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Assembly line balancing with cobots: An extensive review and critiques

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A B S T R A C T

Industry 4.0 encourages industries to digitise the manufacturing system to facilitate human-robot collaboration (HRC) to foster efficiency, agility and resilience. This cutting-edge technology strikes a balance between fully automated and manual operations to maximise the benefits of both humans and assistant robots (known as cobots) working together on complicated and prone-to-hazardous tasks in a collaborative manner in an assembly system. However, the introduction of HRC poses a significant challenge for assembly line balancing since, besides typical assigning tasks to workstations, the other two important decisions must also be made regarding equipping workstations with appropriate cobots as well as scheduling collaborative tasks for workers and cobots. In this article, the cobot assembly line balancing problem (CoALBP), which just initially emerged a few years ago, is thoroughly reviewed. The 4M1E (i.e., man, machine, material, method and environment) framework is applied for categorising the problem to make the review process more effective. All of the articles reviewed are compared, and their key distinct features are summarised. Finally, guidelines for additional studies on the CoALBP are offered.

1. Introduction

The manufacturing sector in the current era of Industry 4.0 is heavily influenced by the emergence of disruptive cutting-edge digital technologies, such as the Internet of things, advanced robotics and sensor technologies, cloud computing, artificial intelligence, machine learning, virtual and mixed reality, augmented reality, additive manufacturing, and so on (Schwab, 2017). Digitised manufacturing systems, in which shop floor activities are visualised and controlled in real-time via digital technologies, enable effective mass customisation of semi-custom products at costs comparable to mass production without sacrificing quality (Monostori et al., 2016). Moreover, software adopted in smart industrialised systems is also able to leverage big data from production databases to adaptively plan resource usage in a dynamic ecosystem (Kusiak, 2017). An assembly line (AL) comprises workers and/or equipment configured systematically, typically in a straight layout, for assembling workpieces or performing repetitive tasks as it travels down the line to effectively mass-produce products at low unit cost (Chutima & Yothaboriban, 2017; Chutima 2020). From automotive to electronics and beyond, industrial robots are the main equipment programmed to replace workers in executing high-risk, complex, tedious and repetitive tasks such as welding, picking and placing, and handling heavy and hazardous materials. Manufacturers gain enormous benefits from robotic assembly lines (RALs), e.g. higher productivity, lower labour cost, higher flexibility, higher efficiency, and shorter time-to-market (Chutima, 2022; Chutima & Khotsaenlee 2022). Additionally, thanks to robots' high-precision operations, waste caused by inconsistencies in workpiece production could be avoided, resulting in greater product quality. Furthermore, fully automated RALs enable manufacturers to operate efficiently and continuously without interruption 7 days a week, 24 hours a day. Because typical robots are huge, massive, rigid, application-specific and equipped with mechanical, electrical

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and electronic components, for safety reasons, they always inhabit their own workspaces that are separate from those used by workers (Vagaš et al., 2020).

Although RALs provide numerous advantages, most small and medium-sized enterprises (SMEs) may be unable to afford to automate their entire production facilities due to product complexity restrictions that need manual skills from labours. Furthermore, doing so may engender substantial expenditure that exceeds the financial capabilities of SMEs (Kinast et al., 2021). Allowing workers and robots to collaborate on their job might be a viable alternative to solely employing manual labourers or automated robots. Collaborative robots, so-called cobots, are tiny, lightweight, low-power robots that are purposefully intended for direct interactions with individuals working in a communal workspace without safety barriers (ISO 2016). Smart sensors, actuators, machine vision, collision avoidance, sophisticated communication, and other technical improvements enable cobots to be aware of their environments and safely execute activities alongside human workers in close proximity (Helms et al., 2002; Tsarouchi et al., 2016). The hybrid workplace's novel technology gives rise to a cost-effective practice for partially automated assembly jobs (Weckenborg & Spengler 2019).

The hybrid assembly system, in which humans and cobots collaborate on carrying out assembly tasks, has the potential to capitalise on the different capabilities of both entities. Humans outperform cobots in terms of intellect, cognitive skills, dexterity, flexibility, versatility, adaptability and unexpected handling of crises; on the other hand, cobots surpass humans in terms of strength, endurance, repeatability and precision (Krüger et al., 2009; Hentout et al., 2019). Furthermore, cobots can work indefinitely without stopping, allowing manufacturers to maximise available production time. Screw driving, loading and unloading, pick and place, heavy object lifting and placing, box packing and unpacking, glue dispensing, soldering, welding, cleaning and washing, and posture aid are just a few of the manufacturing jobs that cobots could assist with (Ajoudani et al., 2018). In addition, the 3D operations (i.e., dull, dangerous and dirty) are good candidate tasks for workers to seek help from cobots (Sherwani et al., 2020).

Aside from increasing productivity, cobots are also used as labour-saving equipment to reduce stressful or dangerous tasks assigned to human workers. Additionally, cobots boost the AL's efficiency by enhancing quality, homogeneity, and assembly rate while minimising errors and waste (Aivaliotis et al., 2019). Cobots can assist humans in carrying out tasks that are dangerous or must be conducted in a toxic environment (Hentout et al., 2019). Without having the support of trained instructors, cobots can be simply taught by moving their arms into predetermined positions resulting in a great reduction in the setup time (Yuvethiekasri et al., 2021).

Human-robot collaborations (HRCs) are classified into five levels by the International Federation of Robotics (IFR 2018, Kopp et al., 2021):

(1) Cell: Humans and cobots undertake separate tasks sequentially across distinct working spaces separated by fences, preventing them from coming into touch with each other. Since autonomous operation safety criteria must be strictly fulfilled, physical contact between humans and cobots is prohibited. This typical operation enables cobots to function at full speed.
(2) Coexistence: Humans and cobots coexist in unshared workspaces without fences, each of them executing unrelated work. Physical contact between humans and cobots is strictly forbidden just as it is in Cell (category 1). Cobots, on the other hand, are permitted to move only at a reduced speed.
(3) Sequential cooperation: Humans and cobots both work in collaborative workspaces, but they take turns executing connected tasks. As a result, only one resource (human or cobot) is functioning at any one moment. Contact between humans and cobots is feasible but not necessary. Because humans and cobots must collaborate closely, cobots are allowed to run at a limited speed. Furthermore, speed and separation monitoring, as well as power and force limitation, are imposed as minimum safety requirements.
(4) Collaboration: Humans and robots are both in action in shared collaboration workplaces, completing their shared responsibilities on the same workpieces at the same time. Human-cobot physical contact is possible and often required. All safety requirements are enforced in the same way that Sequential Cooperation (category 3) is. The collaboration between humans and cobots could be broken down further as follows: (a) Parallel collaboration (also known as synchronous collaboration) occurs when humans and cobots perform different tasks on the same workpiece in parallel; and (b) Joint collaboration comes about when humans and cobots assist each other in completing the same tasks on the same workpiece simultaneously, such as hand-guided control operations.
(5) Responsive collaboration: As in Collaboration (category 4), humans and cobots are co-located and engaged in shared collaboration workplaces. In this situation, however, human gestures can initiate the actions of cobots in real-time.

This study concentrates solely on cobot assembly line balancing problems (CoALBP), in which interactions between a human and a robot in each workstation occur only in HRCs' Sequential cooperation, Collaboration and Responsive collaboration modes (categories 3 to 5). To demonstrate the underlined concept, Fig. 1 depicts various collaboration modes that could occur in a workstation. Assume that 5 tasks could be accomplished by a human, robot, or cobot at a specific AL's workstation. The precedence diagram of the tasks assigned to this workstation is provided, as well as the specific resource to execute each task. The number in the node illustrates the task number, and the capital letter above each node (H = human worker, R = robot, and

C = cobot) indicates the type of resource assigned to carry out the task, and the number following the capital letter denotes the task time. It is shown that Tasks 1 and 2 are completed under sequential cooperation by a human and a robot, respectively; Tasks 3 and 4 are accomplished under parallel collaboration by a human and a robot, respectively; and Task 5 is completed under joint collaboration by a cobot (both a human and a robot assist in performing Task 5 together).

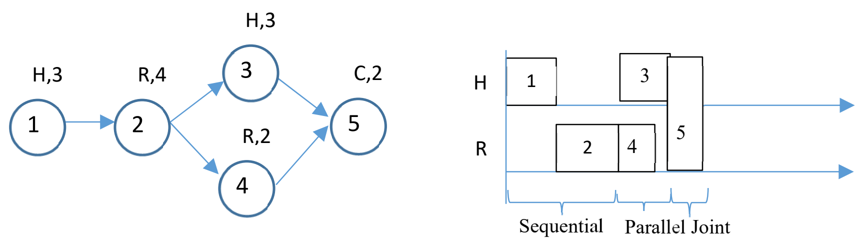

Fig. 1. An illustrative example of collaborative modes in a workstation

CoALBPs are comparable to RALBPs (robotic assembly line balancing problems). The emergence of robots as an indispensable asset in the AL is what connects these two problems. The design intentions of these two systems, however, are somewhat different. First, robots in the RAL are meant to automate the labour of human workers whereas cobots in the CoAL are supposed to work alongside humans to ease their labour strain. Second, in the case of the CoAL, the human-to-robot ratio is often larger than one, indicating that workers are the dominant resource of the AL, as opposed to the RAL. Third, each workstation in the RAL comprises either a worker or a robot, resulting in line balancing that is simply about allocating tasks in accordance with the precedence relation to the resource involved in each workstation. As a result, the manner of collaboration between workers and robots in the RAL is coexistence (category 2). In contrast, each workstation in the CoAL may be accommodated by a worker, a robot, or a worker plus a cobot. As a consequence, possible collaboration modes at each workstation might include sequential cooperation (category 3), collaboration (category 4) and responsive collaboration (category 5). In addition to assigning tasks to resources based on their precedence constraints, scheduling of tasks is of utmost importance meaning the schedule of all preceding tasks must be established in order to determine the earliest time that the succeeding task may begin. For example, in Fig. 1, Task 5 (joint cooperation) cannot start until both Tasks 3 and 4 (parallel collaboration) are accomplished. Since Task 3 is completed later than Task 4, the time that Task 3 is done defines the earliest start time for Task 5. From the prior argument, it is evident that the CoALBP is significantly more challenging than the RALBP since many more decisions must be taken. Although research on the CoALBP has begun just a few years ago (in 2019), an increasing number of academics are paying close attention to this research domain. Although Kheirabadi et al. (2022) recently provided a brief review of the literature on the CoALBP, their assessment encompassed just studies published between 2019 and 2021. Because this research subject is still in its infancy, close monitoring of research progress is vital for in-depth investigations, identifying existing research gaps, and finding directions to advancing research in potential future areas. As a result, this paper encompasses all CoALBP articles published from the past to the second quarter of 2023. All publications collected are clustered, and their contributions towards enhancing earlier studies are underlined. Furthermore, the findings and statistics related to important results are illustrated and graphically analysed. Finally, potential areas for future research are elaborated.

