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Review

Assembly and Production Line Designing, Balancing and Scheduling with Inaccurate Data: A Survey and Perspectives

Yuri N. Sotskov

United Institute of Informatics Problems, National Academy of Sciences of Belarus, 6 Surganov Street, 220012 Minsk, Belarus; sotskov48@mail.ru; Tel.: +375-17-249-61-20

Abstract: Assembly lines (conveyors) are traditional means of large-scale and mass-scale productions. An assembly line balancing problem is needed for optimizing the assembly process by configuring and designing an assembly line for the same or similar types of final products. This problem consists of designing the assembly line and distributing the total workload for manufacturing each unit of the fixed product to be assembled among the ordered workstations along the constructed assembly line. The assembly line balancing research is focused mainly on simple assembly line balancing problems, which are restricted by a set of conditions making a considered assembly line ideal for research. A lot of published research has been carried out in order to describe and solve (usually heuristically) more realistic generalized assembly line balancing problems. Assembly line designing, balancing and scheduling problems with not deterministic (stochastic, fuzzy or uncertain) parameters have been investigated in many published research works. This paper is about the design and optimization methods for assembly and disassembly lines. We survey the recent developments for designing, balancing and scheduling assembly (disassembly) lines. New formulations of simple assembly line balancing problems are presented in order to take into account modifications and uncertainties characterized by real assembly productions.

Keywords: survey; assembly line; optimal line balance; scheduling; uncertainty; stability analysis

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1. Introduction

The assembly line (conveyor) is widely used in large-scale and mass production for the assembly of the same or similar types of products. The assembly line provides strategic production of products close in purpose to existing parts and components, with insignificant costs for training of working personnel. Most assembly lines consist of a linearly ordered set: $S = \{S_1, S_2, \ldots, S_m\}$, of the workstations interconnected by a step-by-step moving belt or other moving mechanism. Each workstation, $S_k \in S$, makes a fixed set, $V_k^b \in V = \{1, 2, \ldots, n\}$, of indivisible assembly operations over a planned cycle time, c. An industrial enterprise organizing a conveyor production must first design an assembly line by determining its composition and configuration. During the exploiting of the designed assembly conveyor, the problem of balancing the assembly line to increase its productivity needs be repeatedly solved. Among the optimization problems that arise at various stages of the assembly line lifecycle, the most important is the problem of balancing the assembly line. Such a problem is denoted by the ALBP (assembly line balancing problem) [1]. To solve the ALBP, it is necessary to optimally distribute a set of all given assembly operations, $V = \{1, 2, \ldots, n\}$, between the available workstations, $S = \{S_1, S_2, \ldots, S_m\}$, which are necessary for assembling the final products of the enterprise.

This review discusses the published results on optimal designing, balancing and scheduling assembly and production lines with inaccurate, not deterministic parameters (such as stochastic parameters, fuzzy parameters or uncertain parameters). The main attention is paid to the most studied simple assembly line balancing problems (SALBP for short) and some of their generalizations (GALBP), which allow a scheduler to more

fully consider the specifics of a particular conveyor production. We use the generally accepted classification of the problems of balancing assembly lines presented in [1–3] and the monograph [4]. The numerical parameters of assembly lines are specified, and the permissible restrictions and conditions are listed in Section 2. Various assembly line designing, balancing and scheduling problems and methods for optimization of them are presented based on the articles published in the last two and a half decades.

Due to the high importance of the assembly line designing, balancing and scheduling for mass and large-scale series production, large amounts of relevant research papers have been published in operational research (OR) literature. Most such papers were surveyed in [5–10]. In particular, the paper by Boysen et al. [5] surveys the OR literature on assembly line designing, balancing and scheduling that has been published after previous review papers appeared in 2006, 2007 and 2009 [6–9]. The authors of [5] cover essential stages of the decision processes, including different approaches to the ALBP. Their survey is a supplement and continuation of the previous survey papers on the SALBP [6], the GALBP [7] and the classification schemes of the ALBP [3,7,9]. Other survey papers published after 2009 cover some specific aspects of the ALBP. In particular, the paper [10] surveys two-sided assembly lines. The paper [11] surveys the requirements of different real-world applications. The papers [12,13] surveyed the ALBP that were solved using soft computing. The paper [14] surveys genetic algorithms used for solving the ALBP. The paper [15] surveys balancing of multiple and parallel assembly lines. The paper [16] surveys cost- and profit-oriented assembly line balancing problems. The paper [17] surveys rebalancing of the unbalanced assembly lines. Disassembly line balancing problems are surveyed in the paper [18]. The paper [19] surveys the ALBP arising in industry 4.0. A bibliographic analysis of the ALBP through the Web of Science in the period from 1990 to 2017 is presented in [20].

This paper is about the design and optimization algorithms for assembly (disassembly) lines. The survey covers assembly line designing, balancing and scheduling problems with inaccurate parameters (i.e., stochastic, fuzzy or uncertain numerical parameters) and different variations from the deterministic manufactory conditions. This survey may be considered as a continuation of the surveys in [21,22]. We first consider deterministic formulations of the SALBP, ALBP and GALBP with different types of variations from the fixed manufactory conditions. Then, we review the stochastic, fuzzy and uncertain formulations of the SALBP, ALBP and GALBP, along with disassembly line balancing problems under uncertainty. This paper covers about 30 surveys and books on assembly and production lines published since 1986, about 100 research papers since 1998 for assembly lines and about 30 research papers since 2014 for disassembly lines.

The sections are ordered with respect to the increasingly considered problem uncertainties. In Section 2, we determine the scope of this survey and describe the considered problem settings. The deterministic ALBP with possible deviation from normal (deterministic) manufactory conditions are considered in Section 3. The ALBP with stochastic or fuzzy parameters are surveyed in Section 4. Designing and balancing production lines of disassembly of similar obsolete products are considered in Section 5. Section 6 addresses to designing, balancing and scheduling assembly lines with uncertain (interval) parameters. Before concluding in Section 8, in Section 7, some unresolved issues are discussed and several new settings for designing, balancing and scheduling the assembly and production lines are proposed, allowing taking into account fuller economic indicators of assembly and production lines, as well as the uncertainty characteristic of operating conveyors.

2. A Division of Manual Labor, Assembly and Production Lines

In 1776, Smith [23] identified the advantages of the division of manual labor, which made it possible to increase labor productivity as a result of the specialization of workers in the joint manufacture of simple products. A century and a half later, on the basis of assembly conveyors that were used in Chicago's food factories in the United States, Ford [24] combined, in a moving stream, the process of assembling a car by operators who

specialized in a limited set of specific assembly operations. In Ford factories, assembly conveyors were used to make car components and to assemble the entire car. Since then, more than a century has passed, and assembly lines are still widely used both for the production of fairly simple products and for the assembly of complex products in large-scale and mass production. Modern assembly lines are specialized production systems designed to assemble similar types of products in rather large quantities. Assembly lines have been used in mass production, ensuring a rhythmic assembly of products with limited operator training costs. Training of workstation operators is carried out in a short time. Workstations of modern assembly lines are often robotic. Industrial robots perform the most complex assembly operations in the absence of people on such types of workstations.

The mathematical statements of the ALBP were first described by Salveson [1], who discussed the various configurations of assembly lines and the optimization problems of assigning (balancing) assembly operations to the workstations. Due to the complexity of the problems of designing and controlling assembly lines, the researchers looked at various constraints that simplified the actual problems of balancing the pipeline. Such simplifications were summarized by Baybars [2], who considered the problem of balancing an assembly line with nine conditions, (1)–(9) (see Section 2.1), simplifying a real assembly problem, called a simple assembly line balancing problem (SALBP). There are many essential differences between the SALBP and the actual assembly lines and production lines. In the OR literature, the approximations of the SALBP to the real conveyor production were based on the easing of certain limitations and conditions of the SALBP. Various generalizations based on the weakening of the conditions of the SALBP are called a general assembly line balancing problem, denoted as GALBP.

2.1. Simple Assembly Line Balancing Problems

Distribution, $V = V_1^b \cup V_2^b \cup \ldots \cup V_m^b$, of the given set of assembly operations, V, between the available workstations, $S = \{S_1, S_2, \ldots, S_m\}$ (i.e., splitting a partially ordered set V of assembly operations on m non-intersecting subsets), is called a line balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, of the assembly line, $S = \{S_1, S_2, \ldots, S_m\}$. A line balance is feasible, if a technological order of all assembly operations that is determined by the precedence digraph, $G = (V, A)$, is not violated, where V denotes a set of vertices and A is a set of directed arcs. A search for the optimal assembly line balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, is called an assembly line balancing problem (ALBP).

Large financial costs for the design, manufacture, installation and equipment of the assembly line can pay off only with a periodical optimization of the line balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, used for the assembly line, $S = \{S_1, S_2, \ldots, S_m\}$. Repeatedly balancing the assembly line increases the productivity of the assembly conveyor, and therefore the efficiency of the entire assembly plant. Balancing the assembly line provides the required performance of the assembly line with minimal (or limited) costs for its assembly operations. The most studied problems of the balancing of the assembly line are the SALBP. As stated in the review in [2] and monograph in [4], the following conditions must be met for the SALBP: (A-1) all input parameters of the ALBP are deterministic, (A-2) each assembly operation is indivisible (its execution cannot be divided between two or more workstations), (A-3) the sequence of indivisible assembly operations is subject to the precedence constraints specified by the digraph $G = (V, A)$ and (A-4) all assembly operations are performed within the cycle time, C, uniquely determined for all workstations of the assembly line.

The ALBP is to distribute assembly operations, $V = \{1, 2, \ldots, n\}$, between the ordered workstations, $S_1, S_2, \ldots, S_m$ (therefore, it is necessary to determine the line balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, of the assembly line, $S = \{S_1, S_2, \ldots, S_m\}$), in such a way that the specified criterion is optimized and the specified conditions are not violated. The optimization criterion and conditions of the ALBP are specified in advance. In addition to the above conditions (A-1)–(A-4), the following conditions must be met for a simple assembly line balancing problem: (A-5) All workstations, $S_1, S_2, \ldots, S_m$, are equipped in such a way that each of them can perform any of the assembly operations V. (A-6) The duration of

the assembly operation does not depend on the workstation, S_k, to which it is assigned, and this duration does not depend on the workstation, S_{k+1}, following the workstation, S_k, nor does it depend on the previous workstation,S_{k-1}. (A-7) An assembly operation can be performed on any available workstation of the set, $S = \{S_1, S_2, \ldots, S_m\}$. (A-8) The assembly line is serial without duplication of parallel workstations and without taking into accounts the operation of the workpieces' feeding mechanisms. (A-9) The assembly line is designed to produce one type of product during its lifetime (during the whole lifecycle of the assembly line).

2.2. Optimal Design of an Assembly Line and Optimization of the Existing Assembly Line

In the process of designing an assembly line, the ALBP of balancing the assembly line with a predetermined (fixed) cycle time, c, arises. This problem is called SALBP-1 in [2,4]. In addition to the above conditions (A-1)–(A-9), the following condition must be met in the SALBP-1: (A-10) the cycle time, c, is assumed to be constant (fixed) during the whole lifecycle of the assembly line. In the SALBP-1, it is required to assign assembly operations, V, to a linearly ordered set of workstations, $S_1, S_2, \ldots, S_m$, and thus to minimize the number of available workstations in use at a given and fixed cycle time, c. In practice, such a problem is solved at the design stage of the assembly line.

In the process of operating the assembly line, it becomes necessary to solve the SALBP-2 for balancing the assembly line with a fixed set of workstations, which consists in determining the optimal balance of the assembly line at a given number m of the ordered workstations. To solve the SALBP-2, it is required to minimize the possible cycle time, c, when assigning assembly operations, V, on the given set, $S = \{S_1, S_2, \ldots, S_m\}$, of the workstations, i.e., it is necessary to find such an optimal line balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, of operations, V, and workstations, $S = \{S_1, S_2, \ldots, S_m\}$, in which the cycle time, c, reaches the minimum possible value. In the SALBP-2, the following condition must be met instead of the condition (A-10): (A-11) a number m, of the workstations, $S = \{S_1, S_2, \ldots, S_m\}$, is given and fixed. The described SALBP-1 and SALBP-2 are two-fold [2].

The OR literature discusses a third more general class of the simple assembly line balancing problems, when neither the number of workstations, m, nor the cycle time, C, is fixed. It is necessary to maximize the efficiency of the assembly line. Such a problem is denoted by SALBP-E [2,4,25]. The efficiency, E, of the assembly line is determined by the following equality:

$$E = t_{sum}/(m \cdot c), \tag{1}$$

where $t_{sum} = \sum_{i=1}^{n} t_i$ denotes the sum of durations, $t_i, i \in V$, of the assembly operations.

