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Review

Mixed Palletizing for Smart Warehouse Environments: Sustainability Review of Existing Methods

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Abstract: Mixed palletizing constitutes one of the problems in the logistics domain aroused from the need for fast product movement to satisfy the continuously increasing number of customers with the demand for highly personalized goods. In a demanding environment, such as warehouses, where break bulk and the consolidation of loads take up most of the working time, the automation of mixed palletizing can lead to increased efficiency and speed while keeping errors to a minimum. Space utilization of pallets enables savings in storage and transportation costs, boosting the overall sustainable role of the Supply Chain sector. This paper presents the proposed approaches to mixed palletizing stemming from different fields, with a focus on recent developments in the application of Industry 4.0 technologies. Our research highlights quite a few areas that require attention from researchers.

Keywords: mixed palletizing; 3D bin packing problem; 3DBPP; Industry 4.0 technologies; literature survey

1. Introduction

Industry 4.0 is considered to be a major technological revolution that will transform manufacturing industries and, consequently, will affect all aspects of social and economic life [1]. In this new industrial stage, the integration of vertical and horizontal manufacturing processes will lead to higher performance as information and communication technologies blend into industries [2]. There are many different applications of the aforementioned technologies according to different industry sectors and their potential is now starting to show. Industry 4.0 technologies include 3D printing, Augmented Reality (AR), Artificial Intelligence (AI), Autonomous Robotics, Big Data Analytics (BDA), Cloud Computing, and the Internet of Things and Simulation, just to name a few, along with their combination [3].

Supply Chain operations can take advantage of these innovations to better handle the flow of products and information along the Supply Chain. In the context of logistics centers, the digital adaptation of Industry 4.0 has found application in internal logistics processes and has led to the emergence of smart warehouses, namely Warehouse 4.0 [4]. The increasing complexity and variety of customer orders handled through warehouses raise the demand for exponential real-time data and challenging contextual information processing [5]. A key operation inside warehouses is picking goods and placing them onto pallets to be dispatched. Mixed palletizing is about the arrangement of heterogeneous packages on pallets while abiding by constraints [6].

A literature search was conducted on databases such as Google Scholar, Science Direct, arXiv, the Institute of Electrical and Electronics Engineers (IEEE), Multidisciplinary Digital Publishing Institute (MDPI), and Scopus. More than 200 scientific papers were searched and reviewed related to their relevance, in accordance with which this procedure appears under various names, like "palletising" [7–9], "palletizing" [10–12], "palletisation" [13,14], "palletization" [6,15,16], "pallet loading problem" [17–19], "pallet placement" [13,14,20], and "3D Bin Packing Problem" (pallet version as opposed to packing packages and loading containers) [21,22]. To address this ongoing issue, a typology was proposed in 1990 [23]

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and in 2007 [24] by researchers that concerns the area of Cutting and Packing problems. Mixed palletizing is a Three-Dimensional Bin Packing Problem (3DBPP) where items are rectangular boxes that are to be fitted orthogonally into as few rectangular containers of identical size as possible [24]. A Distributor's Pallet Packing/Loading Problem is a term that also appears in the literature, with the intent of distinguishing it from its Manufacturer counterpart, where all boxes are identical [18]. In all proposed solutions, there are constraints present (geometry, weight, stability [25], compression [21], center of gravity [26–28], shipment cost [29], fragility [30], packing sequence [31], load bearing [32,33], and profit optimization [34]) that make computations even more complex. Even the complexity of package arrangements on the pallet itself is a practical constraint [35].

In the Supply Chain sector, transportation and storage are critical factors that have a major impact on costs. The palletizing loading efficiency causes direct savings in the total logistics costs and can cut up to 30% of the transportation cost and up to 25% of the storage cost [17]. Mixed palletizing is about achieving a high load efficiency, through space utilization, which leads to a more economical, environmentally friendly, and sustainable role for the Supply Chain sector.

This paper aims to present and review the relevant research conducted in the field of mixed palletizing and is focused on recent developments in the application of Industry 4.0 technologies (Figure 1). In particular, the present review paper studies and analyzes the recent mixed palletizing methods developed in light of different Industry 4.0 applications. To achieve this, a classification of the existing methods is proposed, based on which algorithm-based and technology-based methods are highlighted.