The remaining parts of this paper are organised as follows. Section 2 discusses the technique for discovering pertinent literature on CoALBPs. Section 3 provides a comprehensive assessment of the concerned literature. Section 4 addresses the research investigation of the review articles and offers potential research outlooks. Finally, Section 5 concludes with closing remarks.

2. Research Framework

A systematic strategy outlined by Dolgui et al. (2022) is utilised in searching for relevant papers associated with the CoALBP to be included in the review process. Web of Science, Scopus and Google Scholar are the three main database-collecting sources that are used in combination. When attempting to locate relevant papers, there are no restrictions on the published date of the article, the name of the journal published and the author's name. In addition, the search is conducted anywhere within the article. Since the primary purpose of the search is to uncover articles written specifically about the CoALBP, the search keywords used in combination embrace [cobot AND assembly AND balancing], [human-robot collaboration AND assembly AND balancing], [collaborative robot AND assembly AND balancing], [collaboration of human and robot AND assembly AND balancing], and [human-robot interaction AND assembly AND balancing]. All articles discovered through the searches are compiled in Excel, sorted by chronological order, duplicate removal and then a scan through the title, abstract, keyword and content to check if the main contribution of the article is emphasising the assembly line balancing under the HRC of categories 3 to 5 as required (if not, it is removed from the collection). The snowball search is also carried out. Its mechanism is to investigate the literature review part of each previously eligible article to figure out if there is any relevant article that has not yet been included in the catalogue. Following the completion of all aforementioned processes, only 25 articles spanning from 2019 to the second quarter of 2023 are found directly related to the desired categories of the CoALBP. The classification tactics used to categorise articles have a considerable impact on the literature review process and the identification of research gaps. According to Chutima (2020), a better technique to cluster literature is, to begin with, a broad perspective of the topic (i.e., research highlight) in which each element is mutually exclusive with one another and then gradually drill down to a narrower view. As a result, the CoAL layout shapes are at the top of the classification scheme. Straight, U-shaped, parallel, two-sided, and multi-manned ALs are the basic shapes of the Als. Underneath the layouts, the number of products (single or mixed model) produced from the assembly line is in the second layer of the hierarchy. Finally, the concept of 4M1E (man, machine, material, method, and environment) adapted from Chutima (2022) is used to further streamline the classification structure to the lowest level of the pyramid. The attributes that fall under the umbrella of the 4M1E approach are explained as follows.

Man (worker):

- Types of workers:
  - Physical characteristics: normal, disabled or elderly workers.
  - Homogeneity among workers: single or multiple types.
- Skills of workers: same (i.e., all workers have the same skill) or various skills (i.e., each worker's skill set differs, resulting in someone working quicker than the other and/or one worker can execute certain tasks while the other cannot).
- Safety and ergonomics: in the problem definition, whether any safety and/or ergonomics concerns are referred to.

Machine (Cobot):

- Types of cobots: single or multiple types of cobots are available in the system.
- Capability of cobots: cobot capabilities can be the same or diverse, and each robot can execute every task or just particular ones based on the capability matrix.

Material (task):

- Interaction feature between workers and cobots in each workstation: parallel and/or joint collaboration.
- Task time: deterministic or stochastic, and its value is constant no matter which resource executes it or depending on the assigned resource.

Method:

- Types of problems: I (minimising the number of workstations given the cycle time), II (minimising the cycle time given the number of workstations), Cost (minimising the costs associated with the use of the CoAL), O (others which may be a combination of several fundamental objectives or a new objective created specifically for the given problem).
- Optimised objective: a list of objective functions to be optimised to the CoALBP under consideration, which may comprise single or several objectives.
- Simultaneous decisions: a list of decisions that must be made simultaneously when balancing the CoAL.
- Mathematical formulation: A mathematical description of the CoAL system represented in the form of equations, such as mixed integer programming (MIP), constraint programming (CP), and so on.
- Solution technique: since the CoALBP is NP-hard, the CPLEX solver can only handle small instances; hence, methodologies for solving large instances such as genetic algorithms (GA), simulated annealing (SA), and so on, must be developed.

Environment:

- Environment issue: specify whether or not environmental factors in the workplace, such as PM2.5, light, noise, and so on, are taken into account in the problem formulation.
- Actual use case: describe whether or not a real-world industrial setting is utilised as a basis for model development.

3. Analysis of literature

Manufacturing digitisation renders it possible for HRCs, which have emerged as an essential innovation for the factory of the future. The positive aspects of both human workers and companion cobots are integrated to enable workplaces to employ variable levels of automation to fulfil the growing need for assembly systems' adaptability. Under the context of adopting cobots in the AL, the CoALBP is much more complicated than the traditional ALBP and RALBP since more alternative resources (i.e., a worker, cobot or both) may be available to perform certain tasks in each workstation. The assignment of tasks to appropriate resources and worker-cobot scheduling, which are trivial decisions in the ALBP and RALBP, become essential to discover workable solutions to the CoALBP when cobots and humans cohabit in the same workstation. According to the previous discussion and the typical ALBP is NP-hard, the CoALBP is therefore classified as an NP-hard as well.

In the problem definition of the CoALBP, the following basic assumptions are normally incorporated: (1) The CoAL makes a single product; (2) The relationship between tasks in terms of precedence is specified; (3) Task times are deterministic, constant, and dependent on which resource is assigned (i.e., worker, cobot, or both); (4) Workers with the same set of skills are employed; (5) A single type of cobot is ready for use; (6) Based on the capability matrix, some tasks can only be performed by certain resources; and (7) A worker must be present at each workstation, while one additional cobot may be assigned to each workstation. These assumptions are subsequently relaxed during the succeeding developments to show the growth of the CoALBP research domain. The remaining of this section outlines a review of the pertinent CoALBP literature, highlights the essential characteristics of their models formulated, and pinpoints the effective approaches employed to handle large instances.

Yaphiar et al. (2019) formulated a MIP model to solve the mixed-model straight CoALBP Type Cost. The cost component comprised operational costs (i.e., labour and energy costs), investment costs (i.e., machinery procurement, and workers' hiring and training), and saving costs due to utilising robots and cobots (i.e., quality and/or ergonomic benefits). Since multiple product models were produced by the AL, a combined precedence diagram was constructed to be precedence-relationship representative of all products. However, the prohibition of loading tasks to workstations must not cause the completion time of any product model to exceed the workstation cycle time. Task times were deterministic and dependent on the allocated resources. In addition, a homogeneous type of workers and robots was employed. It was assumed that only a worker, only one type of resource (i.e., a worker, robot or cobot) was active in each workstation. As a result, the operational mode of cobots (HRC) was restricted to collaborative only. The proposed mathematical model was tested only on a small problem (10 tasks). The numerical results demonstrated the efficiency of the model as it solved the CoALBP very quickly.

Samouei and Ashayeri (2019) investigated a semi-automated straight CoAL that allowed two workers to work collaboratively at adjacent workstations. A single type of robot and workers with multiple skill levels (i.e., low, medium and high) were assumed. The skill level of the workers determined their salaries. Mixed-model products were assembled by CoAL, given the combined precedence diagram. A resource feasibility matrix identified which resource (workers, robots or cobots) could perform which tasks. Each workstation could be equipped with a maximum of one worker, robot or cobot. Task times were assumed to be deterministic and given. Two mathematical formulations were proposed for certainty (single objective) and uncertainty (multiple objectives) conditions. The objective to be optimised for the single-objective CoALBP was to minimise total fixed and variable costs, while the weighted sum of total costs (fixed and variable) and cycle time was used for the multi-objective CoALBP. The proposed MIP formulations were solved using the CPLEX solver. The factors of the number of tasks (8 - 83 tasks), workers with different skills, robots, cobots and relative disturbances of the cycle time ($0.1 \leq \propto \leq 0.9$) were experimented with to assess the performance of the proposed MIPs. The result showed that increasing the $\propto$ level increased the total cost and pushed the cycle times close to their lower limit.