2.3. Generalizations of the SALBP and Complexity of These Problems

The OR literature contains investigations of different formulations of the ALBP that result from the weakening of one or more conditions, (A-1)–(A-9). An assembly line can be used to produce several modifications of a product that are divided into batches. Such assembly lines are called multi-model lines. The assembly line can be used to produce two or more modifications of the same product. Different modifications of the product can be mixed in the process of their assembly. Such assembly lines in the OR literature are called mixed-model assembly lines [26–29]. Assembly line configurations can vary. In particular, article [27] discusses a U-shaped assembly line for a mixed-model ALBP. In articles [10,29–33], the SALBP is considered for a two-way assembly line, when workstations are located on both sides of a linear or U-shaped conveyor belt. The assembly line may have parallel workstations that may duplicate one another in the event of a workstation breakdown [34,35]. Other generalizations of the simple assembly line balancing problem can be found in [36,37]. No matter what goal is considered in the problem (minimizing cycle time, C, minimizing the number of workstations or maximizing the efficiency, E), generalized assembly line balancing problems are called general assembly line balancing problems [38]. Thus, the GALBP can denote a generalization of the SALBP-1, the SALBP-2 or the SALBP-E.

It should be noted that «simple» SALBP-1, SALBP-2 and SALBP-E are in fact binary NP-hard even in the simplest possible case, i.e., when $m = 2$ and the given precedence digraph $G = (V, A)$ does not contain any arc, $A = \emptyset$ (it is clear that there is no conveyer with $m = 1$). Thus, one could use the term «ideal» instead of «simple» for the NP-hard SALBP. The proof of the NP-hardness of the SALBP-1, SALBP-2 and SALBP-E follows from the fact that the binary NP-hard scheduling problem, $I2||C_{\max}$ (see monographs in [39,40] on scheduling theory), is reduced in a polynomial number of elementary operations to a determined special case of the SALBP, namely: SALBP-1, SALBP-2 and SALBP-E. Hereafter, a three-field notation, $\alpha|\beta|\gamma$, is used to denote a scheduling problem, in which α indicates the type of processing system, β denotes specified restrictions on the set of jobs to be processed and γ denotes the criterion of optimality (see [41]). In particular, in the problem $I2||C_{\max}$, it is necessary to construct a schedule with minimum schedule length $C_{\max}$ for fulfilling a given set of jobs on two identical machines. The proof of the NP-hardness of the SALBP can be found in the monograph [4].

Before starting the survey section, it would be useful to explain why the remaining Sections 3–7 are mainly devoted to the SALBP. Note that a simple assembly line balancing problem may be rarely met in real-world productions, since the most practical assembly lines violate some or most conditions of (A-1)–(A-11). On the other hand, the most final mathematical results (lemmas and theorems) have been proven only for the SALBP-1, SALBP-2 and SALBP-E. Furthermore, these mathematical results may be used for real assembly and production lines. Due to the limited paper length, the proven mathematical claims are not presented in Sections 3–7 (they are only mentioned in their descriptions). Hopefully, increasing the uncertainty level in the considered ALBP may be useful for constructing a bridge between the ideal SALBP and practical assembly and production lines.

3. Deterministic Problems of Designing and Balancing Assembly Lines with Deviations from Normally Fixed Conditions

If the condition (A-1) for the ALBP is met with a possible change in the other conditions, (A-2)–(A-9), and then such a problem is called a deterministic ALBP. For the deterministic ALBP, the durations of assembly operations, $t_i, i \in V$, are given and do not change during the whole lifecycle of the assembly conveyer. The deterministic ALBP is formulated as follows. A set of assembly operations is specified: $V = \{1, 2, \ldots, n\}$. For each operation, a fixed processing time (duration) is given along with the digraph $G = (V, A)$, which determines the partial strict order on the set V of assembly operations. The deterministic ALBP is to assign assembly operations, V, to the ordered set of workstations $(S_1, S_2, \ldots, S_m)$, such that the precedence relations given in the digraph $G = (V, A)$ are not disturbed and the objective function would take the optimal value. The deterministic SALBP is well-studied, and many exact, approximate and heuristic algorithms have been developed for these problems (see [1–5,10,26–38,42–52]). This section is focused on designing and balancing assembly lines with possible deviations from normal manufacture conditions.

The article [2] presents the exact algorithms for solving the SALBP. In the article [42], the authors divided the published algorithms for solving the ALBP into two groups. The first group includes precise algorithms that guarantee the optimal solution to the ALBP, and the second group includes heuristic algorithms that lead to some acceptable solution to the ALBP, not necessarily optimal. This article contains an overview of heuristic algorithms used for the ALBP, an efficiency comparison of algorithms for solving the ALBP and an overview of the exact and approximate algorithms for solving the multi-model ALBP. The article [43] compared the procedures proposed for solving the SALBP-1. The article [44] presents a hybrid artificial intelligent algorithm, which realizes an artificial immune system in combination with a simulated annealing algorithm. The algorithm aims at enhancing the performance of an artificial immune system via incorporating simulated annealing in order to achieve a global optimum for assembly conveyers with a rather large number of assembly operations. The new algorithm was implemented on a mechanical assembly

composed of seven parts joined by connectors. The algorithm was effective in achieving an optimum with a restricted CPU time compared to other artificial intelligent algorithms.

The article [45] describes the application of a differential evolution algorithm to the SALBP. This algorithm is an evolutionary one, similar to a genetic algorithm for global optimization over continuous spaces. The extensive experimental work over public benchmark test instances showed the effectiveness of this algorithm. In most investigated SALBP, smoothing workstation loads were considered. In the work [46], a differential evolution algorithm was developed for minimization of the workload smoothness index in the SALBP-2. The parameters were optimized based on the Taguchi method. To validate the algorithm, the computational experimental results were compared with other published heuristics. The comparison indicated the effectiveness of the new algorithm. An optimization of the numerical parameters has been addressed in order to minimize a workload smoothness index. After presenting a mathematical model, a differential evolution algorithm was developed to minimize the smoothness index. Some advantages were based on a suitable mutation, which ensures the search diversity and enhances the effectiveness based on properties of the objective function. The values of numerical parameters in the developed algorithm have been tuned based on the sizes of the tested instances. A detailed statistical experiment showed that except for one from the medium-sized problems, the levels of other numerical parameters influenced the efficiency of the addressed algorithms for other problems. The computational results indicated supremacy of the algorithm over tested heuristics for small, medium and large instances.

The article [47] is devoted to supply chain designing and conveyer balancing. These problems cover an optimization of manufacturers, assembly conveyers and customer demands. Due to analyzing the characteristics and complexities of the ALBP, the authors of this article decomposed the problem into an upper-level problem and two lower-level problems. The former was used to determine the assignment amount of each assembler. The latter includes the ALBP inside each assembler and the transportation problem between different layers. In order to solve this problem heuristically, a meta-heuristic was developed. The ALBP was exactly solved by a branch-and-bound method. A table method was developed in order to speed up the computations. A transportation problem was solved via mathematical programming. Due to solving the lower-level problems, the cost function of the upper-level problem was evaluated. In order to optimize the upper-level problem, a meta-heuristic was developed. In a population initialization, the specific heuristics were designed. Several numerical tests demonstrated the effectiveness of the proposed algorithms.

The application of industrial robots in mechanical conveyers usually increases the efficiency of industrial productions. Different robot assembly strategies have been used. Fault monitoring and strategy evaluation have attracted the attention of many researchers. The paper [48] reviews the recent research in this field. Respecting the assembly process, this paper separates the research contents into target recognition, searching and fault monitoring. The main characteristics of each published approach were summarized, and evaluations of assembly strategies were proposed with respect to typical metrics. The known benchmarks for supporting a standardized performance evaluation were surveyed. The challenges and potential directions were discussed.

Multi-manned conveyers are usually used in industries to manufacture similar products of large sizes, where several human operators have to be assigned to the ordered workstations for performing a set of different assembly operations simultaneously on the same unit of the product. In the paper [49], it was mentioned that previously published mathematical formulations were able to solve a few small-sized problem instances exactly, while larger cases were solved heuristically by heuristics or meta-heuristics, which do not guarantee the optimality of the obtained solutions. A mixed-integer linear programming formulation is presented with a symmetry constraint, allowing decomposing the original problem into a Benders' decomposition to solve large problem instances. The proposed model was used to minimize the total number of human operators along the assembly conveyer and the number of used workstations as weighted primary and secondary objectives, respectively.

Feasibility cuts and symmetry break constraints were based on Benders' cuts and several numerical parameters, which were applied as constraints for reducing the solution search space via eliminating infeasible allocation sets. Computational tests conducted on the datasets showed that this mathematical model outperforms published formulations both in the solution quality and CPU time for the tested small-sized problem instances. In particular, the proposed algorithm yielded 117 optimal solutions out of 131 tested problem instances.

In the article [50], a main focus is placed on assembly conveyers, where workstations were used for assembling large and bulk products, such as complex trucks, aircrafts, buses and tool machines. The high number of assembly operations performed on the concrete workstation, the several workers simultaneously involved in the process and the long operation durations make the considered assembly conveyer different from most assembly conveyers studied in the OR literature. A conveyer balancing model was addressed to the total cost minimization provided that human operators have different skills. The proposed algorithm was applied to a real industrial case.

Flexibility in assembly conveyers can be achieved due to the use of assembly robots. The robotic ALBP is determined for a robotic assembly line, where a set of similar or different assembly robots may be included in the assembly conveyer. An assembly robot may need different assembly times to perform an assembly operation, because of different specializations. The solution to such an ALBP includes attempts for optimally assigning the robots to the ordered workstations and balancing the distribution of work between the workstations. It is necessary to maximize the production rate of the assembly conveyer. In the paper [51], a genetic algorithm was developed in order to find a heuristic solution to the considered problem. Different heuristic procedures were used for adapting the genetic algorithm to the ALBP. The assigning robots with different capabilities to the workstations were investigated based on a recursive assignment procedure and a consecutive assignment one. The genetic algorithm was improved by a local optimization (hill climbing) of the workpiece. The conducted computational tests on randomly generated instances showed that the assignment procedure achieves a better solution quality (an average cycle time), while other computational tests determine a better combination of parameters for the genetic algorithm. A comparison of the genetic algorithm with a truncated branch-and-bound method for the ALBP demonstrated that the genetic algorithm provided closed results faster than the exact branch-and-bound method. Workload smoothing on assembly conveyers that aims to evenly assign assembly operations to different workstations may support workforce planning and resource optimization. In the paper [52], the authors studied smoothing conveyers and developed an algorithm to heuristically solve a large-sized problem. To find a good heuristic solution, this algorithm uses a set of known rules for assigning assembly operations based on a probabilistic procedure for closing workstations. A computational experiment was conducted for selecting the best-performing priority rules and for tuning the probabilistic procedure. The efficiency of the proposed algorithm was experimentally tested on the computer.

Since the industrial robots are utilized in U-shaped assembly lines to replace human operators, the focus of such assembly lines is not only on productivity, but also on the carbon and noise emissions. In the paper [53], a multi-objective mixed-integer non-linear programming is proposed to minimize carbon emissions, noise emissions and cycle time, concurrently. In the proposed approach, quantifying a carbon emission and a noise emission was achieved via presentations connected with processing times of assembly operations and industrial robots. Existing constraints of the precedence relations were readjusted into an integrated formula to remove worthless equations and to improve the computational efficiency. A hybrid Pareto grey wolf optimization was used to heuristically solve these multi-objective problems. The algorithm included a code to initialize the wolves and designed two searching procedures to update the position of the wolves. Two crossover operators were designed to enhance the communication between the low-grade wolves. The algorithm was compared with five other multi-objective algorithms and the computational results indicated that the proposed algorithm outperforms the compared algorithms in

the evaluation metrics of the convergence, maximum spread and hyper-volume ratio. The developed algorithm can achieve the trade-off in reducing carbon and noise emissions and minimizing the cycle time.

In the paper [54], a learning effect was studied in the ALBP. In many realistic settings, the produced workers (or machines) continuously develop by repeating the same or similar activities. The production time of the product shortens if it is processed later. It was shown that polynomial solutions can be obtained for both SALBP and U-shaped ALBP with a learning effect. In a mass manufacturing, neither human operators nor industrial robots alone can efficiently perform all assembly operations. Therefore, a human–robot collaborative conveyer shows great potential to ensure flexibility with the high reliability of robot assistance. It is usually challenging to achieve a harmonious coexistence between humans and industrial robots to efficiently complete the assembly operations. In this regard, the paper [55] provides a formalization of the human–robot coexistence and introduces a key issue in a collaborative conveyer. An assembly graph was used for representing the assembly operation of the complex products. The human network based on self-attention can achieve a higher accuracy. Combined with the robustness of a soft actor-critic, the collaborative system improves the ability of the robot in the dynamic conveyer. The effectiveness of the developed algorithm was verified through an experimental analysis. The computational results indicated that the accuracy of the proposed recognition was 91%. It was proven that the reinforcement learning method was feasible to provide an adaptive decision for industrial robots in human–machine collaboration. The convergence speed of the reward function proved the feasibility of the algorithm for adaptive decision-making in a human–robot collaborative environment.

