of metaheuristic algorithms (on a theoretical level), especially those that have already been used successfully in the field of logistics. My hypothesis is that a logical connection can be discovered between the given problem, the input data, and the applied procedure, and from these a framework methodology can be created to associate the algorithms and the tasks to be solved. However, even after reading plenty of articles, it is difficult to discover logical connections and possible similarities, even though there are thousands of researches on this topic. The scientific community has also recognized that there are numerous problems in this area, such as:

- there is a lack of summary studies that demonstrate the common features of metaheuristics,
- in many cases, researchers ignore existing studies, published procedures, and present in their own writing even algorithms that have been tested for similar problems in the past,
- in many cases a study does not clearly describe why the given algorithm works best, what are the framework conditions, constraints, etc.
- source codes are most often not available and other data is missing for adaptations. [16]

The problems described can often lead to “double discovery” and stand in the way of the applicability and evolution of metaheuristics. To address these, a research initiative called “Metaheuristics in the Large” (MitL) has been set up to reduce problems in this field, both theoretically and practically. A further aim is for scientists to use existing procedures and ideas in the literature over and over again and even to communicate with each other about the information needed for adaptations. [16]

Understanding metaheuristic methods is also very important because industrial tasks are becoming more and more complex and in many cases these algorithms are suitable for solving them. The procedures used could be used more widely and in more areas with the right knowledge. However, this requires the elimination or reduction of shortcomings, to which I would also like to contribute with my research.

3.2. Examples of the application of metaheuristics in the field of logistics
In the field of logistics, metaheuristic procedures are also increasingly used. Numerous new procedures and algorithms are appearing for even better optimization, as well as the involvement of logistics sub-areas where the use of metaheuristics was not typical before. In the following, we provide a brief overview of these.

3.2.1. Solving scheduling problems with metaheuristics. The complexity of scheduling problems is constantly increasing due to the increasing complexity of supply chains. In the study of Coelho and Silva
(2021), the metaheuristics already applied to different shop configurations (Job Shop, Flexible Job Shop, Flow Shop, Flexible Flow Shop) were collected. Fifteen different algorithms have been identified, some of which are: Genetic Algorithm, Bat Algorithm, Taboo Search, Variable Neighborhood Search, Hybrid Simulating Annealing-Genetic Algorithm, Hybrid Tabu Search-Particle Swarm Optimization, etc. This article also supports the theory mentioned earlier, according to which comprehensive collections dealing with metaheuristic procedures in a given field or a given problem are lacking. It can be seen that many researchers have already dealt with the metaheuristic procedures used for shop configurations, and several have described the same algorithm or hybrid versions. Based on these, the question may legitimately arise as to whether completely new studies, comparative analyses were needed, or whether the applicability of the given procedure would have been “merely” expanded with an appropriate adaptation. [4]

Another common logistics scheduling problem is the resource-constrained project scheduling problem (RCPSP), which has a wide variety of applications in many areas. A review study by Pellerin, Perrier, and Berthaut (2020) identified 27 metaheuristics applied or suggested for RCPSP, which were classified into three major classes [20]:

- Local search metaheuristics (for example: Greedy randomized adaptive search procedure, Local search, Taboo Search, etc.),
- Population-based metaheuristics (for example: Ant colony optimization, Firefly algorithm, Genetic algorithm, Memetic algorithm, Particle swarm optimization, Scatter search, etc.),
- Learning metaheuristics (Neural network). [20]

It can be seen as well, the examination of the myriad metaheuristics for a given problem, but there is a lack of a concise, conclusive study to support further developments and adaptations.

3.2.2. Recent metaheuristics of decision-making processes. Making a decision is a difficult and complex task, as there are many factors to consider. Automating decision-making processes is particularly complex, as in the traditional case, human experience and intuition help the process. Therefore, in many cases, decision support software works well to help people with these tasks. However, there is a lot of data that can be parameterized, so the decision-making process can also be described as an optimization problem. In this case, metaheuristics may be suitable for this type of problem solving, and ant colony optimization, genetic algorithms, or particle swarm optimization have already been used in decision-making processes. Metaheuristic algorithms can be combined not only with each other, but also with other types of methods. For example, the study by Keivanian and Chiong (2021) presents a fuzzy-metaheuristic approach in which the benefits of each method can be used to achieve even better results in a hybrid approach. The method is based on the Imperialist Competitive Algorithm (ICA), which is one of the latest metaheuristics and has already successfully solved a number of complex, practical operations. Improved versions of this (FAEICA: fuzzy adaptive and enhanced ICA and MOFAEICA: multi-objective FAEICA) and their theoretical success in Multimodal Single and Multi-Objective Optimization Problems are detailed in the paper of Keivanian and Chiong (2021). [21]

3.2.3. Additional new metaheuristics. Metaheuristic algorithms are methods that provide robust performance, adaptability, and flexibility to solve optimization problems. In practice, the tasks of algorithms can be divided into 2 major search procedures: the first is exploration, which operates in the whole area, and the second is exploitation, which examines a local part of the search space. [22] Algorithms of this type usually “work” on the basis of their food-seeking, navigational, or collective intelligence behaviors and simulate these behaviors to solve a given problem. The introduction of new metaheuristics to solve various search problems is growing year by year and is leading to the discovery of many new algorithms. In addition, in recent years there has been an accelerating pace in the introduction of new procedures. The following are some of the new metaheuristics that were created or introduced between 2014 and 2021: Jellyfish Search, Galactic Swarm Optimization, Whale Optimization Algorithm, African Vultures Optimization Algorithm, Honey Badger Algorithm etc. [23] [24]
The number of metaheuristic algorithms is constantly expanding and this will be a definite trend in the coming years. However, the pairing and co-application of the processes will also increase drastically, as the benefits of each process can be best exploited in hybrid processes. [25]

4. Conclusions and future work

The aim of our paper is to provide an overview of Industry 4.0 technologies and metaheuristic algorithms, especially in the field of logistics. We have discussed the pros, cons, and problematic issues of these technologies.

Industry 4.0 technologies have a direct impact on both logistics and supply chains: they can change and influence their structure, architecture, past best practices and processes. All this, of course, in order to create tasks and optimal solutions more efficiently, flexibly, faster, or even cheaper. This raises further research directions, as the benefits, disadvantages, and limitations of the Fourth Industrial Revolution need to be understood, if Industrial 4.0 technologies are to be put to good use in practice.

In the field of metaheuristics, an accurate understanding of procedures is important, and more information is needed for practical application and adaptation of each algorithm to another area or problem. This is not an easy task and, as we highlighted in the article, there are a number of problems surrounding the field of metaheuristics. Nevertheless, the use of metaheuristic algorithms offers a good solution for tasks belonging to the np-hard complexity class, even though in many cases these methods do not guarantee an accurate and optimal solution but are generally able to provide an acceptable approximation. A further question arises as to their industrial applicability for solving real engineering tasks. This is perhaps the biggest challenge, especially for recently released algorithms. Several studies deal with the evaluation of algorithms on design-engineering problems and the test results are generally encouraging. [26] [27] [28] [29]

My goal is to identify additional logistics areas where metaheuristic procedures may have a raison d’être. Furthermore, I am constantly examining the algorithms in order to explore further opportunities and gaps in their application.

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