Weckenborg et al. (2019) considered a straight CoALBP to minimise the cost per cycle. The cost structure included the cost of workstations and resources. Only one product was produced. A worker and a robot (i.e., cobot workstation) were allowed to work in parallel on the same workstation. The capability matrix was used to determine whether the resources (i.e., workers, robots and cobots) were able to perform certain tasks or not. The duration of a task depended on which resource performed it. Workers were exposed to ergonomic risks. The energy expenditure of the assigned tasks was used to determine the average work rate of the workers. For any task whose mean work rate value was greater than an acceptable work level, the actual time of the task was additionally adjusted to limit the workers' ergonomic exposure. A MIP model of the system was developed and solved using CPLEX. In formulating the MIP model for use in the experiments, several process parameters were taken from the high-pressure cleaner assembly process with 17 tasks. Four factors were tested for their impact on the objective function (i.e., workstation cost, worker cost, energy expenditure and cobot speed). The experimental results showed that cost-effective ALs could range from purely manual to fully automated ALs, depending on the specific characteristics of the ALs. Furthermore, cobots were a cost-effective alternative for introducing automation in manual AL.

Dalle Mura and Dini (2019) developed a software tool for balancing a straight CoALBP where a single product was assembled. Various worker skills (i.e., low, medium and high) and robot dexterities (i.e., low and high) were considered. Workers and robots were required to have at least the minimum required skills and dexterity to execute tasks. In addition, an extra device might be needed to perform certain tasks. Task times were dependent on the allocated resources (workers, robots and cobots). Unlike the others, this paper assumed the task times of robots to be less than those of workers (i.e., robots complete tasks faster than workers). The physical effort of workers to perform tasks was assessed through their energy expenditures used. The optimised objective was formalised as the weighted sum of the three normalised sub-objectives, i.e., (1) AL cost, (2) the number of workers and (3) workers' energy load variance. A genetic algorithm (GA) was employed to solve the real case study of a scooter chassis AL where 45 tasks were involved. The results demonstrated that the ergonomic risk of workers, especially from heavy and bulky part lifting, could be relieved with the help of cobots. Moreover, when the labour cost was high, robots were utilised much more frequently as the main working resource.

Weckenborg et al. (2020) formulated a MIP model for a straight CoAL producing a single product to minimise the cycle time (C) of the AL (or ALBP Type II). Initially, the AL was manually operated by workers with a fixed number of workstations. To increase production efficiency, robots were used, however, whose number was less than the number of workstations. It was assumed that all workers had the same skills and abilities. Similarly, a single type of robot was utilised. The workers performed the tasks faster than the robots, but slower than when both worked together in a collaborative mode. The execution times of the tasks were deterministic and dependent on the allocated resources. Since the problem fell into the class NP-hard, a hybrid genetic algorithm (HGA) was developed. The relative performance between MIP and HGA was evaluated under different AL conditions, including problem sizes (20 - 100 tasks), RF, CF, F-ratio and West-ratio. The results showed that a small number of large instances could be solved optimally by MIP. Moreover, in most cases of large instances, the solutions obtained with GA were equal to or better than MIP. The reduction of cycle times could be achieved by increasing robot density, robot flexibility and West-ratio, while F-ratio did not influence the improvement of cycle time.

Rabbani et al. (2020) addressed a four-sided (4SAL) mixed-model CoALBP used for the production of large-scale heavy products. Tasks could be performed on the product from the left, right, top or bottom sides. However, the tasks on the top side could only be performed by robots, while the other tasks could be performed by either workers or robots. Therefore, the interactions between workers and robots at each workstation were limited to parallel mode only. There were also some constraints on the specific site and/or resource (worker or robot) that could perform the task. Since the AL produced mixed models of the product, the combined precedence diagram was created. The task times of each model depended on which resource was performing it and were deterministic and known. A MIP model was formulated to optimise two objectives, minimising the number of stations and minimising the cost of using the resources. Constraints, i.e., positive and negative zoning, and synchronous tasks were also considered. Augmented multi-Objective Particle Swarm Optimisation (AMOPSO) with adaptive uniform mutation and local learning mechanism was proposed to deal with large problem instances. Experiments were conducted with different numbers of tasks (30 - 200), paired stations, product models, workers and robots. The relative percentage increase (RPI) index was used for relative performance comparison between the different solution techniques. The results showed that AMOPSO performed better than MOPSO.

Çil et al. (2021) investigated a straight CoALBP with mixed models to minimise the total cycle time for all models. Different types of robots with different capabilities and homogeneous worker capabilities were used. Task times were deterministic and known, and their values depended on the allocated resources. It was assumed that only one type of resource (either worker or robot) could perform a given task. In other words, tasks that could be done by workers could not be done by robots and vice versa. This restriction meant that interactions between a worker and a robot at the same workstation (if any) were limited to a parallel mode only. A MIP model was developed and solved with the CPLEX solver, which proved optimality for small instances. Large instances were solved with the improved bee algorithm (IBA) and the improved artificial bee algorithm (IABC). The problem instances varied in the number of tasks (7 - 148) and workstations (2 - 13). The results showed that IBA and IABC had a better relative percentage deviation (RPD) than the other nine algorithms.

Boschetti et al. (2021) considered a special case of the straight CoALBP where the AL involved a single workstation where a worker and a cobot shared the workplace and tasks. The AL produced a single product. Task times were deterministic and depended on allocated resources. A MIP was formulated to minimise the makespan. The effects of product characteristics (i.e., parallelism) and product and process characteristics (i.e., task time) on system performance (i.e., makespan and collaboration) were investigated. It was found that a higher parallelism index led to increased collaboration between a worker and a cobot, resulting in reduced makespan. In addition, an improvement in the makespan was also achieved through a higher task time index. Koltai et al. (2021) studied three cases of allocating resources to each workstation in a straight CoALBP, namely (1) only a worker, (2) either a worker or a robot, and (3) both a worker and a robot. MIPs with different objectives, i.e., minimising the number of workstations and minimising the cycle time, were formulated for three different cases of CoALBPs. The AL produced a single product. The task times were deterministic and depended on the allocated resources. The tasks could be performed in parallel if a workstation consisted of a worker and a robot. Workers were assumed to have two skill levels (i.e., low and high). In contrast, a homogeneous robot was used whose skills were comparable to those of low-skilled workers and the robot could only perform certain tasks. In addition, the robots spent more time on the tasks than the workers. To facilitate the solution of CoALBPs, the proposed models were transformed into constraint programming (CP) formulations, which were solved using CPLEX. The results from solving the power inverter CoALBP with 49 tasks showed that a reduction in the cycle times without rising the number of workstations could be achieved by permitting workers and robots to work together in parallel in the same workstation.

Dimény et al. (2021) developed three MIP models for a straight CoALBP to minimise three objectives in lexicographical order: (1) the number of workers, (2) the number of robots, and (3) the cycle time. These models were tested on the power inverter AL with 49 tasks, which combined the efforts of workers and robots. Multiple types of workers and robots with distinct skills and abilities to execute tasks were employed. A variety of workers and robots with varying skills and capacities to carry out duties were deployed. Tasks were divided into groups, and those in the same group could not be assigned to workstations that were more than one workstation far away. Task times were deterministic, and their values were determined by the resource specified to them. If workers and robots were assigned to the same workstation, their operations could only be carried out in parallel, without joint collaboration. The CPLEX solver was applied to solve the models. The results demonstrated that allowing a robot to operate together with a worker in parallel at the same workstation could minimise the number of workers in the AL. Li et al. (2021) formulated a MIP model for a straight CoALBP to achieve two goals simultaneously, namely minimising the cycle time and minimising the acquisition cost of cobots. A single product was assembled by the AL. The workers were homogeneous, while many types of cobots with different acquisition costs were available. The robots could only perform certain tasks. The assigned resource (i.e., worker, robot or cobot) determined the processing time of each task. Task times were deterministic. Tasks performed by workers took less time than robots, but more than cobots. For safety reasons, the cobots could only work in a joint collaborative mode, but not in parallel. The algorithm MMBO (multiobjective migrating birds optimisation) was proposed to find Pareto-optimal solutions for large instances (7 - 279 tasks). The results showed that the CPLEX solver could find optimal solutions for the mathematical formulation with one of the two objectives or the weighted sum of two objectives for small instances. Moreover, MMBO achieved better performance than the other five multi-objective optimisation algorithms.

Shan et al. (2021) investigated a two-sided CoALBP that created a single product. At most, each mating station might have one worker, one robot, or one worker and one robot. Workers had the same skills and wages, and there were no apparent differences in task times among them. In contrast, various robot capabilities were acquired. As a result, different task times might be required to complete the same task depending on their operational modes. More expensive robots performed better and more efficiently than those cheaper ones. Worker and robot task times were deterministic and known. A MIP model was developed to optimise two objectives at the same time: minimising cycle time and minimising the overall cost of procuring robots and hiring workers. Three decisions had to be made: assembly mode, task assignment, and scheduling. To address the challenge, the non-dominated sorting genetic algorithm II (NSGA II) was devised to solve the problem with 12 tasks assigned to two paired stations. The results demonstrated that NSGA II was an efficient algorithm for dealing with the problem.

Sikora and Weckenborg (2022) explored Blenders' decomposition algorithm (BD), which decomposed the original problem into two parts (i.e., main problem and subproblem) and solves them iteratively. Four decomposition versions of BD were investigated to solve a straight CoALBP aimed at minimising cycle time. A single product was the subject of line balancing. Task times were deterministic and predetermined, and the assigned resources (i.e., worker, robot or cobot) determined the values of the task times. Homogeneous worker skills and robot types were used. Worker task times were assumed to be lower than those of robots, but higher than those of cobots. In addition, there was always a worker available at each workstation who could perform all assigned tasks. In contrast, the number of robots was lower than the number of available workstations and they could only do certain tasks. At each workstation, workers and robots could perform tasks together under a joint collaboration mode and also in parallel. The dataset varied in terms of the number of tasks (20, 50 and 100), number of workstations (5, 10, 13, 25 and 50), cobot density (0%, 20% and 40%) and feasibility of task execution by cobots (20% and 40%). The results demonstrated that the MIP formulation could only prove optimality in some of the small instances. BD performed better than MIP in terms of computation time and quality of solutions. However, it could not be determined with certainty which decomposition method of BD outperformed the others.