3.1. Preventive Maintenance and Worker Assignment Problems

The article [56] addresses the mixed-model ALBP, considering preventive maintenance scenarios. A mixed-integer mathematical programming was developed in order to optimize a cycle time and assembly operation alteration. A cooperative algorithm was proposed to simplify a large-sized ALBP due to the divide-and-conquer procedure. An archive was generated to save the obtained complete solutions with better performances, evaluating the fitness of solutions. A mixed-model variable decoding procedure was designed to speed-up the decoding process of the proposed algorithm. An inter-population crossover operator was designed. Four objective-oriented neighbor search operators were proposed to promote the convergence performance of the proposed algorithm. Experimental computational results demonstrated that the algorithm allows obtaining the Pareto solutions for small-sized instances of the mixed-model ALBP. This algorithm outperformed other ones. The obtained Pareto front was close to the true Pareto front.

In the article [57], paced and un-paced assembly lines were compared via simulation on the computer. Human operators can speed-up their processing times when it is needed either to feed other workers downstream or to unblock upstream workers. In the study [57], it was found that un-paced assembly lines were superior to paced assembly lines for some real-world settings, e.g., in the mixed-model production environments with a long assembly line length. The benefit of such assembly lines has been overestimated in previously published studies because of simplifying assumptions, such as disregarding the state-dependent behavior or worker fatigue. With an inhomogeneous workforce, the assembly line efficiency was more sensitive to worker placement. In the un-paced assembly lines, an inexperienced human operator should be placed in the middle of the assembly line; while in paced assembly lines, an inexperienced worker should be placed at the first workstation of the assembly line. Assembly operators capable of speeding up should be placed in the middle of the assembly line in both tested types of assembly lines.

In the article [58], the preventive maintenance in the assembly line balancing problem is investigated for improving the production efficiency and smoothness. For such a two-objective problem, a heuristic rule based on the tacit knowledge and gene expression programming was developed to obtain a good heuristic solution rather quickly. A grey

wolf optimizer was developed in order to achieve a Pareto front solution. The neighbor operators prevent the developed algorithm from trapping into local optima. The conducted computational experiments demonstrated that the heuristic rule used outperformed other published rules. A real-world case study was conducted in order to validate the proposed heuristic rule and the developed meta-heuristic rule.

In the assembly lines, it is reasonable to assume that assembly operation durations are the same for each human operator. In sheltered work centers for disabled workers, this assumption is not valid. Some human operators may execute some assembly operations considerably slower than others capable of executing them. Worker heterogeneity leads to problems, called an assembly line worker assignment and line balancing problem. For a fixed set of workers, this problem is to maximize the production rate of an assembly conveyer by assigning human operators to available workstations and assembly operations to workers, while satisfying precedence constraints between the given assembly operations. In the article [59], a heuristic algorithm and an exact algorithm to solve this problem are introduced. A mixed-integer programming formulation for this problem was also presented. The proposed heuristic algorithm is based on a beam search. The exact algorithm was a branch-and-bound method, which used reduction rules and obtained lower bounds for exact solutions. Computational tests on a set of instances showed that these algorithms were effective and improved compared to other published algorithms.

In a real assembly line, variable production situations, such as customer demand changes, the product structure variations and workstation failures, may affect the existing feasible balance of the assembly line, resulting in the need for the rebalancing of the optimal assembly line. In the desired rebalancing of the assembly conveyer, it is usually assumed in the OR literature that the duration of an assembly operation does not depend on the human operator performing it. However, in many practical cases, the time each operator requires to execute an assembly operation may vary due to several reasons (such as the worker experience, skill and disability of some individuals). In the study in [60], the assembly line worker assignment and rebalancing assembly line problem, which considers that assembly operation durations vary in terms of workers, was introduced in order to fill this gap. The considered problem consists of the re-assignment of assembly operations and workers to non-disrupted workstations after disruptions occur due to breakdowns or shutdowns of workstations to minimize variability in terms of assembly line cycle time and workstation assignments of assembly operations relative to the initial assembly line balance. The objectives of this paper are to describe the problem properties, develop a mixed-integer linear programming model and propose an artificial bee colony algorithm to heuristically solve this problem. The numerical experiments have been designed and conducted using 120 instances. The computational experiments indicated that both developed algorithms managed to obtain optimal assembly line balances for small-sized instances. For large-sized instances, the proposed algorithms showed a higher performance in terms of solution value and CPU time.

3.2. Changing Customer Demand and Optimization of Operation Sequences

The assembly sequence and path planning problem involves finding a proper sequence of parts to be assembled into a finished product and to shorten assembly paths for each such part. This problem combines assembly sequence planning and assembly path planning, which are both NP-hard problems and are therefore intractable for a large problem size. In most published results on this problem, it was assumed that path planning was monotone (i.e., each part was moved only once) and each part was completely rigid. Such simplifications are limiting assumptions. Indeed, most assembled complex products such as ships, aircraft and automobiles are composed of rigid and flexible parts. The required generation of an assembly sequence and a path plan for most real-world complex products requires an intermediate placement of parts to be taken into account. The article [61] presents an algorithm for solving both monotone and non-monotone problems for rigid and flexible parts. This algorithm uses an assembly matrix for describing different relations between all

pairs of parts and the amounts of compressive stresses needed for assembling flexible parts and obtains a tentative assembly sequence using a greedy algorithm. Short assembly paths are iteratively computed from the initial one to the goal configurations of the parts using a sample path planner. In case of a failure, if the part is flexible, it is determined whether the part can still be assembled by undergoing deformation. To evaluate the developed algorithm, two products were designed, and the problem was solved via four combinations of the proposed algorithms. The means and standard deviations of five criteria were calculated. The computational results showed that the greedy heuristic algorithm outperformed other algorithms with at most a 4.6% average gap in path length and a 2.1% average gap in the CPU time compared to the best solution.

The diversification of customer demand poses a great challenge for many manufacturing enterprises and the scheduling problems of material handling affects the efficiency of assembly conveyers. In the article [62], a scheduling algorithm and a static kitting strategy were proposed in order to solve scheduling problems of the material handling for automotive mixed-model assembly lines based on the integrated super-markets. An integer programming was established with the objective to minimize the number of logistic workers. An improved kitting strategy was presented to solve the problem heuristically and a model based on the graph theory was constructed to transform the considered scheduling problem to another known one. The algorithm was developed to solve the scheduling problem. Computational experiments for the proposed algorithms were carried out in order to compare the proposed algorithms with published ones. The feasibility and effectiveness of the proposed algorithms were verified by the obtained computational results.

In the article [63], an assembly plan was investigated as one of the assembly stages to minimize the cost of a manufacturer and to ensure the safety of an assembly part. The problem of assembly sequence planning is how to reduce the deviation from the real manufacturing conditions. The authors of this paper have investigated an approach to automatically generate the assembly sequences for the industrial field. A physically based assembly representation model includes the predetermined basic assembly information (precedence relations between parts or subassemblies, geometric constraints, different assembly types) and the dynamic real-time properties (the center position of gravity, the force strength of the part). This model considered that the influences on optimum sequences by assembly operations will be modified by the feedback from an interactive virtual environment. The authors of the article [63] selected the safety, efficiency and complexity as the optimization objectives. A hybrid search approach may be used to find the optimum assembly sequence, which will be integrated into an interactive assembly virtual environment. The user can adjust the assembly sequences with obvious good objectives via interaction to improve the performance of the search algorithm. A human–machine cooperation algorithm was proposed, by which a human operator can play a pivotal role instead of pure computing. Numerical experiments were performed to validate the performance of the physical approach to generate an assembly sequence, which showed the efficiency and operability to guide the assembly work.

In the article [64], eight multi-objective ant colony optimization algorithms have been developed and compared for solving ten benchmark instances of the SALBP. Experiments on the computer showed that the commonly used heuristic functions deteriorate the performance of the developed algorithms in a limited CPU time scenario. Even neglecting such costs, the developed algorithms achieved a better performance without heuristics. The developed algorithms were ranked according to three multi-objective indicators and the calculated differences between the top four of them were reviewed using statistical tests. The four best-performing algorithms were favorably compared with the other algorithms designed for industrial optimizations.

A supplier selection problem is a strategic decision-making activity for building a competitive advantage in assembly production. Quality suppliers can understand a firm's operational goals and provide high-quality components. Achieving efficient production requires a good plan. A superior competitive strategy should consider the suppliers'

availability and the plant's ability. In the article [65], production line planning was applied to address specific problems associated with a supplier selection by constructing a multi-objective optimization model. The proposed model includes both assembly sequence planning and assembly line balancing. A hybrid algorithm was proposed to heuristically solve the above problems. The proposed algorithm combines a guided search and a multi-objective particle swarm optimization, as well as a particle swarm optimization. A real case of a computer assembly plant was used to verify the algorithm's performance. The computational results showed that the proposed algorithm identifies non-dominated solutions and obtains high Pareto-optimal solution ratios.

Mixed-model assembly lines are widely used in industries where a high variety of products are required in addition to low cost and high responsiveness. When a certain product mix is demanded and different variants require different assembly times on the available workstations, the sequence of variants on the line highly affects the assembly line performance. Although assembly operations are often manual, most sequencing algorithms assume deterministic times for these operations, rendering the obtained results unreliable. The max-plus algebra is a mathematical tool that can model discrete event systems in linear equations analogous to traditional state space dynamic equations. Modeling mixed-model assembly lines with max-plus equations would enable comparing sequences over ranges of values of assembly times, thus increasing the robustness, stability and reliability of the obtained results. In the article [66], mixed-model assembly lines with both closed and open workstations were modeled using the max-plus algebra. The produced models were used to compare possible sequences and to analyze various performance measures of the assembly lines while varying some system parameters. Two examples were presented to demonstrate analyses that can be performed using the proposed model. In the first example, three possible assembly operation sequences were compared and regions of optimality for each sequence were determined. In the second example, the effect of changing the launching rate of work units on the assembly line performance was studied.

The proliferation of just-in-sequence deliveries has raised the vulnerability of assemblies to costly production stoppages or rework due to missing components. Through a real-time supply chain monitoring system, these supply issues can be detected early and affected orders can be removed from planned assembly sequences in time to avoid production disturbances. Using a simulation analysis, the authors of [67] explored the impact of unreliable just-in-sequence deliveries and the mitigation potential of transparent supply chains that allow a rule-based order re-sequencing on a mixed-model assembly line. The obtained results indicated that rework due to unreliable just-in-sequence deliveries can be eliminated and the trade-off between a schedule's uncertainty and optimality can be balanced, making the rule feasible for the considered problem.

Summarizing results published in the papers [1–5,10,26–38,42–67], one can conclude that the deterministic ALBP are convenient for research, and a lot of analytical results have been proven and derived for them. However, for real assembly and production lines, it is not always possible to determine the exact values of the durations of the given assembly operations. Actual operation durations may change during the use of the assembly line for a number of reasons. Among such reasons, one can note a change in the qualifications of the operator, his (her) motivation or fatigue, a change in the composition or purpose of the final products, a possible change in the quality of component materials and assembly parts, as well as characteristics of the operator's workplace.

4. Assembly Line Balancing Problems with Stochastic or Fuzzy Parameters

Assembly (production) line balancing is an important problem for increasing the efficiency of the production processes. However, in practice, a wide range of disruptions can interrupt the current workload balance. A lot of researchers have explored the operation assignment plan for the assembly line balancing problem with the assumption that the assembly processes are smooth with no disruptions. Based on the indicated reason, other researchers and most practitioners have investigated the impacts of disruptions

and explored the assembly operation re-assignments for the assembly and production line re-balancing, with the assumption that the re-balancing decisions have been made. It should also be noted that there is limited OR literature exploring online adjustments (layout adjustments and production rate adjustments) for assembly and production lines in a dynamic environment. This is based on real-time monitoring of assembly processes (this is impossible to perform in the past tense). Furthermore, it is usually difficult to incorporate uncertainty factors into the balancing process because of the randomness and non-linearity of most uncertain factors.

Note that Industry 4.0 peaked the information barriers between different branches of assembly and production lines, since smart, interconnected products, which are enabled by advanced information and communication technology, can intelligently interact, and often communicate with each other and collect production processes and produce additional information. Smart control of the assembly and production lines becomes possible with the large amounts of real-time production data in the era of Industry 4.0. However, currently, there is little OR literature considering this new context of the assembly and production lines. Taking into account possible changes in the duration of assembly operations, other formulations of the ALBP are also considered in the OR literature, namely the stochastic ALBP [68–72] and the ALBP with fuzzy data [26,33]. The durations of assembly operations in such fuzzy ALBP belong to fuzzy sets.

The level of uncertainty in the ALBP with fuzzy data is higher than in the similar ALBP with stochastic data. Nevertheless, surveys of both ALBP are presented in the same section since a probability distribution has to be known for each random variable in the stochastic problem, and a specific membership function has to be known for each fuzzy number in the fuzzy problem. Due to this circumstance, mathematical approaches to the stochastic ALBP and those to the fuzzy ALBP have more similarity than those for the uncertain ALBP surveyed in Sections 8 and 9.