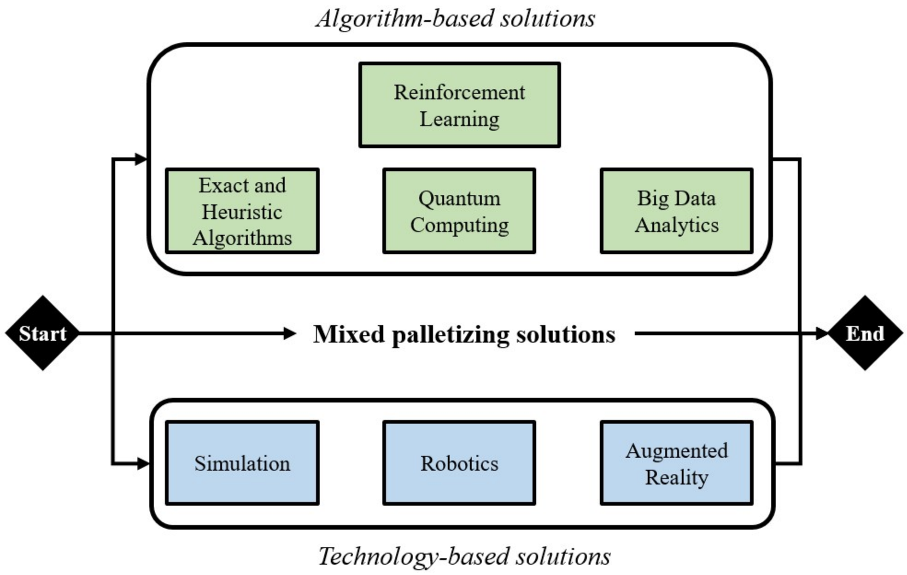

Figure 1. Classification of mixed palletizing solutions.

Regarding the algorithm-based solutions, the first approaches to solve the problem were exact algorithms with the help of computational programming. The next attempts were made with the incorporation of heuristics algorithms, on the grounds of reducing computational times for this NP-hard problem [17]. Heuristics approaches are still being researched at this present time [11]. Finally, the current review intends to highlight existing research gaps and potential future investigations into the sustainable mixed palletizing problem.

2. Algorithm-Based Mixed Palletizing Methods

2.1. Past Literature Reviews

A comprehensive literature review on the Pallet Loading Problem was presented by Vargas-Osorio and Zúñiga [17] in 2016. Papers from 1987 were reviewed and categorized according to their variation (Manufacturer or Distributor), dimension (2D or 3D), method (exact, Simulation, or heuristic), and the software or programming language used. They concluded that all methods have proven some efficiency, but also have limitations, and an increased demand for computational resources and time. Another literature review of the same year, 2016 [36], dealt with methods proposed considering only the solution of the Manufacturer's Pallet Loading Problem. Careful conclusions concerning the reviewed methods were discussed, on the grounds of not being tested on the same datasets that justify ongoing research in this particular area. A software toolbox was developed to test and validate these exact and heuristic solutions that can generate arbitrarily large datasets for 3DBPPs that are based on real industry data [37].

2.2. Exact Algorithms

The exact Martello–Toth-Procedure algorithm was evaluated against approximation algorithms to demonstrate its effectiveness [38], but still, the main aim is to reduce computational time. In [28], an exact analytical mixed integer programming formulation was able to pack items by layers and could be solved efficiently regardless of the item's quantity. A mixed 0–1 integer programming model generated an exact optimal solution for the 3D Pallet Loading Problem in [39]. The solution explicitly defines the desired number of boxes of each size and their coordinates on the pallet but also requires extremely long computational times to reach the final optimal state, rendering it unavailable as an option in real-time applications. More recent research conducted in [33], also based on mixed integer linear programming, examined the mixed palletizing problem while considering logistical features, load bearing, stability, height homogeneity, overhang, weight limits, and robotized layer picking. The effectiveness and fast computational times of their method were tested by the authors. Similarly, in order to further increase the loading efficiency and reduce the operating costs in fresh food Supply Chain industries, a 3DBPP variation was presented in [21]. The compressibility factor of deformable items, like vegetables and fruits, was considered in a mixed integer programming model. Their model is subject to basic size, orientation, non-overlapping, stability, and compression constraints. Their study shows that there is great potential in minimizing packaging and delivery costs when estimating the actual space occupied by fresh food in transportation. Another hybrid greedy heuristic method based on linear programming was presented in [40], where two versions of the algorithm, the first and the extended one, gave results that are comparable to those in the contemporary literature. A mixed integer programming formulation focused on the density of the bottom layers to ensure pallet stability [41]. A relative-position formulation with slicing minimizes height and consolidates fragmented space, thus producing more stable and compact pallets.