Stecke and Mokhtarzadeh (2022) studied a straight mixed-model CoALBP. The processing times of tasks were deterministic, fixed and depended on the allocated resources. There was one worker on duty at each workstation, where a robot and/or equipment needed for certain operations were allocated as necessary. Workers with the same skill could perform all assembly tasks; meanwhile, homogeneous types of robots could execute certain tasks only. Robots could be immobile or mobile. For mobile robots, they could move between two adjacent workspaces to execute tasks allocated at both workstations. The task times of robots were greater than those of workers, while in a joint collaborative mode, workers and robots helped each other in executing tasks and consumed less time. The constraints that existed in the balance shaft module assembly, such as positive and negative zoning, synchronous operations, immediate task execution, and minimum safe time for workers, were also incorporated into the model. Ergonomic risk factors measured through the energy expenditure of workers performing activities were taken into account. In addition, the preferences of operations to be performed by workers, robots, or cobots were classified into green (workers), yellow (no preference), orange (robots) and red (cobots) based on their ergonomically adverse or complex nature. The weighted sum of four objectives was optimised, including (1) minimising the cycle time, (2) minimising the total ergonomic risk (ER) of the AL, (3) minimising the total ER of the workstation with a maximum total ER, and (4) maximising the total number of operations assigned to preferred resources. The MIP and CP formulations were developed. The CPLEX solver was used to solve MIP and BD, while CP was solved by the CP optimiser. Seven configurations of CoALs varied in terms of tasks (21–89), workstations (5–17), collaborative robots (0–30), models (1-3), and passive resources (0–30). The results showed that the cycle time and ER could be reduced by the implementation of mobile robots. In addition, BD was useful in finding feasible solutions for large instances, but CP outperformed the others for small and medium instances.

Dalle Mura and Dini (2022) considered a straight CoALBP where workers rotated their jobs periodically to decrease monotony and ergonomic risks. In addition, workers could not be placed in the same workstations where they were assigned in the previous rotation cycle(s) of a given shift. Individual workers had their own characteristics, i.e., gender (men and women), age, weight, height, technical skill level (low, intermediate and high), and energetic limit. The physical fatigue of workers from manual operations was measured by their energy expenditures, and no worker could work beyond his/her physical capability. The AL produced a single product. Task times were deterministic and depended on the assigned resources. Manual task times were assumed to be higher than automatic and cobot task times. All manual tasks could be done by workers, given that their skill levels were equal to or greater than the levels necessary to perform such tasks. Each workstation had to be equipped with the necessary equipment since they were essential for completing assembly tasks. The weighted sum of two objectives was optimised, including minimising the cost of utilising AL (number of workstations and equipment) and minimising the energy load variation among workers. GA with three layers of chromosomes (i.e., task-, equipment-, and job rotation-oriented chromosomes) was developed to solve a real case of the vehicle front-end assembly with 29 tasks. The results showed that GA could produce a cost-efficient CoAL configuration. In addition, job rotations could smooth the distribution of energy expenditure among workers.

Weckenborg et al. (2022) examined a straight CoALBP in which the AL produced a single product. Apart from such typical resources as workers and cobots, the impact of exoskeletons, a piece of orthotic equipment that linked the bodies of workers to reduce their biomedical loads, was also investigated. The study attempted to investigate how to reconcile the competing objectives of minimising economic and ergonomic concerns. The annual cost of the AL was set as the economic objective, whereas the highest possible energy expenditure per period experienced by workers was specified as the ergonomic objective. Workers, cobots and exoskeletons were homogeneous, and processing times to complete tasks were deterministic, constant and depending on the resources used. The energy expenditure consumed by workers while completing a task was deterministic and known. In addition, the use of exoskeletons by workers did not reduce their processing times, but it did lessen their energy expenditures. A MIP model was formulated for the problem. Pareto optimal fronts were used to display non-dominated solutions. The experimental results from the 20-task CoALBP revealed that the usage of exoskeletons allowed for the harmonisation of economic and ergonomic objectives simultaneously.

Abdous et al. (2022) addressed a straight CoALBP that was integrated with the equipment selection problem and named it the assembly line design problem (ALDP). The challenge comprised equipment-based task allocation, which meant that task allocation to workstations was also dependent on the equipment assigned to that workstation. Two objectives were optimised concurrently, i.e., minimising overall investment costs and maximising worker ergonomics with fatigue and recovery. It was expected that each workstation was staffed by one person. To equip the workstation, a selection of collaborative (e.g., cobot) or non-collaborative (e.g., exoskeleton) components was available to be selected. Furthermore, the task time and physical stress were determined by the equipment used. To determine the Pareto-optimal front for 7-148 task instances, a MIP model was developed and a ε-constraint technique was devised. The results demonstrated that the proposed method could locate the Pareto fronts for all small and medium instances with fewer than 10 pieces of equipment and 25 tasks.

Nourmohammadi et al. (2022a) examined an actual CoALBP in the automobile sector that made a mass balancing system. A single product was assembled using a straight AL. Two workstations, each with one worker and one robot, were utilised for performing 28 tasks. In collaborative work, the robot was employed to assist the worker in doing repetitive and heavy lifting duties, while the worker provided a guide to the robot's movement to the assigned working area. Workers and robots with varying skills and capacities were used, resulting in operator-dependent task durations. However, the task times of cobots were equal to those of workers. A MIP model was developed to optimise the weighted sum of cycle time (primary goal) and total number of employees and robots (second goal). For large instances, a simulated annealing (SA) technique with adaptive neighbourhood selection was developed. Aside from the industrial instance, the proposed methods were evaluated against a variety of scenarios varying in the number of tasks (7-111), workstations (2-16), and the maximum number of workers (1-2) and robots (1-2) per workstation. The results suggested that the adaptive SA outperformed MIP for medium to large instances. Furthermore, allowing many humans and cobots to work jointly in a workstation resulted in a significant reduction in cycle time. Nourmohammadi et al. (2022b) addressed their prior straight CoALBP problem where 28 jobs were allocated to two workstations (Nourmohammadi et al., 2022a). Diverse sorts of workers and robots with varying skills and capacities were deployed. To analyse the impacts of worker and robot heterogeneity on the cycle time, two scenarios were investigated: (1) best first: sort workers/robots from fastest to slowest task times, and (2) worst first: sort workers/robots from slowest to fastest task times. GA was applied to minimise cycle time. The findings demonstrated that GA was a successful solution technique for a wide range of problem scenarios. Furthermore, the best first strategy achieved faster cycle times than the worst first strategy.

Dimény and Koltai (2022) explored the impact of introducing robots to a straight AL on the overall labour workload. The system assembled a single product. The following assumptions were made when creating a MIL model. Each workstation was occupied by a worker, resulting in an equal number of workstations and workers. Workers and robots were multi-skilled and had diverse capabilities; therefore, task times were deterministic and dependent on the resources employed to process them. Some resources were unable to complete specific tasks. Furthermore, activities were only completed in parallel, not jointly, if one worker and one robot shared a workstation. The model was optimised hierarchically in two steps: (1) minimising the number of robots in relation to the number of workstations and workers, and (2) minimising the total amount of work allocated to workers. The CPLEX solver was used to solve the developed model. The outcomes of the instances with 28-35 tasks demonstrated that there was a limit beyond which adding extra robots to the AL could not reduce workers' workload.