4.1. Stochastic Assembly and Production Line Balancing Problems

In the stochastic ALBP, the durations of assembly operations are random variables with a known law of distribution of their probabilities (usually, the normal law of distribution of a random variable with known mathematical expectation and variance is used). The stochastic ALBP can be formulated as follows. The set, $V = \{1, 2, \ldots, n\}$, of assembly operations is given, and the duration of each assembly operation is a random variable for which the probability distribution law is specified before solving the ALBP. The precedence digraph $G = (V, A)$ is given, which determines the partial strict order on the set V of the given assembly operations. The problem is to assign assembly operations, V, to the ordered workstations, $S_1, S_2, \ldots, S_m$, in such a way that the precedence relations determined by the digraph $G = (V, A)$ are not disturbed, and the mathematical expectation of the objective function would take the optimal (respectively, minimum or maximum) value for the desired balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, of the assembly line.

As for the deterministic version of the assembly line balancing problem, for the stochastic ALBP, there is a finite but sufficiently large number of feasible solutions (line balances) at large values of m and n. In the article [3], the algorithms for solving stochastic problems of balancing the assembly line were divided into the following three classes: (1) modifications of algorithms developed for the deterministic ALBP [68,72], (2) study of the specific properties of the stochastic ALBP on the basis of computer modeling, with a subsequent comparison of the obtained results of solving the stochastic version and the deterministic version of the ALBP [69], and (3) algorithms developed specifically for the stochastic ALBP [70,71].

Articles [68–72] are devoted to the generalizations of the SALBP as a result of restriction of the condition (A-1). It was assumed that the durations of assembly operations are random variables with laws of probability distributions, which are known before solving the problem. Instead of a deterministic criterion, a corresponding stochastic criterion has to be optimized. Namely, in the stochastic SALBP-1, the mathematical expectation, Em, of

the number of the used workstations, m, has to be minimized for the fixed cycle time, c. In the stochastic SALBP-2, the expected value of the cycle time, c, has to be minimized for the given number, m, of the used workstations.

The Industry 4.0 concept aims to bring more flexibility and agility to the assembly and production shop floor. The sequencing and scheduling problems are important issues of Industry 4.0. In fact, a good (or optimal, which is better) schedule has to guarantee a high performance level, which allows a scheduler to take into consideration possible changes and machine perturbations occurring in the production workshop. In [73], the different approaches aim to find stochastic, fuzzy, robust or stable schedules capable of optimizing corresponding single or several criteria, considering possible machine perturbations and variations of assembly operation durations. With the new requirements of the modern production workshop and the high importance of a decision-making process when implementing the constructed schedule, it is essential to extend the scheduling problem with inaccurate data to be adaptable to the needs of a decision-maker in evaluating with respect to properties of the stochastic, fuzzy, robust or stable schedules.

In the paper [74], it is considered a robust scheduling problem. Based on a decision-making framework, a robust specification was developed to evaluate the possible schedule perturbations. The robust measure was based on the service level with a robustness metric. It is defined as a framework gathering several relevant tasks of robustness. Instead of simply trying to evaluate and maximize a single robustness measure, authors of [74] showed that the robust scheduling problem can be enriched. The robust schedule is a multi-faceted issue, which can be used in order to study different points of view, such as stability, sensitivity and the level of service. It is important since the main objective is to support a decision-maker to be able to preserve the different points of view in a robust schedule. It was also illustrated how these robust scheduling problems can be effectively utilized by a decision-maker in solving a real-world scheduling problem with inaccurate data.

Mixed-model assembly lines are usually operated with inaccurate data, such as stochastic product sequences. Balancing such assembly lines can be challenging as their estimation can be difficult to determine in the case when asynchronous pace and buffers have to be taken into account. Several works have addressed problem versions with a target throughput, while a few authors have studied a version of throughput maximizations of the mixed-model ALBP. The paper [75] addresses the ALBP with a fixed number of workstations and a buffer between each pair of the connected workstations. A so-called make-to-order environment was studied and modeled as a stochastic sequence of products with a known rate of the demands. A cycle time simulator was conducted, and a heuristic algorithm was proposed to exploit the cycle time simulator for assessing the cycle time of an assembly line and to provide good line balances. The heuristic algorithm was applied to a dataset with several buffer layouts. The calculated solutions were compared to those of the OR literature. The comparisons showed that the obtained line balances outperform the benchmark ones. The line balance quality difference was greater for tested instances with more buffers, which highlights the capacity to conveniently exploit buffers in the mixed-model assembly lines.

Two-sided assembly lines are used in the factories producing large-sized products. In most OR literature, the assembly operation durations are assumed as deterministic, while these assembly operations may have varying durations in many practical applications, which cause the reduction of performance quality or the infeasibility of the schedule. The ignorance of the specific constraints, including a positional constraint, zoning constraint and synchronism constraint, may result in the invalidation of the constructed schedule. In the paper [76], in order to solve such a stochastic two-sided ALBP with multiple constraints, a hybrid teaching learning-based optimization algorithm is proposed, which allows combining a teaching learning-based optimization for a global search and a neighborhood search with seven neighborhood operators for a local search. A priority-based decoding algorithm was developed in order to ensure that the selected assembly operations satisfy most of the constraints identified by the priority rules and to reduce the idle times related to a sequence

dependence among assembly operations. Experimental results on benchmark instances demonstrated the efficiency and universality of the developed decoding algorithm and the comparison among other algorithms showed its effectiveness.

The quality of the balance of the mixed-model assembly line is related to the determined production sequence of assembly operations. Two problems are incompatible in time since balancing is realized simultaneously with planning the assembly line, while assembly operation sequencing is an operational problem closely related to possible market demand fluctuations. In the paper [77], an exact procedure to solve the integrated assembly line balancing problem and assembly operation sequencing problem showed that the demands are stochastic. The searched optimal line balance is required to be flexible in order to cope with possible demand scenarios. A paced assembly line was considered, and the utility work was used as recourse for workstation border violations. A Benders' decomposition algorithm was developed along with different inequalities and a preprocessing stage as a solution algorithm. Three datasets were proposed and used for testing the developed algorithm and treating uncertainty in the mixed-model assembly line. The integration of the strategic ALBP with the operational sequencing one was used in robust assembly lines.

Most of the research papers related to different assembly lines are concentrated on the ALBP, provided that the precedence relations among the given assembly operations are not violated and the objective function is optimized in the desired line balance. The multi-objective ALBP with stochastic assembly operation durations is an important practical topic of the traditional ALBP involving conflicting criteria, such as minimizing the cycle time, variation of workload or the processing cost under uncertain manufacturing conditions. The paper [78] proposes a hybrid multi-objective evolutionary algorithm for heuristically solving such an ALBP, with stochastic assembly operation durations to minimize the cycle time and the processing cost with the given fixed set of the workstations. The special fitness function was adopted, and a hybrid selection was designed to improve the convergence of the solution process. The computational experiments with tested instances showed that the developed multi-objective evolutionary algorithm could display a better convergence distribution performance than other published algorithms.

The paper [79] includes a multi-objective genetic algorithm for heuristically solving a mixed-model ALBP, simultaneously considering the cycle time and number of available workstations. A mixed-model assembly line is capable of producing different types of products to respond to uncertain market demands, while minimizing capital costs of designing a multiple assembly line. According to the stochastic environment of the considered assembly productions, a mixed-model assembly line was put forth in the make-to-order environment. A multi-objective genetic algorithm was developed for solving the corresponding ALBP and a decision-maker was provided with the subsequent replies to pick one of them based on the specific situation. A computational comparison on the computer was carried out between six multi-objective evolutionary algorithms in order to determine the best algorithm to heuristically solve the specified ALBP.

Possible variations of the assembly operation durations in the manufacturing assembly line can result in a longer processing time to complete assembly operations than a given cycle time. This may lead to the assembly line stoppage and to loss of the production time. In practical assembly production, a portion of the cycle time is often allocated as a predefined fixed-size buffer time, which is determined based on experience for accounting uncertain variations of the durations of assembly operations for a paced assembly line without storage-buffers between workstations. The size of the required buffer time in each available workstation depends on the variation levels of the durations of the assembly operations and the desired conservatism level for preventing a cycle time violation. There are uncertainties in other added activity times in available workstations, which are called inter-operation times. Although many studies on designing a stochastic manufacturing assembly line focused on minimizing the cost incurred when the cycle time is exceeded due to assembly operation duration variations, they mostly disregarded the inter-operation times. Therefore, it is worth studying the simultaneous effect of the manufacturing time

uncertainty and that of the conservatism level on the cycle time. The paper [80] proposes the algorithm for a robust manufacturing assembly line design that incorporates the conservatism level and uncertainties in the assembly operation and inter-operation times. This interpretation of the non-productive times in available workstations was presented by introducing the concept of the fractal buffer time to manage the effect of manufacturing uncertainties. To overcome the problem of excessive robustness, a robust algorithm with conservatism-level flexibility was used, focusing on the cycle time in a bottleneck workstation. The effect of the uncertainties and conservatism levels on the cycle time was analyzed through several numerical instances. Computational results of the study can be used for improving a manufacturing system in which uncertainties in assembly operations and inter-operation times may significantly degrade its productivity.

Human learning algorithms were developed in many research fields, including the ALBP. Despite the plethora of real contributions and different algorithms used for solving the optimization problems, the autonomous learning phenomenon (the time-dependent or position-dependent reduction of the assembly operation durations due to possible process repetitions) should be explored using a stochastic model, which has been disregarded. In the paper [81], a cost-based stochastic balancing property was coupled with a time-learning curve in order to investigate the role of learning in the rebalancing of the existing assembly conveyers with repetitive assembly operations. A real case study was conducted to demonstrate the applicability of the new algorithms.

The paper [82] presents a mixed-model assembly operation sequencing problem with stochastic operation durations in a multi-workstation assembly line. A mixed-integer nonlinear programming was developed to minimize a weighted sum of the expected total workstation overload and workstation idleness, which was converted into a mixed-integer linear programming to optimally solve small-sized instances of the sequencing problem. Due to the proven NP-hardness of the considered sequencing problem [82], a simulated annealing algorithm was developed. This algorithm employs a learning procedure to select an appropriate heuristic through a search process. Several numerical results were presented on the tested and benchmark instances taken from the OR literature. The computational results of the statistical analysis indicated that the developed algorithm was quite competitive in comparison with the published software packages. The developed algorithm was superior to other published simulated annealing algorithms. These computational results highlight the advantages of the mixed-model sequencing in comparison with deterministic algorithms used for the mixed-model sequencing problems. Assembly lines of determining the optimal order of the available workstations in the U-shaped assembly lines with stochastic durations of the assembly operations were studied in the paper [82], as well.

The ALBP is highly important for efficient and cost-effective assembly production of similar products. Different uncertain events might cause a variation in the assembly operation duration. Due to these variations, there remains a possibility that the completion time of the assembly operations might exceed the predetermined cycle time. To hedge against such an issue, a single-model ALBP with the uncertain operation durations and multiple objective functions was studied in [83]. This research aimed to minimize the cycle time in addition to maximizing the probability that completion times of the operations on the workstations will not exceed the predetermined cycle time and will minimize the smoothness index. A Pareto-based artificial bee colony algorithm was proposed to obtain a Pareto solution for the multiple objective functions. The proposed algorithm introduced extra steps, as follows: sorting of food sources, a niche technique and preserving some elitists in the traditional artificial bee colony algorithm to obtain a Pareto solution. The main parameters of the developed algorithm were tuned using the Taguchi method. Computational experiments were conducted to solve the standard ALBP, which were taken from the OR library. The performance of the developed Pareto-based artificial bee colony algorithm was compared with a multi-objective algorithm, NSGA II. Computational results showed that the proposed algorithm outperforms the NSGA II algorithm in both Pareto solution quality and CPU time.

In [84], a workforce assignment is studied in the assembly line with several workstations and executing final parts of different types. The objective is to minimize the number of human operators over the assembly conveyer. Due to the complex market environment, possible changes in product demands have an influence on production balancing and scheduling. The uncertain demands were investigated in [84]. An ambiguity set was applied to portray the demand uncertainty. A chance-constrained programming was developed. Two probability-distribution-free algorithms were chosen: approximations based on Markov inequality and a mixed-integer second-order conic program, to approximate the chance constraints of the tested problems. Computational experiments were conducted to compare the performances of the two proposed algorithms.

The model assembly conveyer is an industrial arrangement of the available workstations, needed equipment and assembly operators for continuous flow of workpieces in mass production operations. The reliability of the assembly production has been investigated by taking into account operation duration uncertainties. The paper [85] provides a reliability metric which encompasses two types of operation duration uncertainties. A multi-objective mathematical model was developed to maximize the reliability and efficiency of the conveyers. Neighborhood search methods with two restart mechanisms were devised to solve the problem, and then they were compared. The computational results showed some managerial implications for the production planners. The methodology proposed in [85] can be applied to many assembly industries when some historical data of uncertain inputs are available, while some others are not. In [86], chance-constrained binary programming for the stochastic straight- and U-shaped line balancing problems were proposed and investigated. The proposed algorithms were used for solving several instances, which are available from the OR literature. The obtained computational results were described and compared. A goal programming algorithm was also developed for increasing the assembly line reliability, which is needed to investigate the stochastic ALBP.