2.3. Heuristic Algorithms

Heuristic packing algorithms are still popular in the present day, where the problem at hand is approached in different ways. For example, a 3D binning algorithm consists of three consecutive and iterated steps: the construction of all possible blocks according to cargo order, the selection of optimal blocks, the calculation of the remaining free space in all three dimensions after the optimal block has been placed, and starting over [11]. The CrossLog project builds on a heuristic approach to generate 3D packing patterns that are efficient, safe, and which collaborate with other modules in warehouses [42]. Another approach explains a formal mathematical description that creates layers and pallets as subproblems, and then heuristic, metaheuristic, and matheuristic algorithms are used to solve the main problem [43]. In particular, one matheuristic approach for solving palletizing problems has two phases. Firstly, classical 2D packing algorithms define the number of layers, and secondly, the calculated layers are packed on pallets by means of a specialized mixed integer linear programming model solved with Gurobi solver [18]. In the same way, a two-step strategy algorithm is proposed where an Extreme Point heuristic algorithm is utilized to group items into layers, while an exact method algorithm stacks layers to form pallets [44]. Also, in [32] a novel formulation and a column generation solution approach are proposed. The subproblem of generating columns is solved optimally as well as heuristically by employing several techniques, such as item grouping and replacement, layer reorganization, and spacing. Based on the aforementioned approach, the authors in [45] extend it to accommodate different item shapes, vertical support, load bearing, reduced support surfaces, planogram sequencing, and bin weight limits. Second-order cone programming and a graph representation are used to achieve it. A column generation-based algorithm where a heuristic pricing method is employed is proposed in [46].

A novel method for solving the Pallet Loading Problem presented in [47] uses a branch and bound algorithm, which considers only a heuristically favorable subset of possible solutions, thus reducing computational time. An online packing heuristic algorithm for the 3DBPP in dynamic environments and in the Physical Internet context is presented in [48]. This proposed algorithm is competitive against other solutions in terms of running time, space utilization, and number of bins. A Quasi-Monte-Carlo Tree Search heuristic algorithm integrates conventional heuristic skills into the Monte-Carlo Tree Search classic algorithm and provides an efficient and effective technique to solve 3DBPPs [49].

One interesting branch of algorithms is the genetic algorithm (GA) approach. These are iterative optimization procedures, which constantly apply the GA operators (selection, crossover, and mutation) to a group of solutions until some criterion of convergence is satisfied [50]. One metaheuristic approach that consists of a genetic algorithm hybridized with a heuristic technique was developed in [50]. This preliminary study shows promising results which could be enhanced with the use of machine learning techniques. The authors in [51] presented a new modeling approach to support different heuristics algorithms for mixed palletizing. This discrete event system model imports new events and implements different heuristics algorithms so as to take account of the production and transport influence of the palletizing activity in the logistics flow. In [34], the researchers propose another hybrid approach, using heuristic and genetic algorithms, that prioritizes more profitable cargo to be loaded onto pallets. Heuristic algorithms were used to calculate profitability and stability aspects and genetic algorithms were employed to run the profit optimization. A smart packing simulator for optimized box arrangements combined with the minimization of the outer container box size, which is based on GAs, is shown in [52]. Researchers developed an adaptable chromosome length GA, where the number of boxes controls the length. A parallel coevolutionary algorithm is proposed in [53], which is based on the island model and makes possible the communication and solution exchange between subpopulations. This parallelization of the algorithm allows for the shortening of the processing time. Another innovative approach to 3DBPPs is the Taboo-Search algorithm [54], where a specific heuristic algorithm prevents recently visited areas of the search space from being visited again. The results are not very different from those of genetic algorithms and present close performances. In [55,56], an application that is based on a genetic algorithm and differential evolution algorithm is developed to solve the problem, with better results compared to those with human experience. A hierarchical approach consists of a two-stage genetic algorithm paired with mixed integer linear programming and has favorable results when dealing with factual loading delivery constraints [30].