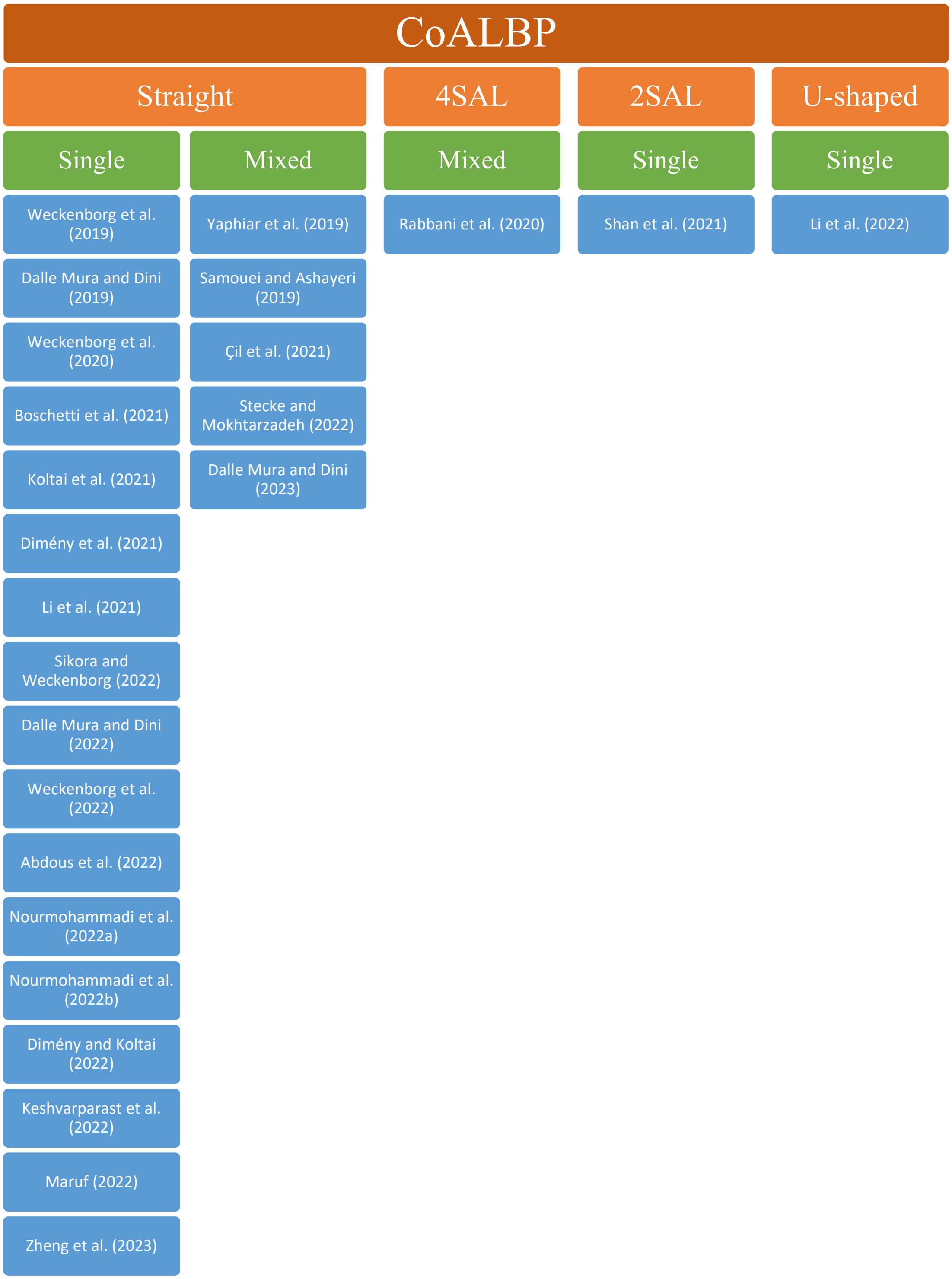

Fig. 2. Summary of the CoALBP research contribution relation diagram

Keshvarparast et al. (2022) proposed a bi-objective optimisation model of a straight CoALBP using heterogeneous workforces. Three degrees of worker experience (low, medium and high) were employed, which were reflexed in their corresponding processing times (from high to low). Furthermore, workers were not permitted to work beyond their physical limitations. To ease workers' physical burdens, a single type of robot was used to assist them in handling heavy parts. While workers could perform any task, robots could only execute a restricted number of operations. A MIP model was created to simultaneously minimise cycle time and workers' overall maximum workload for a vehicle front-end assembly line which needed 29 tasks to be completed by 6 people and 2 robots in 4 workstations. To find Pareto optimum fronts, a ε-constraint technique was applied. The results revealed that cobots were effective in circumstances where workers had poor physical power, and they could concurrently reduce cycle time while lowering the maximum physical workload of workers also.

Li et al. (2022) researched a U-shape CoALBP that produced a single product with the goal of reducing the AL's cycle time. In each workstation, a homogeneous sort of worker with the same skill and ability was deployed. However, many types of robots with varying purchase prices and capabilities were accessible for selection within the boundaries of the budget. When a worker and a robot were partnered in the same workstation, they could only interact in sequential and joint collaborative modes. The resource selection controlled the task time. Three MIPs were developed for dealing with small instances. For big instances, an improved artificial bee colony algorithm (IABC) and an improved migrating birds optimisation algorithm (IMBO) were developed. These algorithms were tested against a variety of scenarios including 7-297 tasks. The findings demonstrated that both IABC and IMBO were effective in resolving large instances. Furthermore, the presence of cobots could result in a reduction in cycle time.

Maruf (2022) analysed the effects of the number of available robots, tools, and setup times on the CoAL's cycle time. A straight AL was configured to produce only a single product. In terms of skills and capacities, both workers and robots were homogeneous. Each workstation had one employee accommodated in it. Unlike workers who could carry out any task, robots could only execute specific duties. Task execution times were determined by the resources allocated. Tools may be required for robots and/or cobots to do work. There were setup delays between tool changes. To minimise the cycle time, a MIP was developed. Only a small instance with 10 tasks was tested. The results suggested that when the number of tools decreased and setup times increased, the cycle times increased. Furthermore, differing numbers of available robots might alter worker, robot, and cobot allocation provisions.

Dalle Mura and Dini (2023) created a GA-based software solution for a straight CoALBP that assembled mixed-model products. Men and women with varying skill levels (poor, moderate, and high) were employed. Furthermore, workers at manual and collaborative workstations were subjected to periodic displacement to different workplaces from where they previously worked throughout a working shift. The ergonomic risks posed to workers by their operations (measured by energy expenditure) and working environment (measured by noise exposure) were taken into account. Aside from cobots, various equipment required to complete specific jobs has to be assigned to workstations. Task times were predetermined and given. To accomplish a given task, a worker needed to possess at least the skill level required by the task. A MIP was developed to minimise the weighted sum of three objectives: (1) AL cost (workers and equipment), (2) variance in workers' energy load, and (3) variance in workers' noise. GA was developed to design the AL with 32 tasks that resulted in two electric scooter variants. The results demonstrated that implementing the job rotation strategy could smoothen workers' ergonomics and workload variation.

Zheng et al. (2023) reduced certain redundancies in the mathematical model of the straight CoALBP provided by Wekenborg et al. (2020). The new models had the following features. The AL assembled a single product. Workers were taught to the point where they were all equally skilled. However, the types and capacities of robots varied. If workers and robots were assigned to the same workstations, their interactions were in parallel and/or joint collaborative forms. The resource used determined the task times. To minimise cycle time, two MIPs were developed. IABC and IMBO were put forward for big instances. The efficiency of the suggested methods was evaluated using tested instances ranging from 7 to 297 tasks with varying numbers of workstations. The findings showed that the proposed algorithms produced high-quality answers in a reasonable amount of CPU time.

Table 1
Summary of research contributions on CoALBPs

Year	Author	Problem Type	Distinctive Features of the CoAL: Layout	Product	Task: Feature	Task: Time	Worker: Type	Worker: Skill	Worker: Safety & Ergonomics	Robot (Cobot): Type	Robot (Cobot): Capability	Issues on Environment	Simultaneous Decision	Optimised Objective	Mathematical Formulation	Solution Technique	Actual Use Case
2019	Yaphiar et al. (2019)	Cost	straight	mixed	joint	allocation-dependent and deterministic	normal & single	same & can execute all tasks	ergonomic benefit implied in the objective function	single	same & can execute all tasks & allow pure robotic workstations	-	robot assignment	min Cost	MIP	CPLEX	-
2019	Samouei and Ashayeri (2019)	two models: (1) Cost & (2) O	straight	mixed	joint	allocation-dependent and deterministic	normal & multiple	various skills & executable tasks were defined by the resource feasibility matrix	-	single	same & executable tasks were defined by the resource feasibility matrix	-	robot assignment & workers at two adjacent workstations can help each other	(1) min Cost; (2) min weighted sum of Cost and C	MIP	CPLEX	-
2019	Weckenborg et al. (2019)	Cost	straight	single	parallel	allocation-dependent and deterministic	normal & single	same & executable tasks were defined by the capability matrix & a manual worker must be assigned to each workstation	ergonomic risk (energy expenditure)	single	same & executable tasks were defined by the capability matrix & number less than workers	-	robot assignment	min Cost	MIP	CPLEX	high pressure cleaner process
2019	Dalle Mura and Dini (2019)	O	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & multiple	various skills & cannot execute some tasks & a manual worker must be assigned to each workstation	ergonomic risk (energy expenditure)	multiple	various dexterity & cannot execute some tasks	-	robot assignment & equipment assignment	a weighted sum of: (1) min assembly line cost; (2) min number of workers; (3) min energy load variance	-	GA	scooter chassis process
2020	Weckenborg et al. (2020)	II	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & single	same & can execute all tasks & a manual worker must be assigned to each workstation	-	singles	same & number less than workers & cannot execute some tasks	-	robot assignment	min C	MIP	HGA	-
2020	Rabbani et al. (2020)	two objectives: (1) II & (2) Cost	4SAL	mixed	parallel	allocation-dependent and deterministic & considered positive and negative zoning, and synchronous tasks	normal & single	same & cannot execute above-sided tasks	-	single	same & can execute tasks from any side	-	robot assignment	(1) min number of stations; (2) min resource utilisation costs	MIP	GAM, AMOPSO	-
2021	Çil et al. (2021)	I	straight	mixed	parallel	allocation-dependent and deterministic	normal & single	same & tasks to be done by workers could not be done by robots	-	multiple	various & tasks to be done by robots cannot be done by workers	-	robot assignment	min total model cycle time	MIP	IBA, IBAC	-

Table 1

Summary of research contributions on CoALBPs (cont.)