In the real assembly lines, production planning and inventory control are often subject to different types of uncertainty. The paper [87] is devoted to a control problem for a single-level multi-component inventory, which arises in the assembly line replenishment under stochastic component procurement lead times. In order to follow the common assumption of the MRP software tool, the discrete distributions of random component lead times were investigated. The latter was expressed as the number of the tested time periods. Since the finished product was assembled using several component types simultaneously, the assembly process was stopped if a single type of component was delayed. The assembly stoppage forced by a component delay or stock-out was penalized by a backlogging cost. The considered objective aimed to minimize the total cost composed of holding and backlogging costs. To solve this problem, a joint chance-constrained algorithm was developed based on an equivalent linear reformulation. The practical advantages of the developed approach were estimated in its release from backlogging costs, which are difficult to quantify in the real-world industrial assembly productions.

Summarizing the results of [68–87], one can conclude that the stochastic SALBP turned out to be more complex than the deterministic SALBP. However, stochastic problems do not quite correspond to some real assembly conveyor productions, where it is not possible to obtain sufficient information to determine the probability distribution of a random duration, x_i, of each assembly operation, $i \in V$. Even if the probability distributions of random durations are determined in advance (before solving the problem), these distributions may be very useful when there are a large number of implementations of the fixed line balance under unchanging assembly production conditions. However, in a specific implementation of the assembly process, the given probability distributions may be of little use. In particular, in an unsuccessful case for the fixed balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, conditions, this line balance sheet may not only be worse than the factually optimal line balance, but even unacceptable for the worst case for assembly line conditions.

The question also arises whether it is possible to determine the law of probability distribution of random assembly operation durations. Such a law can be determined on

the basis of reliable statistics. In other words, it is necessary to conduct a sufficiently large number of full-scale tests (or computational experiments on the computer), which themselves can be expensive, and it will take a lot of time to conduct the needed computational experiments. It is also necessary to analyze the obtained statistics, and only after that is it possible to draw a more or less plausible conclusion about the law of the probability distribution of the random assembly operation durations. The resulting law will reflect the future actual (sometimes unique) probability distribution of random durations of assembly operations only with a certain (possibly gross) approximation level. It is almost impossible to exactly determine the law of probability distribution of random operation durations. How, then, is it possible to obtain reliable statistics if a sufficiently large number of full-scale (computer) tests cannot be carried out due to a lack of time (which is limited in modern market competition) or due to limited resources of the enterprise? Even reliable statistics may not be of great importance for a particular implementation of the assembly production and for several successive implementations of the assembly process, if the production conditions are different from the production conditions for obtaining statistics and, accordingly, the distribution of probabilities of random assembly operation durations, in fact, may be violated in practice.

4.2. Assembly and Production Line Balancing Problems with Fuzzy Parameters

The input data for many practical ALBP are uncertain or questionable, and so only some limits can be set on the original data. The data questionability can be represented by fuzzy numbers to reduce possible errors associated with input data. The duration of assembly operations in such an ALBP can be represented as fuzzy numbers. Such problems are called fuzzy ALBP and can be formulated as follows. Let the set of assembly operations, $V = \{1, 2, \ldots, n\}$, be given. The duration of each operation is presented by a fuzzy number. The precedence digraph $G = (V, A)$ is given, which determines the partial strict order on the set V. The problem is to assign a set of operations, V, to the ordered workstations, $S_1, S_2, \ldots, S_m$, in such a way that the precedence constraints are not disturbed and the objective function would take an optimal fuzzy value [26,33,88,89].

The articles [88,89] provide approximate solutions to the ALBP with fuzzy durations of the assembly operations. A genetic algorithm was developed to minimize the maximum total duration of the assembly operations assigned to each workstation. Genetic operators suitable for solving the fuzzy ALBP were considered. The article [88] provides a heuristic solution to the ALBP with fuzzy durations of the assembly operations. In [26], a mixed-model assembly line is designed to assemble several types of the final product. The optimal sequence of product models was determined to minimize the number of assembly conveyor stops required to move from assembling one product model to assembling another model of the same product. When the operating conditions of the assembly line change or the requirements for the product model change, it is important to determine the assembly sequence of all models of the product, for which the stops of the assembly conveyor would be minimal and there would be no frequent need to rebalance the assembly line. Three objective functions conflicting with each other were considered. To solve the fuzzy ALBP, a mathematical programming method with a fuzzy goal was developed.

The mixed-model assembly lines are highly adopted in the automobile industry and so the part feeding process becomes critical. In [90], the dynamic part feeding scheduling problem was studied for optimization of the throughput of the mixed-model assembly lines, along with the total delivery distance of the automatic guide vehicles. A process considering the feeding operation generation, the loading, sequencing and dispatching problems was analyzed, determining appropriate models and algorithms. To heuristically solve these problems, the research [90] contains a hybrid fuzzy–neural dynamic scheduling algorithm, which integrates the self-organizing maps with a fuzzy algorithm and a knowledge base. This algorithm was adapted to the pre-cluster status of the mixed-model assembly line in order to optimize the initial clustering centers. After that, the algorithm was availed to guide the clusters in a way to improve the clustering performance. The com-

putational experiments were conducted in order to evaluate the scheduling performance in the dynamic manufacturing environment and verify the algorithm's superiority over the benchmark ones. The developed algorithm allows a decision-maker to select a rational scheduling scheme based on the decision impacts in the productivity, feeding costs and the real-time status of the assembly conveyers.

The paper [91] presents the results of the investigation of a single-model SALBP with fuzzy assembly operation durations. This problem is referred to as a fuzzy SALBP-E, consisting of finding the best combination of the number of workstations and the cycle time as well as a respective assembly line balance, such that the determined measure of efficiency of the single-model assembly line is maximized. A fuzzy SALBP-E is an extension of the deterministic SALBP-E under fuzziness of input data. The formal definition of the considered problem was given with the assembly operation durations presented by triangular fuzzy membership functions. The considered problem is known to be NP-hard, and therefore a meta-heuristic based on the genetic algorithm was developed for its heuristic solution. The performance of the proposed algorithm was studied and discussed over several benchmark instances. The computational results demonstrated a satisfactory performance for the developed algorithm in terms of solution CPU time and quality.

The research of the paper [92] addresses both the straight ALBP and the U-shaped ALBP. It is written in this paper that many attempts in the OR literature were made to study the deterministic ALBP and the attention was not given to those with inaccurate data. In [92], a bi-objective fuzzy mixed-integer linear programming was developed, with triangular fuzzy numbers being employed in order to represent uncertainty and vagueness, which are associated with the assembly operation durations arising in the real assembly productions. In the proposed algorithm, two objectives (minimizing the number of available workstations and minimizing the cycle time) were considered with respect to the set of usual constraints presented in Section 2.1. An appropriate strategy was proposed, where two-phase interactive fuzzy programming was used as an algorithm for finding a compromise solution. The validity of the proposed algorithm was evaluated though numerical tests. An experimental comparison study was conducted over several test problems in order to assess the performance of the proposed algorithm. The computational result demonstrated that the interactive fuzzy algorithm can not only be applied to the fuzzy ALBP but was also capable to handle different practical models. The proposed model and algorithm may constitute a framework aiming to assist a decision-maker to deal with inaccurate data in the ALBP.

Due to the main role of the efficient assembly and production lines in modern manufacturing systems, the research of the paper [93] was devoted to both straight and U-shaped assembly line balancing problems. The considered ALBP includes conflicting objective functions that should be optimized subject to a set of constraints. This paper endeavors to develop a fuzzy linear programming algorithm. Having dealt with the inaccurate nature of the real assembly production, triangular fuzzy numbers were employed in order to represent fuzzy input data with possible vagueness associated with the assembly operation durations. The developed algorithm can be regarded as a background of fuzzy programming for further practical development in the ALBP. To heuristically solve the fuzzy ALBP, a multi-objective genetic algorithm was developed. Having respected several important characteristics of the fuzzy straight ALBP and fuzzy U-shaped ALBP, the algorithm includes an initial generation, encoding and decoding schemes and a genetic algorithm. The developed algorithm was evaluated based on several benchmark instances and compared with the exact algorithm. The presented computational results demonstrated the efficiency of the developed algorithm over other ones suggested in the OR literature.

Sequencing and balancing manual mixed-model assembly lines is challenging in assembly production due to the high complexity and uncertainty of human operators' activities. The control of a predetermined cycle time and the sequencing of assembly production can mitigate large losses due to non-optimal line balancing in the case of open-workstation production, where the human operators can work ahead of a normal

schedule and try to reduce a backlog. The objective considered in [94] was to provide a cycle time control algorithm, which can provide the efficiency of the assembly line production in the situations based on an appropriate mixed-sequencing strategy. To handle the uncertainty of human operators' activity durations, a fuzzy mixed-model-based solution has been developed. As the production process was modular, the fuzzy sets represented the uncertainty of the activity durations related to processing the modules. Both optimistic estimates and pessimistic estimates of the completion of activities were extracted from the fuzzy model and incorporated into a predictive control algorithm to ensure the constrained optimization of the predetermined cycle time. The applicability of the proposed algorithm was demonstrated using a wire-harness manufacturing process with a paced assembly conveyor. The developed algorithm can handle continuous assembly conveyors as well. The computational results confirmed that the developed algorithm is applicable in the cases where a production line of the supply chain is not well-balanced, and the activity durations are uncertain.

The paper [95] is devoted to both multi-objective straight assembly line balancing problems and U-shaped ALBP with fuzzy operation duration. Four objectives were considered (minimizing numbers of workstations, maximizing fuzzy assembly line efficiency, minimizing the fuzzy idleness percentage and minimizing the fuzzy smoothness index). Two problems were formulated, including uncertainties, variability and imprecision that usually occur in a real-world production. The durations of assembly operations were determined by triangular fuzzy numbers. To heuristically solve this fuzzy problem, a hybrid multi-objective genetic algorithm has been developed. A one-fifth success rule was deployed for selection and mutation operators to improve this genetic algorithm. The results in the genetic algorithm application were controlled in convergence and diversity by means of controlling the selective pressure rate. A fuzzy controller to the selective pressure was employed for the genetic algorithm toward its better implementation. The Taguchi design of the computational experiments was used for the parameter control and calibration. The numerical examples were presented to compare the performance of the proposed algorithm with the existing ones. The computational results showed a better performance of the proposed algorithm. Similar ALBP, modified algorithms and closed results are presented in the paper [96].

Balancing the workloads of available workstations is a key point in the efficiency of the assembly line. An initial line balance can be broken by the changing processing abilities of machines because of their degradation, and therefore re-balancing of the assembly line is inevitable. The impacts of unexpected events on assembly line re-balancing are usually ignored in the OR literature. Using the advanced sensor technologies and Internet of Things, the machine degradation can be continuously monitored, so condition-based maintenance can be implemented to improve the health state of the machine. Using the technology of robotic process automation, workflows of the assembly process can be smoothed, workstations can work autonomously and a higher level of process automation can be achieved. Real-time information of the processing abilities of machines will bring about opportunities for automated workload balance via an adaptive decision. In [97], a fuzzy control system was developed to make real-time decisions to balance the workloads based on the processing abilities of the workstations, given the policy of condition-based maintenance. Fuzzy controllers were used to decide whether to re-balance the assembly line and how to adjust the production rate of each workstation. The conducted numerical experiments showed that the buffer level of the assembly line with the fuzzy control system was lower than that of the assembly line without a control system (the buffer level of the assembly line with another control system was the lowest). The product demands can be satisfied by assembly lines, except the one with another control system since there were too many production losses sacrificed for the low buffer level. The stability analysis of the control performance to the numerical parameter settings was conducted. The effectiveness of the developed fuzzy control was demonstrated. The intelligent automation can improve

the performance of the assembly process by the proposed fuzzy control system since real-time information of the assembly line can be used for the adaptive decision-making.

In [98], a fuzzy control system was developed to analyze real-time information of the assembly line with two types of fuzzy controllers. The first type of a fuzzy controller was used to determine whether the assembly line should be re-balanced to satisfy the changed product demands. The second type of fuzzy controller was used to adjust the production rate of each workstation in time, to eliminate blockage and starvation. Hence, the utilization of available workstations increased. Compared with the three assembly lines without the fuzzy control system, the assembly line with the fuzzy control system performed better in terms of the blockage ratio, the starvation ratio and the buffer level. With the improvement of information transparency, the performance of assembly line production was better. The research findings shed light on the smart control of the assembly line production and provide insights into the impacts of Industry 4.0 on the ALBP.

Summarizing the above results published in the papers [26,33,88–98], one can conclude that a fuzzy ALBP is a harder problem than a deterministic or stochastic ALBP with the same problem size. The fuzzy ALBP need complex algorithms to obtain either a good heuristic solution or an exact fuzzy solution. Since fuzzy algorithms are time-consuming, finding a fuzzy optimal solution in a reasonable CPU time is possible only for a fuzzy ALBP with small or moderate sizes.