Another novel approach to packing problems is space defragmentation [57]. With this technique, the fragmented space is combined into a continuous usable space, which allows for the packing of additional items. Researchers stated that their defragmentation technique is of the same quality as considerably more complex metaheuristic approaches. The authors in [58] proposed a novel 3D bin packing optimization algorithm and an accompanying cross-platform application built with 3D models for visualization. The proposed model can efficiently pack boxes into pallets while considering dimensions, weight, and load-bearing constraints. The application has a user-friendly interface for inputting data, initiating the algorithm, visualizing the packing results, and generating dynamic reports. A similar approach consists of two data systems, a main and a secondary system [59], which describe the spaces that are necessary for the computation of the placement of the packages. The search algorithm based on these two systems reduces the workload of searching for the optimized placement while constantly organizing and editing the two data systems. The automation of the heuristic design process offers a lot of possibilities for handling the palletizing problem [60]. The goal is to build computer systems that can design heuristic methods and are competitive with the heuristic methods already present in the literature. The methodology, as presented by the authors, offers a more general system as it can handle problems in all cases, such as 1D, 2D, and 3D.

The literature shows that algorithms developed for solving the mixed palletizing problem before 2008 were primarily heuristic or exact. Their main methods were G4-heuristic [61], G5-heuristic [62], linear programming [63–67], tabu search [68,69], greedy search [70], tree search [71], L-approach [72], branch-and-bound [73], Bischoff and Dowsland heuristic [74], genetic algorithm [75–78], and strategic oscillation methods [79].

2.4. Quantum Computing

Quantum Computing is a promising, innovative alternative to various Artificial Intelligence problems, such as supervised learning, and involves the reformulation of the original problem as a Quadratic Unconstrained Binary Optimization (QUBO) problem, while employing quantum annealers to find the optimal solution [80]. The Quantum Augmented Lagrangian method for Bin Packing (QAL-BP) is introduced in [80], which is a novel QUBO formulation designed specifically for bin packing and quantum computation. This approach utilizes the augmented Lagrangian method to facilitate the incorporation of the packing constraints into the objective function and demonstrates the potential dynamics of quantum computation in solving the mixed palletizing problem. Other instances of quantum computation utilization are presented in [81,82]. In these articles, a hybrid quantum–classical framework for solving 3DBPPs is discussed, while also considering many constraints, such as package and bin dimensions, overweight items, dependencies among item categories, and preferences for item ordering. The researchers also propose a dataset and an instance generator for real-world bin packing problems that can facilitate Quantum Computing researchers [83].

2.5. Big Data Analytics

BDA refers to the strategy of analyzing large volumes of data to uncover hidden insights and meanings [3] that will help to make documented business decisions. However, the application of BDA in the logistics industry is limited and there is a gap between theory and practice [84]. Solutions that rely heavily on data processing and analysis provide new tools to tackle the palletizing challenges. Algorithms that analyze package dimensions, find suitable groupings, and create layers with similar heights that can support the weight above produce near-perfect solutions with small computational times [6]. These algorithms have already found application in a mixed-case palletizing system based on IRB660, an ABB robot variant [85]. Another data-driven column generation algorithm based on the packing pipeline of Huawei is presented in [86]. By exploiting the historical data from packing records and input orders to be packed, the computational load can be greatly diminished, since the 3DBPP can be reformulated as a set cover problem. Another algorithm that has been deployed in Huawei Logistics Systems is shown in [87]. A data-driven tree search algorithm, compared with a convolutional neural network that is trained with historical data from Huawei, can accelerate the process and lead to increased efficiency and loading rates. These researchers were the first to insert pruning networks into tree searches to tackle large-scale 3DBPPs.