Year	Author	Problem Type	Distinctive Features of the CoAL										Simultaneous Decision	Optimised Objective	Mathematical Formulation	Solution Technique	Actual Use Case
			Layout	Product	Task		Worker			Robot (Cobot)		Issues on Environment					
					Feature	Time	Type	Skill	Safety & Ergonomics	Type	Capability						
2021	Boschetti et al. (2021)	O	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & single	same & can execute all tasks	-	single	same & can execute all tasks	-	robot assignment	min Makespan	MIP	CPLEX	box assembly
2021	Koltai et al. (2021)	I and II	straight	single	parallel	allocation-dependent and deterministic	normal & multiple	various skills	-	single	same & can execute only some tasks & skills comparable to low-skilled workers	-	robot assignment	(two formulations) (1) min N_w (2) min C	MIP, CP	CPLEX	power inverter
2021	Dimény et al. (2021)	O	straight	single	parallel	allocation-dependent and deterministic	normal & single	same & can execute all tasks	-	multiple	various & can execute only some tasks	-	robot assignment	(lexicographical order) (1) only a worker (2) either a worker or a robot (3) both a worker and a robot	MIP	CPLEX	power inverter
2021	Li et al. (2021)	II & Cost	straight	single	Joint	allocation-dependent and deterministic	normal & single	same & can execute all tasks	-	multiple	various with different purchasing costs & can execute only some tasks	-	robot assignment	(Pareto & weighted sum) (1) min C (2) min total cost of workers and robots	MIP	CPLEX, MMBO	-
2021	Shan et al. (2021)	II & Cost	two-sided	single	parallel/ joint	allocation-dependent and deterministic	normal & single	same & can execute all tasks	-	multiple	various with different purchasing costs & can execute only some tasks	-	robot assignment	(Pareto) (1) cycle time (2) total cost of workers and robots	MIP	NSGA II	-
2022	Sikora and Weckenborg (2022)	II	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & single	same & can execute all tasks	-	single	same & can execute only some tasks	-	robot assignment	min C	MIP	BD	-
2022	Stecke and Mokhtarzadeh (2022)	O	straight	mixed	parallel/ joint	allocation-dependent and deterministic	normal & single	same & can execute all tasks	ergonomic risk (energy expenditure)	single	same & can execute only some tasks	-	robot assignment	(weighted sum) (1) minimising the cycle time (2) minimising the total ER of the AL (3) minimising the total ER of the workstation with a maximum total ER (4) maximise the total number of operations assigned to preferred resources	MIP	CP, BD	balance shaft module
2022	Dalle Mura and Dini (2022)	O	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & multiple	various skills	ergonomic risk (energy expenditure)	single	same & can execute only some tasks	-	robot assignment & equipment assignment	(weighted sum) (1) cost of utilising AL (2) energy load variation among workers	-	GA	vehicle front end

Table 1
Summary of research contributions on CoALBPs (cont.)

Year	Author	Problem Type	Distinctive Features of the CoAL										Simultaneous Decision	Optimised Objective	Mathematical Formulation	Solution Technique	Actual Use Case
			Layout	Product	Task		Worker			Robot (Cobot)		Issues on Environment					
					Feature	Time	Type	Skill	Safety & Ergonomics	Type	Capability						
2022	Weckenborg et al. (2022)	O	straight	Single	parallel/ joint	allocation-dependent and deterministic	normal & single	same	ergonomic risk (energy expenditure)	single	same & can execute only some tasks	-	robot assignment & exoskeleton assignment	(Pareto) (1) min annual cost of the AL (2) maximum energy expenditure per period	MIP	-	-
2022	Abdous et al. (2022)	O	straight	Single	parallel/ joint	allocation-dependent and deterministic	normal & single	same	ergonomic risk (energy expenditure	multiple	various with different purchasing costs & can execute only some tasks	-	robot assignment & equipment assignment	(Pareto) (1) minimise overall investment costs (2) maximising worker ergonomics with fatigue and recovery	MIP	ε-constraint technique	-
2022	Nourmohammadi et al. (2022a)	O	straight	Single	parallel/ joint	allocation-dependent and deterministic	normal & multiple	various skills	-	Multiple	various & can execute all tasks	-	robot assignment	(weighted sum) (1) cycle time (2) total number of employees and robots	MIP	SA	mass balancing system
2022	Nourmohammadi et al. (2022b)	II	straight (maximum of 2 workers and 2 robots allowed in each workstation)	single	parallel/ joint	allocation-dependent and deterministic	normal & multiple	various skills	-	multiple	various & can execute all tasks	-	robot assignment	min cycle time	-	GA	mass balancing system
2022	Dimény and Koltai (2022)	O	straight	single	parallel	allocation-dependent and deterministic	normal & multiple	various skills	-	multiple	various & can execute all tasks	-	robot assignment	(hierarchically) (1) min the number of robots (2) min the total amount of work allocated to workers	MIP	CPLEX	-
2022	Keshvarparast et al. (2022)	O	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & multiple	various skills	-	single	same & can execute only some tasks	-	robot assignment	(Pareto) (1) cycle time (2) workers' overall maximum workload	MIP	Epsilon constraint technique	vehicle front end
2022	Li et al. (2022)	II	U-shape	single	joint	allocation-dependent and deterministic	normal & single	same	-	multiple	various & can execute only some tasks	-	robot assignment	min cycle time	MIP	IBA, IBAC	-
2022	Maruf (2022)	II	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & single	same	-	single	same & can execute only some tasks	-	robot assignment & tool assignment & setup time	min cycle time	MIP	CPLEX	-
2022	Dalle Mura and Dini (2023)	O	straight	mixed	parallel/ joint	allocation-dependent and deterministic	normal & multiple	various skills	ergonomic risk (energy expenditure)	single	same & can execute only some tasks	noise (noise exposure)	robot assignment & equipment assignment	(weighted sum) (1) AL cost (workers and equipment) (2) variance in workers' energy load, (3) variance in workers' noise	MIP	GA	electric scooter
2023	Zheng et al. (2023)	II	straight	single	parallel/ joint	allocation-dependent and deterministic	normal & single	same	-	multiple	various & can execute only some tasks	-	robot assignment	min cycle time	MIP	IABC, IMBO	-

4. Review Discussion and Future Outlooks

Following a thorough review of the literature in the preceding section, Table 1 summarises the standout characteristics of these CoALBP research studies. The research contribution relation diagram produced to demonstrate the clusters and extension of research contributions chronologically made in each direction is also shown in Fig. 2. In this section, each key finding revealed from the literature review is presented, followed by a discussion of some intriguing research gaps that merit further investigation.

Number of publications:

- Fact: In 2019, the breakthrough CoALBP research began. Compared to the ALBP and RALBP, the number of articles published under the CoALBP's scope is still incredibly low, averaging around 5 articles a year. With 12 articles, 2021 is the year with the most publications (Fig. 2).
- Research gap: The research endeavour of the CoALBP is currently in its early stages. It is expected that a significant increase in the number of publications will be emerged in this field in the near future, per trends (see the dotted line in Fig. 3).

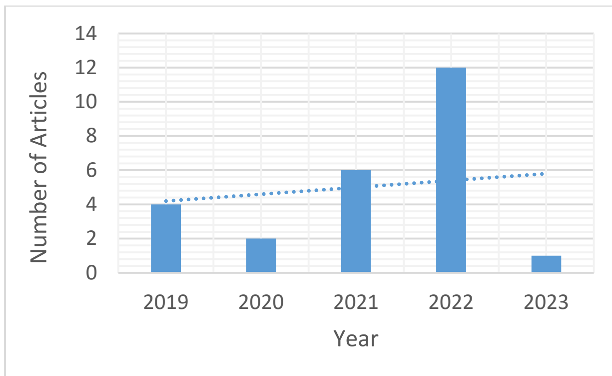

Fig. 3. Number of publications per year (from 2019 until Q2 of 2023)

Layout of the AL:

- Fact: The straight-shaped AL dominates the layout configurations in the CoALBP research, with 4-sided (Rabbani et al., 2020), 2-sided (Shan et al., 2021) and U-shaped (Li et al., 2022) ALs each appearing in one article (Fig. 4).
- Research gap: It is not surprising that the straight AL stands out from others in terms of research activities since it is the most basic one. However, more advancements in this kind of layout are probably close to reaching their saturation point since most of the prior studies have concentrated on this kind of layout. As a result, undertaking additional studies on U-shaped, two-sided, parallel, and multi-manned CoALs still presents numerous challenges in terms of enhanced research contributions. Therefore, more investigation into these largely unexplored layouts is necessary.

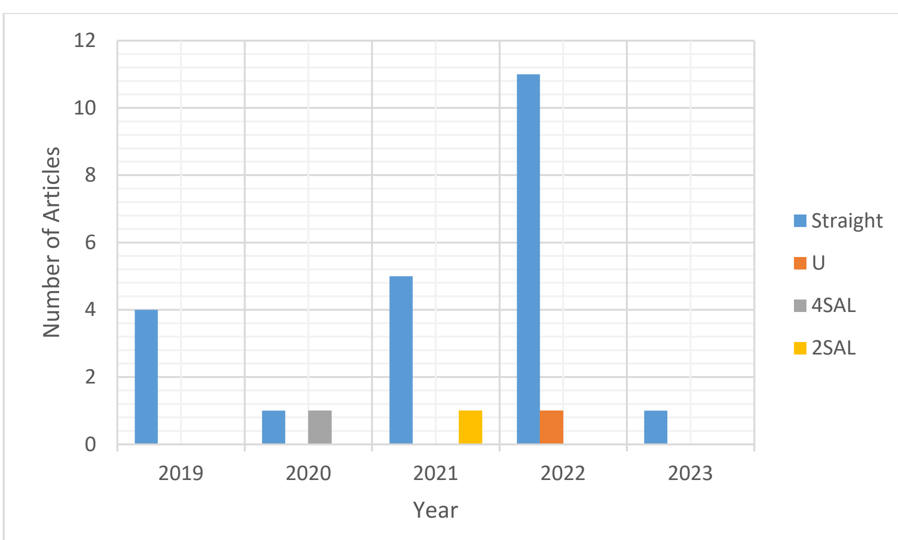

Fig. 4. Annual number of articles per layout

Product mix:

- Fact: The AL that produces just a single product is the subject of the majority of the CoALBP research.
- Research gap: Further research should concentrate on the production of mixed products by the AL. When considering the task-to-station assignments, the majority of studies that claim to be researching mixed models of products adopt a similar approach used in the single product by utilising a common precedent diagram. Additionally, their objective functions do not reflect the impact of the existence of the mixed product at all, e.g. minimising the average workload variation among different models in each workstation. Also, in practice, it might not be feasible to assign tasks to a workstation with a total task time of any model that exceeds the cycle time under the assumption that there will be an abundance of utility workers available to take on additional work left over by workers in each workstation. As a result, a superior resolution on this issue would probably be to distribute tasks to a workstation so that the cycle time is not exceeded by the maximum total task time for all models. In this case, not only are no utility workers required, but also there will be no AL interruption whatsoever.