5. Designing and Balancing Production Lines of Disassembly of Obsolete Products

Due to the rapid development of modern technologies and changes in the consumer market, many products have begun to quickly become obsolete and are subject to destruction. Considering this, it is necessary to disassemble products with an expired period of use and then restore such products. A disassembly of obsolete products is required for their subsequent processing and restoration. In recent years, many specialized production disassembly lines have been created, which are effective for processing obsolete products. Improving the efficiency of the production line is associated with a solution of the DLBP (disassembly line balancing problem), which is aimed at optimizing the disassembly of products in such a way that the total disassembly time spent on each available workstation would be approximately the same for all available workstations and approach the time of the specified cycle of the production line [25,31]. Disassembly operations at workplaces in the disassembly shop are required to ensure the removal of valuable components from the disassembled product and reduce the undesirable environmental impact of everything that remains after the disassembly of the obsolete product. In contrast to the assembly production, which is more stable due to the deterministic durations of many assembly operations, the disassembly of obsolete products often has inaccurate parameters and so the DLBP are usually uncertain.

Obsolete product disassembly may include a separation of the reusable pieces. It is often possible to operate remanufacturing processes on several of the pieces while others may be sold to suppliers [99]. In a robotic disassembly line, the robot may complete repetitive operations with rather continual efficiency. Since most industrial robots cannot handle complex disassembly operations, a human–robot involvement in the disassembly process was proposed to flexibly and efficiently disassemble the obsolete products, with less damage to the environment, a lower operation cost, less energy consumption and a minimal cycle time. The robotic disassembly line balancing problem (RDLBP) is determined as disassembly processes collaboratively carried out by humans and robots or the disassembly performed by robots autonomously. Such a problem has two main avenues of research published in the OR literature, as follows: robotic disassembly line balancing and robotic disassembly sequence planning. The review paper [100] is devoted to the RDLBP and is organized based on the above subjects. The RDLBP is an optimization problem, where the objective is to find an optimal sequence for disassembling the obsolete products. Similar problems may include disassembly sequencing, disassembly sequence optimization, disassembly planning and human–robot collaborative disassembly problems. Disassembly sequence

planning may involve three steps, as follows: to decide whether the disassembly mode should be complete or partial, to construct a disassembly model by preventing the generation of unfeasible disassembly sequences and to employ a selected planning algorithm according to the disassembly objective and the used optimization models and techniques. The articles [25,31,101,102] investigated the disassembly line balancing, which may consist of the aggregate machines, mechanisms and devices located in accordance with the sequence of operations of the technological process of disassembling the obsolete product and transport devices that move the disassembled product. The duration of disassembly operations cannot be accurately determined but a few studies are published on the DLBP with inaccurate durations of disassembly operations.

The timely recovery and disassembly of waste electronic and electrical equipment obtained a higher economic benefit and can reduce the impact of hazardous substances on the environment. The parallel disassembly line can disassemble different types of waste electronic and electrical equipment and improve the disassembly efficiency. A parallel disassembly line balancing model with stochastic disassembly times is studied in [102]. The evaluation index of the disassembly line includes a number of workstations, workload smoothness and disassembly profits. A genetic simulated annealing algorithm was proposed to optimize a disassembly line balance. The decoding and encoding strategies were proposed based on characteristics of a partial disassembly and parallel layout. Two-point mapping crossovers and single-point insertion mutations were designed to ensure that the disassembly sequence meets the given precedence and disassembly constraints. The simulated annealing algorithm was applied to the results obtained by the genetic operation. The proposed algorithms obtain better solutions than a tabu search for stochastic parallel DLBP. The proposed algorithm has a better performance than the CPLEX solvers, genetic algorithms and simulated annealing algorithms for parallel DLBP. Parallel disassembly lines for waste refrigerators and televisions were constructed. The performance of the proposed multi-objective algorithm was superior to those of five other multi-objective algorithms. The computational results showed that the proposed model and algorithms have better practical application ability.

To reduce disassembly costs for enterprises and improve the disassembly efficiency of waste products, the paper [103] investigated a partial sequence-dependent DLBP and established a multi-objective model to minimize the number of used workstations, the total disassembly operation duration, the idle balance index and the number of used disassembly tools. A Pareto-discrete hummingbird algorithm was proposed to address a partial sequence-dependent disassembly line balancing problem. This algorithm includes two stages, as follows: a self-searching stage and an information-interacting stage. With these stages, the exploration and exploitation abilities of the Pareto-discrete hummingbird algorithm may be balanced. The effectiveness and superiority of the Pareto-discrete hummingbird algorithm were verified by comparing it with other algorithms for two instances of the DLBP. The mathematical model and Pareto-discrete hummingbird algorithm were applied to the optimization of a partial sequence-dependent disassembly line of waste laptops. The optimization results showed that the partial disassembly can make the disassembly line smoother and the utilization efficiency of workstations higher than full disassembly. The Pareto-discrete hummingbird algorithm was superior in solving the partial sequence-dependent DLBP.

Studies in production engineering focused on disassembly and assembly planning for improving the profitability of remanufacturing. The presentation of assembly and disassembly sequences by analyzing geometrical and technical precedence constraints is an essential necessity of assembly and disassembly planning. A specific and/or graph is used to represent a product's feasible assembly and disassembly sequences, including alternative subassemblies and parallel operations. A lot of researchers have studied the automatic extraction of geometrical precedence constraints by collision analysis within 3D models. Since most of the published approaches focused on collision analysis to identify precedence relations, the generation of and/or graphs for complex products from collision analysis re-

sults remain inefficient for many industrial cases. In [98], a computer-aided design interface from previous studies is used to extract liaison and moving wedge information from 3D models. A top-down approach and a bottom-up approach for generating complete and/or graphs from the extracted data were introduced. These approaches for computing performances were analyzed on the several test cases and the developed computer-aided design models. The bottom-up approach performed better for the tested samples. It has been found that the amount of moving wedge constraints has a strong effect on the computing performance. It is an indicator to estimate the complexity of products under examination. The exponential behavior of the needed computing resources can be estimated beforehand. For complex products, graph simplifications or alternative graph representations with less information richness were considered. The obtained computational results contribute to automated assembly and disassembly sequence planning from complex products and increasing remanufacturing profitability.

In [104], a multi-period integrated decision-making model is investigated for the heavy-duty equipment maintenance, involving disassembly, inspection and assembly, with uncertain numbers of replaced parts within a fixed-time horizon. There are large numbers of subway cars exported from other countries and the maintenance is difficult to be conducted in Hong Kong due to the limited space, machinery and technical support teams. Thus, efficient maintenance planning is required to ensure the quality of transportation services. To resolve this problem, a deterministic mixed-integer optimization model was developed to achieve integrated optimization of disassembly and assembly. The model minimizes the total operation cost, consisting of a purchasing cost and a repair cost subject to capacity constraints. A real-life case study from mass transit railway in Hong Kong is presented to verify the proposed model.

The aim of the paper [105] is to reverse an assembly line using a mobile platform equipped with a manipulator. Reversibility means that the assembly line is able to perform disassembly as well. For this purpose, a (dis)assembly line balancing and a synchronized hybrid Petri nets model were used to model and control a (dis)assembly line, with a fixed number of workstations, served by a wheeled mobile robot equipped with a robotic manipulator. The model is of a hybrid type, where the (dis)assembly line is a discrete part while the wheeled mobile robot with a robotic manipulator is a continuous part. The model operates in synchronized mode with signals from several sensors. Disassembly starts after the assembly process and after the assembled piece fails the quality test in order to recover the parts. The wheeled mobile robot with a robotic manipulator was used only during disassembly, to transport the parts from the disassembling locations to the storage locations. Using these models, a real-time control structure has been designed and implemented, allowing automated assembly and disassembly, where the latter was assisted by a mobile platform equipped with a manipulator. The paper [106] aims to study a specific type of disassembly line with multi-robotic workstations, where multiple industrial robots perform different disassembly operations on the obsolete products of different models. The industrial robots on the disassembly line were differently skilled and had non-identical disassembly operation durations along with energy consumption. Considering the given conditions of the returned products, a task-based operation digraph and a subassemblies-based and/or graph were used to represent the precedence constraints of the disassembly operation sequence. A mixed-integer mathematical programming was developed for the considered problem, with three conflicting objectives of minimizing the cycle time, the peak-total energy consumption and the cost of hazardous tasks. Successfully solving practical disassembly line balance problems is usually subject to a great number of uncertainties in the real-life problems. The uncertainties in disassembly operation durations were solved by stochastic, fuzzy and interval programming algorithms. Computational results of the conducted experiments on problem instances were presented.

The disassembly line is one of the most important tools to handle large quantities of waste electronic and electrical equipment. The DLBP is to assign disassembly operations to each available workstation reasonably while satisfying various given constraints, which is

one of the challenging topics. Considering the uncertainty, environmental protection and economic benefits of disassembly, the paper [107] established a stochastic partial DLBP that comprehensively evaluates the number of used workstations, workload smoothness, energy consumption and disassembly profit. To obtain feasible solutions with a high quality, a multi-objective discrete flower pollination algorithm was developed. This algorithm establishes heuristic rules, discrete operations and multi-objective algorithms combined with the characteristics of the partial DLBP. The effectiveness and application ability of the proposed model and algorithms were verified by a disassembly example of a waste printer. Various disassembly schemes were obtained, which can provide guidance for a decision-maker to construct disassembly lines.

End-of-life products with large sizes are suitable for disassembly operations on the two-sided disassembly line. The destructive disassembly is required in the disassembly process. The negative impacts caused by destructive disassembly during the disassembly process are usually ignored in the OR literature. In the paper [108], a probability-based operation destructive disassembly model was constructed in the two-sided DLBP, and the negative impact on the total disassembly cost, workload smoothness index and the impact of destructive disassembly operations on other adjacent but unconnected operations were determined. A mixed-integer programming was used to minimize the above objective functions. A multi-objective restart genetic algorithm was developed, which combines the genetic operations and flatworm regeneration processes with an embedded restart mechanism. The effectiveness of the model and the efficiency of the developed algorithm were verified by disassembling mobile phones, laptops, printers and engines on the two-sided disassembly line. Through the application of car disassembly, it was shown that the developed algorithm can assist a decision-maker to choose the preferred disassembly schemes.

The RDLBP is one of the central problems in designing disassembly lines. This problem is used to find the disassembly operations to be optimally assigned to each available workstation for a given obsolete product [109]. There are two classes for disassembly line balancing problems. The first one is based on the variety of obsolete products, including single-model, mixed-model and multi-model disassembly lines. Only one type of obsolete product can be disassembled on a single-model disassembly line, while more than one type of obsolete product could be disassembled simultaneously on a mixed-model disassembly line. Thus, a mixed-model line is more flexible to the product type change and this advantage may reduce disassembly line building and costs. In a multi-model disassembly line, several obsolete products in separate batches are disassembled, though rarely performed. The second class is the classification based on the types of lines, including straight lines, U-shaped lines and those with parallel layouts.

The paper [48] provides a review of robotic publications (225 papers) utilizing optimization techniques from 2005 until 2021. In this review, most developments in robotic problems are cited. A robotic manufacturing system usually includes an industrial robot as a material handling device, a co-worker with human or autonomous robots and other relevant systems. Due to the lack of a deep analysis and complete listing of the robotic articles which apply optimization techniques, this paper aims to report an extensive archive of robotic papers on a structured classification for robotic problems, including robotic cell, robotic disassembly and robotic assembly. Descriptive statistics were provided, including the number of publications and the authorship analysis, and future trends towards the robotic studies were introduced. The review in [48] shows that heuristic or meta-heuristic algorithms are the most frequently used tools to solve the robotic application problems. This review stimulates theoretical and applied studies of industrial robots in order to establish a foundation for robotic problems arising in the industry.

The application of robots in mechanical assembly may increase the efficiency of the industrial production. With the requirements of flexible manufacturing, it has become a research hotspot for accomplishing diversified assembly operations safely and efficiently in unstructured environments. Several advanced robot assembly strategies have been proposed. Fault monitoring and strategy performance evaluation have attracted the at-

tention of researchers and practitioners. To promote the development of robotic assembly, the authors of the paper [110] analyzed the research in this field. According to the assembly process, they separate the research contents into target recognition and searching, compliant strategies for fine insertion motion and fault monitoring. The characteristics of each model and most methods were summarized. A performance evaluation for assembly strategies was proposed with typical metrics. The authors surveyed the benchmarks to provide support for standardized performance evaluation. The challenges and potential directions for future research were discussed. The paper [110] presented the state-of-the-art robotic assembly approaches used in recent years based on the assembly action procedure, including target search, fine motion strategies, along with fault diagnosis and strategy performance evaluation.

A disassembly process is often characterized by a high level of uncertainty due to the quality and types of the end-of-life products. The paper [111] presents an approach for designing disassembly lines with the objective to maximize the disassembly line profit. Disassembly operation durations were assumed to be random variables with probability distributions known before solving the problem. The and/or graph was used to model the precedence relationships among disassembly operations, subassemblies and the disassembly alternatives. A Monte Carlo sampling-based solution algorithm was developed to deal with uncertainties. The obtained results of the conducted computational experiments on the test problems were presented and discussed.