2.6. Reinforcement Learning

Reinforcement Learning is an effect technology that can solve combinatorial optimization problems [16]. Deep Reinforcement Learning can train algorithms for complex behavior using a reward function, which leads to better results when compared to legacy heuristic algorithms [22]. The recent advances in Artificial Intelligence allowed machine learning methods to also enter the domain of mixed palletizing through Reinforcement and deep Reinforcement Learning. Reinforcement Learning (RL) is a type of machine learning where an agent learns to make decisions by constantly interacting with an environment. The agent takes actions in the environment, receives feedback in the form of rewards or penalties, and uses this feedback to improve its future decision making. Deep Reinforcement Learning (DRL) uses neural networks with multiple layers (deep neural networks) to model and solve complex tasks. These networks are capable of automatically learning hierarchical representations of data, which is useful for tasks with intricate patterns [88].

Such an innovative approach that effectively utilizes both a physics and a game engine for DRL is presented in [22]. Utilizing a game engine (like Unity3D) to visualize the 3D environment and a physics engine to conduct the training of the algorithm can lead to the automation of the loading process in such virtual scenarios. Another instance of Reinforcement Learning, which optimizes pallet loading inside factories this time, produces better results than legacy heuristic methods. The proposed learning algorithm employs a policy-based method that directly finds the optimal policy [89]. In cases where package dimensions are not known beforehand in automated robot warehouses, a computer vision-based method that uses a deep convolutional neural network can classify them with high accuracy [90]. In this way, applications that rely on dimensions to run palletizing algorithms can be installed in automated warehouses.

Taking into consideration that 3D palletizing is basically an online and time-sensitive process, partially observable Markov decision processes can reduce computation complexity. Thus, a DRL algorithm achieves higher space utilization when compared to conventional heuristics algorithms [16]. In a similar approach, a constrained Markov decision process was proposed to solve the same problem. A constrained DRL method under the Actor–Critic framework is able to achieve policy optimization based on a prediction-and-projection scheme [91]. The on-policy-actor framework is adopted to solve a Markov decision process in [92] with constrained action space, in a scenario where the items are delivered to the agent without giving information of the full sequence and must be packed immediately.

Researchers in [93,94] propose a novel multi-task framework that is based on Selected Learning which produces a heuristic-like policy for the mixed palletizing of cuboids. A model is trained by a hybrid loss function which combines supervised and Reinforcement Learning processes. The procedure can be divided into tree-related tasks, sequences, orientations, and the spatial locations of items to be packed. Similarly, in [95] researchers propose a DRL agent that addresses three subtasks, sequence, orientation, and position, and can solve large-scale instances of 120 boxes or more. Also, the agent is integrated into constraint programming to further improve the solution quality.

In an effort to combine the legacy heuristic approach with DRL, the researchers in [96] designed three different heuristics algorithms based on packing experience and real-world constraints and modeled them into a DRL framework to produce efficient results. Likewise, in a two-stage algorithm model, a hybrid genetic algorithm was coupled with a feedforward neural network, providing an optimal solution [97].

By combining DRL with the Monte Carlo tree search algorithm, the online 3DBPP can lead to an efficient and robust packing strategy that has practical applications in the real world [98]. The model was trained by an improved Actor–Critic algorithm, and the packing configuration tree model was used to overcome the cases when DRL cannot converge. A similar approach [99] established a model that solves the problem using incomplete information since Reinforcement Learning does not require global information.

A buffer can be employed to allow for multi-item action selection, and an agnostic data augmentation strategy paired with a model-based RL method can lead to results that outperform the state-of-the-art solutions in space utilization [100]. This model was based on the popular algorithm AlphaGo, which is a great adaptation for tackling the mixed palletizing problem without the need for heavy computational resources.