Worker type:

- Fact: All articles employ only normal workers in the system.
- Research gap: The primary drivers of labour shortages in many nations are declining birth rates and an ageing population. In the decade to come, a sharp decline in the population of working age is anticipated. In certain nations, an innovative option is to reward participating organisations in the form of monetary and/or non-monetary benefits for helping to promote employment of the old and disabled. However, because each worker's group has its own constraints associated with the assigned jobs, employing these two groups of workers may pose a significant problem to the industry at large. More specifically, because of their limitations, disabled individuals may not be suited for performing certain jobs, whereas elderly workers typically have lower physical strength and stamina than younger ones. As a result, while delegating responsibilities to these individuals, consideration must be given to their physical capabilities and constraints. Further study of the CoALBP research should take into account the advantages and disadvantages of hiring elderly and disabled workers, as described above.

Worker skill:

- Fact: In roughly sixty per cent of the articles, the same level of worker skills is assumed, which most research in the later years is well-liked by various skills of workers.
- Research gap: The normal practice in the industry is to employ individuals with a variety of competencies because each production step often has unique skill requirements. However, given the wide range of skilled workers available, it might be difficult to assign suitable workers to workstations based on their skill sets because certain workstations may require several different skills from an individual at the same time. The issue is made even considerably more complex when merged with the diverse types of workers (i.e. disabled and/or elderly) as mentioned in the previous section. As a result, this research direction is still open for further exploration.

Safety, ergonomic and workplace environment:

- Fact: Only one article takes into account noise issues brought up in the work environment, despite safety and ergonomics being taken into consideration in around one-third of articles. Additionally, apart from cobots, just one article discusses the usage of an extra advanced device, such as an exoskeleton, to further assist in lowering ergonomic risks for workers.
- Research gap: The ergonomic risks of manual workers on assembly lines at work have received significant attention in recent years. Ergonomic injuries may culminate in long-term health issues for workers (such as musculoskeletal pain, strain and fatigue), which may affect their quality of life. They can also result in indirect expenses for manufacturers including absenteeism, higher defect rates, and lessened productivity. Cobots are the primary cutting-edge device used in the CoAL environment to help reduce workers' ergonomic risks, as assessed through their energy expenditure, by assuming responsibility for extremely physically demanding tasks. Various ergonomic devices, including posture-correcting clothing, adjustable workstations, ergonomic chairs, wearable technologies, anti-fatigue mats, footrests, elbow supports, back supports, etc. are also available to help workers' bodies withstand a higher level of stress and strain. Depending on the industry and specific type of work, further research is required to investigate the best additional ergonomic devices to work hand in hand with cobots to ensure a more secure and pleasant workplace for workers. In addition, when designing the CoAL, cognitive ergonomics, which addresses the mental components that make up individuals, is equally important as physical ergonomics. Stress at work is a cognitive aspect of ergonomics that can, in turn, affect workers' physical ergonomics. To prevent injury, workers should be given an appropriate degree of cognitive workload. As a result, another research gap is to design the CoAL that does not only balance the physical workload of the workers but also their cognitive workload. Moreover, job rotation is another factor that could prove advantageous to workers since it can decrease ergonomic risks accumulated while working, especially for repetitive manual tasks. Hence, further research is needed on the topic of job rotation scheduling considering worker training and learning curves. The introduction of cobots improves not only the physical and mental workload of workers but also the working environment, which may impact the well-being of workers. These environmental conditions at work include

those linked to light, noise, dust, air, temperature, humidity, etc. It's also exciting to find out how the environmental issue is correlated to balancing the CoAL.

Cobot type:

- Fact: Nearly half of the articles employ just a single type of cobot. However, most recent research appears to assume a variety of cobots.
- Research gap: Preparing more than a single type of cobot accessible in the assembly system provides numerous benefits. One type of cobot might be proficient at doing a certain task (e.g. material handling), whereas another type might be better at completing another duty (e.g. repetitive task handling). Hence, choosing the best cobot for every particular task can boost the system's efficiency and productivity. In addition, a cost-effective investment can be achieved with the right combination of cobots. Besides, the system can swiftly adapt to shifting customer requirements and market dynamics thanks to the flexibility offered by having a large collection of cobots. Future studies should concentrate on the usage of various cobot types for the purpose to be consistent with industrial practice.

Cobot capability:

- Fact: Most research assumes that cobots, regardless of their types, can only execute certain kinds of tasks.
- Research gap: A practical reality that should be applied as a guideline for future assumptions is that cobots are capable of executing fewer kinds of tasks than human workers. The rationale is that human workers have incredibly dexterous fingers and hands, whilst cobots, especially those without sophisticated robotic grippers or arms, may be restricted by their ability to execute tasks that necessitate precise or complex gestures. Moreover, Cobots are excellent at executing routine tasks that can be effectively programmed, but they lack the cognitive capacity to deal with unfamiliar or unforeseen circumstances.

Collaboration type and task time:

- Fact: Most articles appear published under the category of parallel/joint collaboration between workers and cobots, followed by purely parallel and purely joint collaborations (Fig. 5). In addition, all studies make the assumption that task times are deterministic and that the resource used for carrying out them determines their values.
- Research gap: Future studies should address the gap relating to the assumption that task time is stochastic in light of the facts that have been uncovered in the literature. The task time determinism assumption, seen ubiquitously in the CoALBP articles, appears to be an area of research that has reached saturation. In contrast, given that it takes into consideration the system's intrinsic variability and uncertainty, stochastic task times enable greater precision in the modelling of the system. When processing times are uncertain due to machine effectiveness, quality of materials, worker efficiency (arising from tiredness, competence levels, or individual variances), or influence from external/unforeseen causes (such as breakdown of machinery, cobots or tools), stochastic task times are a legitimate assumption in the AL. In addition, the manner in which human-cobot interactions, at each workstation, must facilitate both parallel and joint collaborations if the incorporation of cobots in the assembly system is to be fully beneficial. Moreover, in conjunction with the parallel and joint collaborations, responsive collaboration, which has never previously been explored in the CoALBP research, is an intriguing pioneering area of study.

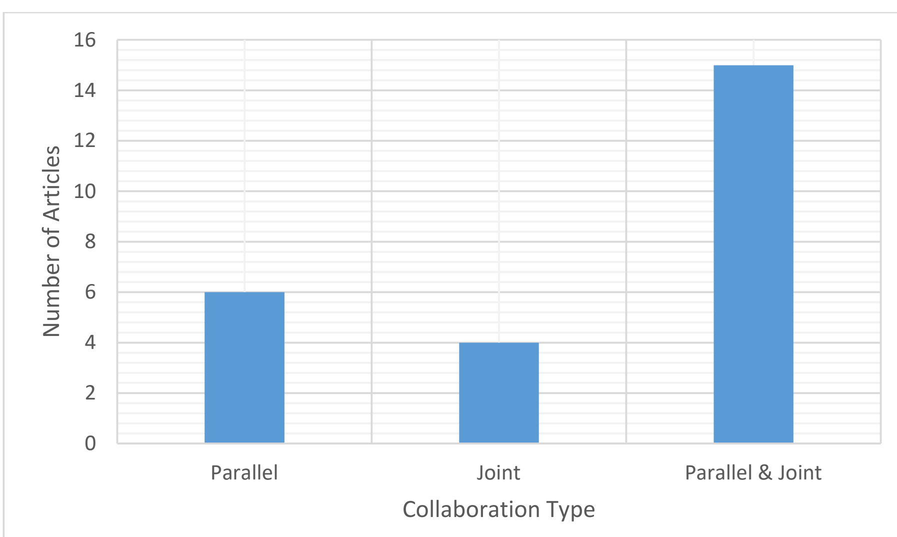

Fig. 5. Number of articles with specific collaboration types

Problem type and objectives:

- Fact: Type O (other) is the most frequently employed objective function, followed by Type II, Type Cost and Type I (Fig. 6). Most articles attempt to determine the optimal solution with one particular objective, whereas, under the multiobjective optimisation, most research employs the weighted sum approach (W), which is followed by Pareto optimum (P) and hierarchical satisfaction (H) techniques (Fig. 6).
- Research gap: The CoALPB type I is unlikely to be widespread since this type of study entails the establishment of new ALs to minimise the number of workstations, given the cycle time, provided that cobots exist in abundance for usage. In practice, however, this is unlikely to be materialised owing to financial restrictions. Yet, if the number of accessible cobots is unlimited, all workstations will deploy cobots alongside workers since task times attributed to parallel/joint collaborations between workers and cobots are minimal. As a consequence, if CoALBP Type I demands investigation, constraints on the number and types of cobots that can be employed should be imposed to reflect industrial reality. CoALPB type II, which is more prevalent than CoALBP type I, entails balancing the AL to maximise cycle time given the number of workstations as well as the accessible quantity and types of cobots. This challenge is consistent with industrial practises because an established AL will not create a single product indefinitely but must constantly react to ever-changing market demand. However, because of space limitations on the shopfloor (i.e. line length), the ALs can only be accommodated with a limited number of workstations. Furthermore, the configuration of each workstation may necessitate the preparation of the workspace and facilities to meet the demands of each particular production process. Another intriguing objective function is to find the least cost CoALBP. CoALBP type Cost, quite similar to CoALBP type II, pertains to distributing cobots to work together with workers in the face of a restricted amount of available budget and a limited number of workstations. However, in the context of cost-effective CoAL, other objectives, such as minimising cycle time, are likely to take precedence. As a result, the majority of research tends to integrate several objectives and optimise them together using weighted sum or Pareto optimum approaches. This problem is known as CoALBP type O. It is hardly surprising that researchers prioritise type O of CoALBP beyond any other type because multiple objectives, such as productivity-related, cost-related, ergonomic and safety-related, and environmental-related objectives, etc. should be addressed concurrently in order to maximise the overall efficacy of the CoAL. As a result, future research ought to centre on identifying an optimal solution for many objectives. Which objectives should be chosen, however, is dictated by the context of the CoAL system being investigated at the moment. In addition, according to Fig. 7, the Pareto optimum approach (P) should be considered as the primary approach for multi-objective optimisation over all others (e.g., weight-sum method (W), hierarchically optimisation method (H)) due to its efficacy in determining optimal trade-offs between many conflicting objectives.