The aim of [112] was to reverse an assembly line using a mobile platform equipped with a manipulator. By reversibility, the authors of this paper mean that the assembly line is able to perform disassembly as well. For this purpose, an assembly/disassembly line balancing and a synchronized hybrid Petri net model are used to model and control an assembly/disassembly line, with a fixed number of workstations, served by a wheeled mobile robot equipped with the robotic manipulator. The synchronized hybrid Petri net model is a hybrid type, where the assembly/disassembly line balancing is a discrete part, and the wheeled mobile robot with the robotic manipulator is a continuous part. The model operates in synchronized mode with signals from sensors. Disassembly starts after the assembly process and after the assembled piece fails the quality test, in order to recover these parts. The wheeled mobile robot with the robotic manipulator is used during disassembly, to transport the parts from the disassembling locations to the storage locations. Using these models and a Lab-View platform, a real-time control structure has been designed and implemented, allowing automated assembly and disassembly, where the latter is assisted by a mobile platform equipped with the robotic manipulator.

Disassembly of end-of-life products is a main step in remanufacturing and recycling. Disassembly sequence planning is the process that finds the optimal sequence of components being removed. An element of disassembly sequence planning is a suitable mathematical representation that describes the interference of components in the product. Most studies on disassembly sequence planning have tended to focus on the interference that is fixed. The interference may be uncertain due to complex end-of-life conditions such as deformation, corrosion and rust. To deal with uncertain interference, the paper [113] proposes an interference probability matrix as a mathematical representation that uses probability to indicate uncertainty in the interference. A multi-threshold planning scheme is established to generate optimal disassembly sequences. Three cases are presented to demonstrate the use of the proposed approach. The performance of four multi-objective optimization algorithms that can be adopted in the planning scheme is tested.

Since the disassembly of end-of-life products is affected by many dynamic and uncertain factors, many mathematical models and algorithms were established for uncertain DLBP. With more extended objectives, constraints and different algorithms of disassembly, inconsistent models relating to product representations and types of disassembly lines have become the main barriers for the transfer of research to disassembly practice. In [114], an overview of recent models to summarize the input data, parameters, decision variables, constraints and objectives of the DLBP was presented. After discussing the adaptation

and extensibility of the published models for different environments, a unified encoding scheme was designed to apply typical multi-objective evolutionary algorithms on the DLBP, with extensive decision variables and seven significant objectives. Algorithm comparison on four typical cases was carried out based on commonly used products to verify the optimization process for the integrated version of existing models and demonstrate the overall performance of the typical multi-objective evolutionary algorithms on the DLBP. Experimental results can be a baseline for further algorithm design and practical algorithm selection on the DLBP scenarios.

6. Designing, Balancing and Scheduling Assembly Lines with Uncertain Parameters

The uncertainty may be modeled by specifying a set of scenarios containing possible vectors of the ALBP parameters which may occur. No additional information for the given scenario set, such as a probability distribution or membership function, is provided. To choose a line balance, the robust or stable optimization framework may be applied (see [73]). In Section 6.1, the goal is to find a line balance with the best worst-case performance over the given set of possible scenarios. This performance can be measured by a min-max regret criterion based on regret theory.

6.1. A Robust Approach to the ALBP with Uncertain Parameters

A design for a disassembly line is the essential procedure in determining the disassembly and recyclability of the end-of-life products. An efficient procedure aims to provide the disassembling and recycling. The recent trends of disassembling and recycling include environmental and social sustainability. Due to a shortage of energy and deterioration of the ecological environment, the sustainable production is an active research topic to use the economic benefits as the evaluation standard of a design scheme and environmental characteristics. The paper [115] provides an approach for designing a disassembly line based on sustainability. A hybrid multi-attribute decision-making algorithm integrating the regret theory and the entropy weighting procedure was developed. To implement the proposed algorithm, several criterions were used (disassembly energy consumption, disassembly accessibility, fastener ratio, toxic material proportion, material recovery rate, disassembly expense, waste emissions, production and use noise). To better describe the fuzziness of human thinking and to avoid a loss of information and distortion during information aggregation phases, the evaluation information given by experts was presented by the interval linguistic intuition of fuzzy numbers. The weighted vector of the index structure was determined by the entropy weighting procedure under a fuzzy environment. The regret theory was employed to obtain a final order of alternatives via considering and guaranteeing the risk attitude and the regret attitude of experts. To show the applicability of the developed algorithm, a case study including four kinds of refrigerator schemes was conducted to validate the proposed algorithm. A comparison with other algorithms along with a sensitivity and stability analysis of experiments was executed to verify the effectiveness and reliability of the developed algorithm. The computational experimental results showed that disassembly accessibility, the fastener ratio, waste emissions and disassembly energy consumption have a large impact on the scheme selection based on sustainability. The proposed algorithm outperforms other tested ones. The chosen scheme was a winner in majority of the sensitivity and stability analyses.

Robotic disassembly sequence planning is a research area that looks at the sequence of actions in the disassembly intending to achieve autonomous disassembly with high efficiency and low cost in remanufacturing and recycling applications. Key information being factored in disassembly sequence planning is the interference condition of a product (a mathematical representation of the spatial location of components in the assembly in the form of a matrix). An observed challenge is that the interference condition can be uncertain due to variations in the end-of-life conditions. Therefore, there is a lack of tools available in disassembly sequence planning under uncertain interference. To address this challenge, in [116], a disassembly sequence planning algorithm is proposed that can cope

with uncertain interference conditions enabled by the fuzzification of disassembly sequence planning. This algorithm is a fuzzy and dynamic modeling one, in combination with an iterative re-planning strategy. The fuzzification of disassembly sequence planning offers the capability for the disassembly sequence to adapt to failures and self-evolve online. Three disassembly products were used to demonstrate the properties of this algorithm.

In [21], the case of the ALBP-1 is considered, in which assembly operation durations are worker-dependent and uncertain, and being expressed as segments (closed intervals) of possible duration values. The main goal is to find an assignment of assembly operations and workers to a minimal number of used workstations such that the resulting productivity level is in respect to a desired robust measure. Two mixed-integer programming settings were proposed for this uncertain ALBP-1 and explain how these settings can be adapted to handle the special case, where one must integrate a particular set of workers in the assembly line. A construction heuristic was developed that yields high-quality solutions in a fraction of the CPU time needed to solve the uncertain ALBP-1 to optimality in the robust sense. Computational results showed the benefits of solving this robust optimization problem instead of its deterministic counterpart.

The problem of placing the inventory over a network, which is used for assembling a final product, is a challenging issue in supply chain designs because the manufacturer wants to reduce inventory over the supply chain. The process of designing a supply chain and placing inventory, to offer a higher service level at the lowest possible cost, is not an easy choice for a decision-maker. In the paper [117], the authors used the supply chain representation, where a supply chain was divided into supplying, manufacturing and delivering stages. The main problem was to select a resource option in order to perform each above stage based on the selected options and to place an amount of inventory at each stage in order to offer satisfactory customer service with a low total supply chain cost. A resource option represents suppliers, manufacturing plants (production lines) and transport modes in the supplying, manufacturing or delivering stage. The assembly algorithm based on an ant colony optimization was developed to minimize the total supply chain cost and the lead time of the products to ensure all product deliveries without delays.

The concerns of most companies related to economic savings, optimal utilization of resources along with increasing environmental protection regulations prompt the manufacturer to be focused on recycling the products that are at the end of their life. In [118], a job-shop scheduling problem is considered with reverse flows under uncertainty. Since most parameters of the model (e.g., operation durations) were tainted with uncertainty in real-world applications, a robust programming was used. Due to the complexity of solving the job-shop scheduling problem, an exact algorithm for small-sized instances and simulated annealing with a discrete harmony search for large-sized instances were developed. The model performance was evaluated by comparing the computational results available from the OR literature. The performance of the proposed meta-heuristic algorithms was evaluated by comparing the obtained schedules with the exact algorithm for small-sized instances and with three meta-heuristics (the discrete particle swarm optimization, the invasive weed optimization and the greedy algorithm) for medium-sized and large-sized instances. The satisfying results showed that the presented model and proposed algorithms ensure a good solution quality within a reasonable CPU time for the tested instances.

Assembly operation duration variations in a manufacturing production line can result in a longer duration to complete operations than a predetermined cycle time, leading to a production line stoppage and loss of production time. In practice, a portion of the predetermined cycle time may be allocated as a predefined fixed-size buffer time, which is determined based on the experience, to account for such uncertain duration variations for a paced assembly line without storage-buffers between workstations. The size of the required buffer time in each workstation depends on the variation levels of operation durations and the desired conservatism level for preventing cycle time violations. Moreover, there are uncertainties in other nonviable activity durations in the workstations, which are known as inter-task times. Although many studies on the stochastic manufacturing

assembly line design focused on minimizing the cost incurred when the predetermined cycle time is exceeded due to operation duration variations, they mostly disregarded the inter-task times. It is worth studying the common effect of the manufacturing duration uncertainty level and that of the conservatism level on the predetermined cycle time. The paper [74] proposes an algorithm for a robust manufacturing assembly line design that incorporates the conservatism level and uncertainties in the assembly operation and inter-task times. This interpretation of the non-productive times in the workstations is presented by introducing the concept of the α-fractal buffer time to manage the effect of manufacturing operation duration uncertainties. To overcome the above problem of an excessive robustness, a moderate robust approach with conservatism-level flexibility has been used, focusing on the predetermined cycle time in the bottleneck workstation. The effect of the uncertainties and conservatism levels on the predetermined cycle time was analyzed through several numerical examples. The obtained computational results can be used for improving the manufacturing production line, in which uncertainties in assembly operation and inter-task times may considerably degrade the productivity.

Balancing U-shaped assembly lines under uncertainty is addressed in [119] by formulating a robust optimization problem and developing an optimization model and heuristic algorithm. U-shaped assembly layouts were shown to be more efficient than conventional straight lines. A great majority of studies on U-shaped assembly lines assume deterministic environments and ignore uncertainty in the assembly operation durations. In [119], the robust optimization was used for U-shaped assembly planning. It was assumed that the assembly operation durations are not fixed and can vary from time to time. A robust optimization that considers worst-case scenarios was employed. To avoid over-pessimism, the authors of this paper assumed that only a subset of assembly operation times may take their worst-case values. To heuristically solve such an uncertain problem, an iterative heuristic algorithm has been developed. The efficiency of the developed algorithm was evaluated with computational tests. In [120], an algorithm for robust scheduling on parallel unrelated (or uniform) machines is proposed [40,41]. The proposed algorithm is based on the combination of a robust model and discrete event models, which are iteratively called one after another in order to converge towards a robust schedule, with the required robustness determined by a decision-maker. Computer experiments in a small instance (10 jobs and 2 unrelated machines) and in a large instance (30 jobs and 6 uniform machines) showed that the proposed algorithm permits to quickly converge to a robust optimal schedule, even if the probability distribution of the random job durations is not symmetrical. The proposed algorithm achieved a better rate of convergence than those of the OR literature's algorithms.

Digital material structure is a lattice composed by discrete elements, which are connected to create assemblies that can exhibit the high-performance mechanical characteristics. The paper [121] presents the development and robustness of the processing system, which is called the gantry autonomous robotic integrator. This integrator is designed to automatically assemble these digital material structures. The relative positioning tolerance of the connecting elements and algorithms increasing the reliability of the automated assembly of these structures have been specified in this paper. A compact end-effectors design was presented, which showed a high precision and adjustability. The calibration procedures for building a plate were determined. The bolting reliability for the end-effectors was analyzed in order to identify tolerance requirements and establish performance benchmarks for component feed workstations. Two external cases for testing the bolting reliability of the end-effectors were explored.

Human operators are often faced with accelerating job demands, such as elevated cognitive complexities. An objective measure of a mental workload is in high demand, as indicated in theory and practice. The article [122] explored the wearability and external validity of pupillometry, a measure of mental workload, estimated robustly and validated in laboratory settings and deployable in work settings, demanding human operator mobility. In an ecologically valid work environment, participants performed two manual assembly operations (one of low complexity and another of high complexity) while wearing eye-

tracking glasses for pupil size measurement. The obtained results revealed that the device was perceived as fairly wearable in terms of physical and mental comfort. In terms of validity, no significant differences in mean pupil size were found between the assemblies, even though the subjective mental workload significantly differed. Exploratory analyses on the pupil size when attending to the assembly instructions were inconclusive. It is suggested that current laboratory-based procedures might not be adequate yet for mobile pupillometry. These findings invite a more nuanced view on the current validity of laboratory-validated physiological measures of mental workload when applied in real-life problem settings.