3. Technology-Based Mixed Palletizing Methods

3.1. Augmented Reality

Regarding the technology-based solutions, tools from Robotics, Simulations (e.g., Digital Twin), and AR have been introduced. AR refers to such activities where the real world is blended with superimposed virtual elements to enhance human senses and abilities. AR can improve several Supply Chain activities in nearly every field but is still in a nascent stage of development [101]. In the case of a lack of any robots in a warehouse, AR can play a significant role in minimizing handling and placing errors. Workers equipped with smart devices can be guided to correctly stack packages on a pallet, one by one, while a simple algorithm that runs in the background decides the order of the placement [19]. A first comprehensive approach to evaluate AR applications in palletizing scenarios is presented in [15], where workers were guided via paper, a tablet, and AR glasses. Overall, the performance was improved in the AR condition, while the usefulness of AR becomes clearer in complex and uncertain circumstances. Earlier, in [102], researchers found that AR devices can facilitate logistics workers, but the design requirements of AR applications need to be honed for palletizing scenarios. A framework to assist operators with immersive packing with the help of AR can facilitate smart packing [103]. Several heuristic algorithms produce viable solutions for the 3DBPP, and the best of them can be sent to the AR application to immerse logistics workers in the packing process. The authors stated that DRL, instead of the proposed heuristics algorithms, will greatly increase the efficiency of their developed framework.

3.2. Robotics

A robotic palletizer is used to implement the pallet patterns already developed by algorithms in an automated palletizing operation, and it is imperative to consider the physical aspects and restrictions of the actual placement of the packages [13]. A novel human–robot collaborative approach to the mixed palletizing problem is presented in [12]. While the chosen algorithms (Guillotine, Maximal Rectangles, and Skyline) have already been discussed in many papers before, the results demonstrated in the proposed framework have a high potential to boost the productivity and ergonomics of laborers, paving the way for Industry 5.0. Industrial robots that handle mixed case palletizing are presented in [10]. A Robotics-based solution consists of two main components, the calculating algorithm and the gripper concept (mainly vacuum and fork style). The author stated that, still, in 2016 no major improvements had been made in mixed case palletizing software products, and the sector demands flexible and adaptable solutions to accommodate the trend of more frequent but lower order quantities of goods. A challenge to make robotized palletizing applications available to small- and medium-sized enterprises is discussed in [9]. The proposed algorithm can automatically generate the robot program for a reconfigurable palletizing application, thus moving the software complexity from robot to PC software.

In an effort to consider the actual placement restrictions of box packages on a pallet by robots, some papers present a methodology for efficient pallet pattern implementation [13,14,20]. The authors propose four different pattern placement strategies for robotic palletizing while taking into account pallet and gripper parameters. There is an uptrend in the use of robotic palletizing systems, which have high performance but lack adaptability [104]. To address this issue, the authors propose an automated palletizing solution based on the principles of integrating advanced modularity techniques into the design and development phases.

There are a lack of datasets that are accepted by the community for benchmarking 3DBPP algorithms in the present day; thus, a benchmark dataset for robotic bin packing, which is based on realistic data, is presented in [105]. Two heuristic approaches for solving the online robotic 3DBPP in an automated sorting center are also presented in [106], one for bench-marking and one for real-time deployment. In this highly demanding environment, a robot must make decisions within a tight time frame so as to pick up a box from the conveyor and place it in its final place onto the pallet.

In [107], autonomous mobile robots are part of an Automated Pick to Pallet System (APPS), which is a fully automated parts-to-picker configuration and, thus, mixed pallets are created. The authors develop an agent-based simulation that can estimate the performance of the system and can also be adapted to consider different operating policies. In an effort to alleviate the gap between the 3DBPP algorithm and the robot packing system, the authors present a solution that enables a robotic arm to pack varied items into a container densely and reliably [108]. The calculating packing algorithm is a DRL-based one (Markov decision process) and is trained using an Advantage Actor–Critic with a Generalized Advantage Estimator.

3.3. Simulation

Simulation can play a significant role in comparing the quality of a mixed pallet with well-automated metrics [109]. In one study, a Pallet Viewer application is employed to evaluate the quality of a pallet plan, based on geometry and placement, and a Unified System for Automation and Robot Simulation (USARSim) is used to evaluate the pallet build process and the final pallet. In [110], a model is proposed to assess the stability of a pallet during transportation and under the effects of inertia. The simulations can effectively reduce the amount of film used to secure the mixed pallet, as there is a definitive limit quantity of the stretch film wraps beyond which there is no improvement. Building mixed pallets with more stability reduces the need for extra load protection from the stretch film.