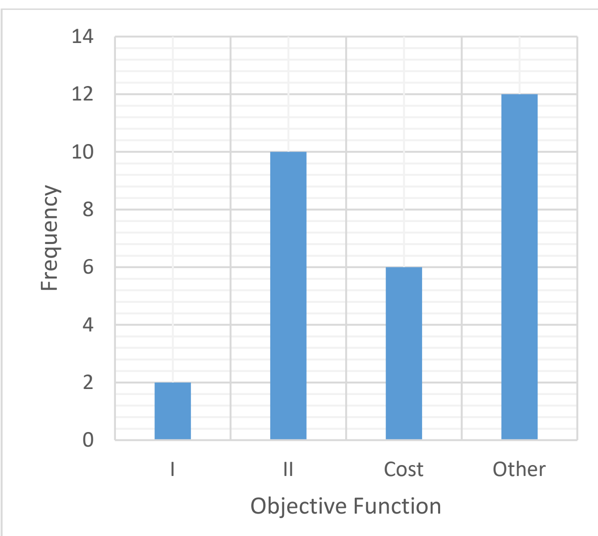

Fig. 6. Frequency plot of objective type

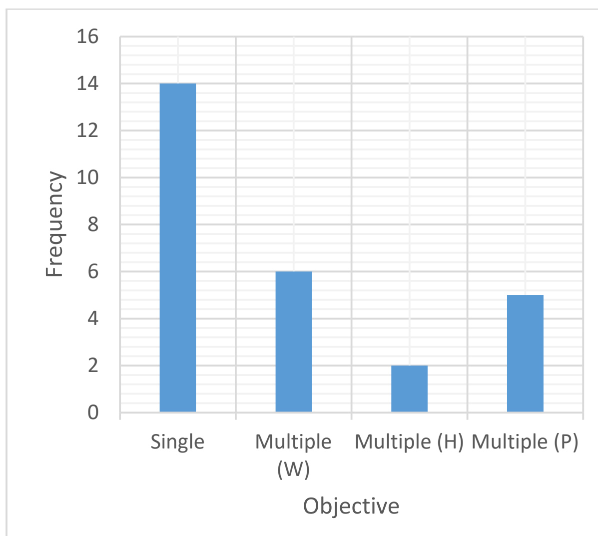

Fig. 7. Frequency plot of objective optimisation technique

Solution technique:

- Fact: The CoALBP mathematical model is always expressed in the form of MIP. According to all articles, CPLEX can only be used to solve small instances. For large instances, a variety of techniques are available. The effective algorithms developed for the CoALBP are designed using the evolutionary algorithm as a basis. GA, a type of evolutionary algorithm, is the most widely utilised (Fig. 8).
- Research gap: The CoALBP is widely acknowledged to be an NP-hard problem. As a result, using the CPLEX solver to solve the formulated mathematical model for a particular problem setting is only achievable for small instances. Furthermore, while this technique can illustrate the correct relationship between the defined mathematical variables, it cannot provide significant benefits to the real world. It has been noticed that during the past two decades, evolutionary algorithms, a class of optimisation algorithms that emulate natural evolution and genetics mechanisms noticed in

biological systems, have been commonly employed to deal with various complex problems. Although numerous algorithms have been deployed in the CoALBP, e.g. IBAC, IBA, MMBO, IMBO, etc., many more have recently been created but have not yet been tested on the CoALBP environment, e.g. bat algorithm, grey wolf optimiser, firefly algorithm, etc. As a result, the performance of these freshly developed algorithms should be evaluated to that of established algorithms that have been demonstrated to be superior to others. Furthermore, as previously indicated, the CoALBP's nature encompasses several objectives that must be optimised simultaneously, leading to the problem in the form of the multi-objective (optimising less than three objectives simultaneously) and many-objective (optimising more than three objectives simultaneously) optimisation CoALBP. As a result, another research area that should be prioritised in the future is the employment of multi- and many-objective evolutionary algorithms for addressing such challenges. An example collection of noteworthy multi-objective evolutionary algorithms may be found as follows: Pareto envelope-based selection algorithm II (PESA-II), multi-objective evolutionary algorithm based on decomposition with dominance (MOEA/DD), S-metric selection evolutionary multi-objective optimisation algorithm (SMS-EMOA), indicator-based evolutionary algorithm (IBEA), multi-objective evolutionary algorithm based on decomposition (MOEA/D), and non-dominated sorting genetic algorithm II (NSGA-II). Furthermore, the following are some notable examples of evolutionary algorithms for the CoALBP having more than three objectives to optimise simultaneously (known as many-objective optimisation problems): hybrid Pareto front estimation algorithm (HYPE), many-objective Surrogate-assisted evolutionary algorithm (MSOPS), reference vector-based evolutionary algorithm (RVEA), Pareto archived improved convergent evolutionary algorithm-G (PICEA-G), and non-dominated sorting genetic algorithm III (NSGA III).

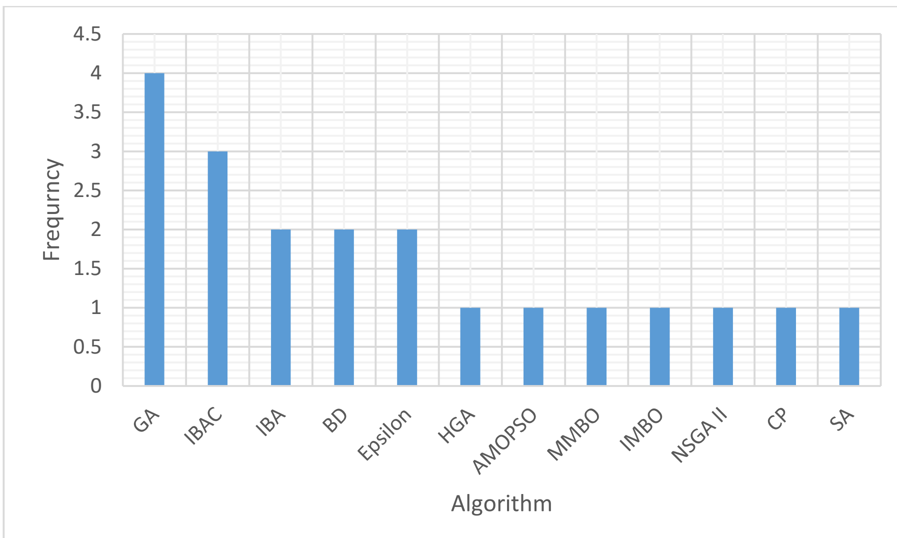

Fig. 8. Solution techniques to solve CoALBP

Real use case:

- Fact: Only around 40% of the articles employ real-life work environments as blueprints for modelling.
- Research gap: Actual case studies should be the primary focus of future research when developing models for the CoALBP. The justification is that actual case studies supply the information required for constructing mathematical models. They enable researchers and practitioners to acquire an in-depth understanding of the features, restrictions, essential variables, parameters and their relationships as well as the intricate nature of the problem that may never appear in the basic model. Not only could the system's overall efficiency be optimised, but researchers may also create predictions, look into how the system will behave in different scenarios, and assess the consequences from various perspectives. Assumptions like positive and negative zoning, synchronous work, worker walking time, mobile cobots, collaborative work by workers at adjacent workstations, worker learning and forgetting curves, etc. are some examples of such assumptions that rarely appear in almost all articles but may be prevalent in certain real-life manufacturing environments. These unconventional yet practical assumptions offer a piece of colour and distinctiveness to research works, while also posing a considerable challenge to both academics and practitioners. Academically speaking, constructing models using real-world examples can prove helpful, and the industry can benefit from them by leveraging the simulation outcomes for developing efficient policies for further actual use.

5. Conclusion

Reviewing the CoALBP literature from its inception in 2019 until the present is the main objective of this article. Unsurprisingly, compared to the classical ALBP and RALBP, there has been very little research undertaken because the field of study on the CoALBP is relatively new. On the bright side, researchers should be delighted since there is still a great deal of opportunity waiting to expand upon the studies that have already been done. According to the knowledge gleaned from the literature review, it is of the utmost importance that the CoALBP research investigation should utilise real industrial case studies to form practical models. Aside from the straight CoALBP which has already received much study, other forms of the CoALBP layouts such as U-shaped, parallel, two-sided, etc. need additional attention. Research should be more concentrated on multi- and many-objective optimisation of the CoALBP than a single objective one due to the nature of the problem which requires an optimal solution for several objectives at once. What comes next is the development and comparison of effective algorithms for simultaneously tackling multiple or many-objective functions. In addition, future research is very interested in the integration of multi-skill workers and cobots with a variety of capabilities to work parallelly and jointly in an AL that is susceptible to unforeseen events which can be essential in making task times stochastic variables. Finally, the CoALBP research is anticipated to grow rapidly from this year forward in both quantity and quality, serving as best-practice examples for the industry to deploy cobots for optimum benefits.

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