4. Summary of Industry 4.0 Technologies in Mixed Palletizing

Figure 2 depicts all cited corresponding references to Industry 4.0 technologies for mixed palletizing. It is clear that Reinforcement Learning has the most references, while Robotics comes in second place. Moreover, after 2020 the number of papers that deal with mixed palletizing showed an uptrend, justifying the renewed interest in this particular field.

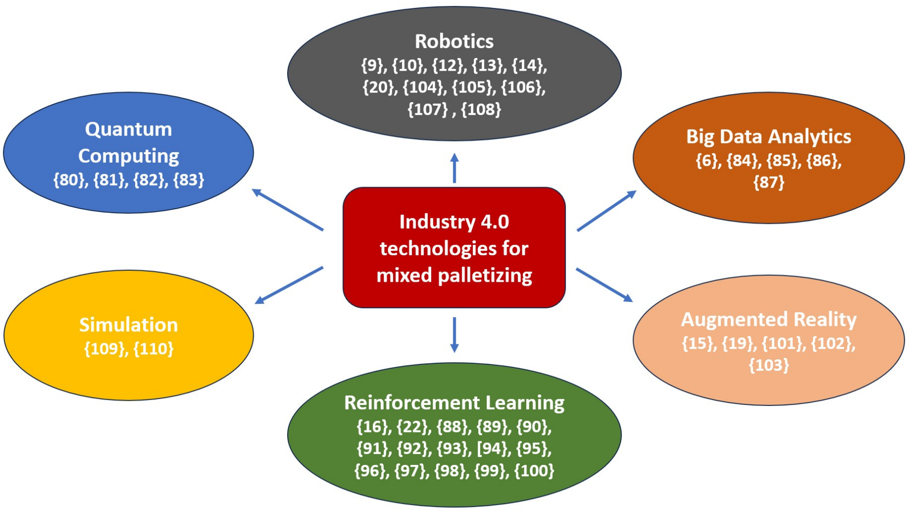

Figure 2. Industry 4.0 technologies for mixed palletizing.

5. Research Gaps and Future Work

The previous analysis reveals that there are still several research gaps that have to be covered in the domain of mixed palletizing that will steer future research work.

Optimization complexity: There are a plethora of parameters that can be used in optimization techniques, the determination and initialization of which is not a trivial problem. This requires an abundance of data which are not widely accessible. To this end, developing more efficient and effective optimization algorithms for mixed palletizing is a common research area. This includes addressing combinatorial optimization challenges, considering various constraints, and improving the scalability of algorithms.

A lack of realistic datasets: This still remains a problem to this day. There have been some efforts from researchers to propose the datasets used in their research, either generated or industry-based, as benchmarks for new research. Future works could be focused on building realistic datasets that are industry-specific and have potential applications in real-world scenarios. Another solid direction for future work, as presented in the literature, is accounting for additional practical constraints to the proposed approaches to mixed palletizing. Also, in this case, constraints that are industry-specific are expected to be more than welcome.

Applicability in the real world: When it comes to deploying the developed solutions from theoretical models to real environments, there are major barriers that have to be bypassed. Handling constraints such as weight limits, stacking stability, and the compatibility of items is not straightforward and a solution that fits them all does not exist. Moreover, regarding the applicability of automation approaches, e.g., the robotic handling of goods, important barriers exist that constitute active research topics from other domains, e.g., computer vision, robot navigation, etc. Robot perception systems are vulnerable in diverse illumination conditions, the packages of goods are not exhaustively defined, and this prohibits the manipulability of a wide range of objects. In addition, palletizing systems can operate in dynamic environments where the set of items to be palletized can change. Adapting mixed palletizing algorithms to dynamic scenarios, where items are added or removed during the process, still remains an open research area.

Human–robot collaboration: The utilization of a sole robotic system to address mixed palletizing imposes several constraints. Advanced robotic manipulation and gripping techniques are required to improve the ability of robots to handle a diverse range of items, including different shapes, sizes, and weights, which is important for efficient mixed palletizing. Investigating how humans and robots can collaborate effectively in mixed palletizing tasks is an emerging area. This involves understanding the role of human operators in the process and designing systems that enhance collaboration and productivity.

Adaptive learning: The major challenge in the machine learning techniques for the creation of training models that successfully address the 3DBPP is the limited access to datasets. In the presence of the data available, the creation of well-trained models for the 3DPBB could involve learning from historical data, adapting to changing environments, and improving decision making during the palletization process.

Efficiency and scalability: Until now, the presented methods were focused only on the performance in terms of accuracy and repeatability and did not cover the optimization of the resources required to address the 3DBPP. Research gaps may exist in designing mixed palletizing systems that are more energy-efficient. This may include the optimization of the movements of robotic arms, the reduction of idle times, and the consideration of energy consumption as an additional objective in optimization models. On the other hand, a study of the scalability aspect of the proposed solution is important, especially when it comes to large-scale industrial applications. A future research direction could be the exploration of how mixed palletizing algorithms can scale efficiently to handle a high volume of items and diverse pallet configurations.

In Table 1, several research gaps with their mitigation strategies are presented for mixed palletizing.

Table 1. Research gaps and mitigation strategies.

Research Gaps	Mitigation Strategies
Optimization complexity	The development of more efficient algorithms
Lack of realistic datasets	Building industry-specific datasets
Applicability in the real world	Adapting algorithms to dynamic scenarios
Human–robot collaboration	Investigating human–robot interactions
Adaptive learning	Creating well-trained models
Efficiency and scalability	Designing energy-efficient, versatile systems

6. Discussion

It is clear that Supply Chain companies have a critical role in sustaining the quality of life that our world enjoys. Transportation and warehousing count for the biggest impact on the costs of these companies. Any research proposal that has even a small contribution to diminishing these logistics costs is welcomed, as the applied scale is huge. Cutting and Packing problems have been present in the literature for decades, which attests to the importance of dealing with them. Every scientific contribution in this matter helps us solidify our sustainable future. Mixed palletizing is one of these matters that enjoys research attention, as demonstrated above with the abundance of proposed approaches. The solutions come from the fields of exact and heuristic algorithms, genetic algorithms, Quantum Computing, Big Data Analytics, Reinforcement Learning, Augmented Reality, Robotics, and Simulation. These proposals try to enhance the efficiency of the mixed-case palletizing operation. Exact algorithms suffer from the high need for computational resources, and they cannot be used in real-world applications. But, as computer processing power technology advances, exact algorithms will become more viable. On the other hand, heuristic algorithms produce results quickly and are applicable to live operations, but their solutions are not optimal in many cases, suffering from a lack of generality. Quantum technologies show quite the potential for speeding up computational procedures, and that makes them excellent choices for combinatorial optimization problems, such as mixed palletizing. Every instance of a pallet with its unique item placements is a wealth of information for every application that is based on Big Data analysis. This kind of information can be used to provide solutions that have already been tested for efficiency. Reinforcement Learning has great potential for producing effective results for the 3DBPP, as it is well suited to dealing with combinatorial optimization and learning complex behavior. Augmented Reality offers a new vision perspective to manually mixed palletizing and facilitates human logistics workers. On the other hand, robots free up human resources when employed in mixed palletizing, although all algorithms designed for Robotic applications need to account for such use. Simulation has its own merit in evaluating the proposed solutions. All these approaches provide different views and solutions to the same problem and this literature review shows the huge interest mixed palletizing enjoys.

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Abbreviations

The following abbreviations are used in this manuscript:

3DBPP	Three-Dimensional Bin Packing Problem.
AI	Artificial Intelligence.
APPS	Automated Pick to Pallet System.
AR	Augmented Reality.
BDA	Big Data Analytics.
DRL	Deep Reinforcement Learning.
GA	genetic algorithm.
IEEE	Institute of Electrical and Electronics Engineers.

MDPI	Multidisciplinary Digital Publishing Institute.
QAL-BP	Quantum Augmented Lagrangian method for Bin Packing
QUBO	Quadratic Unconstrained Binary Optimization
USARSim	Unified System for Automation and Robot Simulation

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