Industry 4.0 reflects a new stage for production workshops. This concept aims to bring flexibility and agility to the production workshop. The scheduling problem is an important issue. A schedule has to guarantee a high level, able to take into consideration several possible changes and duration perturbations occurring in the workshop. The algorithms proposed in [123] aim to find a robust optimal schedule capable of optimizing both the usual scheduling theory criterion and robust criterion, considering a possible operation duration perturbation. With these requirements of the workshop and the importance of decision-making when implementing the constructed schedule in the uncertain environment, it is essential to extend the robust scheduling problem to be adaptable to the needs of a decision-maker in evaluating robust properties. In [123], a robust scheduling framework was proposed based on a robustness specification. The paper demonstrates the use of this framework in a decision-making context.

Mass customization requires a frequent product changeover that leads to the need of manufacturing systems endowed with the flexibility and reconfiguration capabilities in order to be robust to possible changes in the production scenarios. Manufacturing companies face a risk when making strategic decisions on the system resources. This risk can be mitigated by exploiting performance evaluation models (such as analytical ones and a discrete event simulation) that may be adopted to estimate the performance of suitable system configurations. Decision-support tools for optimizing production system configurations can be loosely coupled with performance evaluation models. Hence, such models undermine the actual optimization of the production system, even more if production requirements may evolve in the future. The paper [124] presents a methodology for supporting the optimization of a manufacturing system configuration and reconfiguration subject to evolving production requirements. The proposed analytical methodology integrates a stochastic analytical model for a performance evaluation of manufacturing production lines into a mixed-integer programming based on the original problem linearization. The advantage of using the proposed methodology was shown on a production line configuration problem, where buffer capacity and machine capability have to be jointly optimized in order to minimize total costs and satisfy the target performance.

The approach described in [125] attempts to integrate agility aspects used in the APRS project, which was developed at the National Institute of Standards and Technology. The main idea for the APRS project was to develop the measurement science in the form of an integrated agility framework, enabling manufacturers to assess and assure the agility performance of the used robot systems. This includes robot agility performance metrics, several information models, test algorithms and some protocols. A model for a planning domain definition language was presented, which is used within the APRS project. It was an attempt to standardize artificial intelligence planning languages. The described model has been defined in the XMLS language and in the Web ontology language for kit building applications. Kit building is a process that brings parts that will be used in assembly operations together in a kit, and then moves the kit to the area where the parts are used in the final assembly. The paper [125] presented a tool that was capable of automatically and dynamically generating files from the model in order to generate a plan from scratch. The ability of the tool to update a problem file from a relational database for re-planning to recover from failures was also presented.

A frequently changing order stream and product variety require specific robust planning and control, along with a flexible system structure to fulfill the higher customer

service level and to keep the total production costs at a reasonable restricted level. In [126], combined production planning and capacity control algorithms for assembly lines were proposed, aiming at balancing the workload of the operators and decreasing the production costs on a considered time horizon. Instead of using an ideal cycle time and manufacturing control rules, the proposed planning and control algorithms were based on adaptive calculations, which were taken from the continuously updated historical production data. The manufacturing execution data were applied for building regression models, predicting the capacity requirements of the possible production scenarios. The historical production data were used as a direct input of discrete-event simulations in order to determine the proper control policies of operator allocations for the possible scenarios. In order to calculate a reliable feasible production plan, the regression models and control policies were integrated in the mathematical programming model for minimizing the total production costs.

The final assembly of the vehicles is frequently designed as a mixed-model assembly line, which effectively produces at a fixed ratio of possible variants. Market forecasts indicate a volatile future demand for the different types of vehicles, including the electrified ones. The resulting uncertainty of the demand affects the ALBP. In [127], a planning algorithm is presented to provide a decision support for the ALBP with an inherent variant flexibility while maintaining the feasibility robustness. In the first step, a worst-case scenario analysis of the uncertain production program was conducted. As a result, assembly operation duration buffers were derived from the expected fluctuations in the model mix. The ALBP was solved by the proposed algorithm, which focused on the trade-off. It aims to distribute the different durations of assembly operations in such a way that the aggregated possible fluctuation of the assembly steps assigned to a workstation was minimized. The number of workstations was to be kept to a minimum. By presenting the resolution options of the trade-off, it was possible to show which options for an action were open to a decision-maker. The combined approach of scenario analyses and the line balancing optimization was developed. The proposed algorithm was applied to the use case in the automotive industry.

The paper [128] addresses production optimization in the case of uncertain parameters. A standard framework for solving such type of problems was depicted in a three-step algorithm. The first two steps were analyzed in [128]. These steps consist of off-line characterization of the problem and the calculation of solutions with the desired performance. A generic algorithm to implement these off-line steps was developed. This approach relies on the calculation of robust off-line solutions. A generic framework of robustness was determined. Five standard optimization problems were derived and related to the stability and sensitivity analysis. The generic approach was applied to a multi-purpose machines problem. The paper [129] addresses the ALBP with the uncertain operation durations. Special machines are used, where the assembly operation duration can be any real number between the given lower and upper bounds. These special machines can compress the durations of assembly operations. This action may lead to a higher cost due to cumulative wear, erosion, fatigue, etc. The cost was described in terms of operation durations via a linear function. A bi-criteria non-linear integer programming was developed, which comprises two inconsistent objective functions (minimizing the predetermined cycle time and minimizing the specific machine total costs). In order to sustain the considered objectives concurrently, the authors of [129] applied the linear programming algorithm for making a combined dimensionless objective. A genetic algorithm was described to heuristically solve the ALBP. Design of experiments was used to tune various parameters of the proposed genetic algorithm.

Assembly lines are manufacturing systems in which a product is assembled progressively in workstations by different workers or machines, each executing a subset of the needed assembly operations. In [130], it is considered the case in which operation execution times are worker-dependent and uncertain, being expressed as intervals of possible values. The goal is to find an assignment of operations and workers to a minimal number of workstations such that the resulting productivity level respects a desired robust measure. Two mixed-integer programming formulations for this problem are proposed. It is shown how

these formulations can be adapted to handle the special case in which one must integrate a particular set of workers in the assembly line. A fast construction heuristic is presented that yields high-quality solutions in just a fraction of the time needed to solve the problem to optimality. Computational results showed the benefits of solving the robust optimization problem instead of its deterministic counterpart.

6.2. Stability Analysis of Assembly and Production Lines

The paper [131] deals with the optimization problem, which arises when a new simple assembly line has to be designed subject to a fixed number of the workstations, a predetermined cycle time constraint and the precedence constraints determined on a set of assembly operations. The studied ALBP consists in assigning a set of assembly operations to workstations so as to find the robust assembly line, which can withstand operation duration uncertainty in the robust sense. The assembly line robustness was measured by an indicator called a stability factor. The studied ALBP was proven to be strongly NP-hard, upper bounds were derived on the stability factor and the relation of the stability factor with the stability indicator, called a stability radius, was investigated. A mixed-integer linear programming was proposed for maximizing the stability factor. An alternative formulation was derived when uncertainty originates in the used workstations only. Computational results were reported on a collection of ALBP instances derived from benchmark data used in the OR literature for the deterministic SALBP.

The paper [132] is devoted to study optimization problems arising if a transfer line has to be designed subject to a limited number of available workstations, a cycle time constraint and predetermined precedence relations on the set of assembly operations. The considered problem consists in assigning a set of operations to blocks and the determined blocks to workstations in order to construct a robust transfer line configuration under operation duration uncertainty. The robustness of a transfer line configuration is measured by the stability radius, determined as the maximal amplitude of deviations from the nominal value of the durations of uncertain operations that do not violate the solution feasibility. In order to consider different hypotheses on operation duration uncertainty, the stability radius was based on the Manhattan norm or the Chebyshev norm. The considered problem was proven to be strongly NP-hard. A mixed-integer linear programming was proposed for addressing these problems. In order to accelerate the search for an optimal transfer line, two heuristic algorithms and several reduction rules were derived for the mixed-integer linear programming. Computational results were reported on a collection of instances derived from benchmark data used in the OR literature for the deterministic transfer line balancing problems.

The paper [133] is devoted to the SALBP, which arises when a paced simple assembly line has to be designed for the limited number of workstations, predetermined cycle time and precedence constraints given on a set of the assembly operations. The studied problem consists in assigning a set of assembly operations to available workstations in such a way that the constructed line configuration (a feasible solution) will be robust under the operation duration variability. The solution robustness was measured via the stability radius, which is equal to the maximal amplitude of deviations of assembly operation durations that do not violate the solution feasibility. In this paper, the concept of the stability radius was considered for the Manhattan and Chebyshev norms. For each of these norms, the SALBP was proven to be strongly NP-hard, and a mixed-integer linear programming was developed for addressing these uncertain problems. To accelerate the search for optimal solutions, an upper bound on the stability radius was proven and integrated into the corresponding mixed-integer linear programming. Computational results were reported on uncertain instances derived from benchmark data used for the deterministic SALBP.

In [38], the GALBP was studied, where several workplaces were associated with each available workstation. The sets of assembly operations assigned to the workstation have to be partitioned into blocks. Each assembly operation block regroups all assembly

operations to be performed at the same workplace of the workstation. The product items visit workplaces sequentially. The blocks are preceded in a sequential way. The assembly operations grouped into one block are executed simultaneously, and therefore the execution of all operations of the block takes the duration of the longest operation in this block. Such a parallel execution of the assembly operations from the block modifies the manner to take into account the assembly conveyer cycle time. The precedence relations and exclusion constraints exist for available workstations and workplaces. The considered GALBP objective is to assign all given assembly operations to the available workstations and workplaces in order to minimize the assembly line cost, which is estimated as a weighted sum of the number of used workstations and workplaces. The main goal of the article [38] is to propose a stability measure for feasible solutions of the GALBP regarding possible variations of the durations of a certain subset of assembly operations. A heuristic algorithm, providing a compromise between the above objective function and the used stability radius measure, was developed and evaluated on the modified benchmark set of the deterministic instances.

The paper [134] addresses the ALBP, where assembly operation durations are not known before solving the problem but there are the given segments of their possible real values. The objective is to assign the assembly operations to available workstations to minimize the number of workstations while respecting the precedence constraints and the predetermined cycle time of the conveyer. A robust optimization model was developed to hedge against the worst-case scenario of the assembly operation durations. To find a robustly optimal line balance, a breadth-first search algorithm was proposed and evaluated on benchmark problem instances. The computational results obtained were analyzed and some practical recommendations were presented. The SALBP is considered in [135] for describing a special case of the above problem with the infinitely large stability radius of the fixed optimal line balance. For the general case of the SALBP, the lower bounds and upper bounds on the stability radius of the fixed optimal line balance were obtained in the case of an independent perturbation of the numerical assembly line parameters.

The paper [136] deals with a study of the uncertain SALBP-1 with durations of the assembly operations, $t_i, i \in V$, such that segments, $[l_i, u_i]$, of possible durations are only known in advance. When implementing an assembly line balance, the duration, $t_i, i \in V$, of the assembly operation may be equal to any real value enclosed between the lower bound, $l_i \geq 0$, and the upper bound, $u_i \geq l_i$, including these boundaries. A special case of such an uncertain ALBP has been studied, when the lower limit of the allowable segment of possible durations of assembly operations is zero: $l_i = 0$, and the upper limit of the allowable segment is not limited: $u_i = \infty$. The actual duration of the assembly operation, $t_i, i \in V$, must belong to the semi-interval, $[0,\infty)$. In the considered SALBP-1, it is assumed that the set V includes the following two types of assembly operations: A subset $\widetilde{V}$ of the set V contains all assembly operations for which it is impossible to determine exact values of the duration of their execution (such assembly operations include manual operations, that is, operations performed manually without a special automation). The duration of each of the other assembly operations is precisely determined in advance and does not change during the pipeline lifecycle. To analyze the stability of the optimal line balance, the radius, $\rho_{b_1}(t)$, of its stability (called a stability radius) is used. If the stability radius of the optimal line balance, b_1, is strictly positive, then any joint and independent changes in the durations of manual operations, $t_i, i \in \widetilde{V}$, within a ball with the radius, $\rho_{b_1}(t)$, in $\widetilde{n} = \left|\widetilde{V}\right|$-dimensional real space with the Chebyshev norm, must maintain the optimality of the line balance, b_1. If the stability radius of the optimal line balance is zero, then there will be arbitrarily small changes in the durations of the manual operations, which can deprive the optimality of the line balance, b_1. The paper [136] contains the criterion for the stability of the optimal line balance for the SALBP-1 and the formula for calculating the stability radius of the optimal line balance for a general case of the SALBP-1.

In [137], the uncertain SALBP-2 is considered. The assembly operation set is partitioned into two subsets, manual and automated. The durations of the manual operations

are variable and those of the automated operations are fixed during the whole period of using the assembly line. A stability analysis is conducted for this uncertain problem. First, a sufficient and necessary condition for the optimal line balance is derived to have an infinitely large stability radius. Second, formulas and an algorithm for calculating the stability radii for the optimal line balances are derived. Third, computational results for the stability analysis of the benchmark instances are reported. Managerial implications of the stability results are outlined for choosing the most stable line balances, which save their optimality despite the variations of the assembly operation durations, and for identifying the right time for the re-balancing of the assembly line.

The book chapter [138] is devoted to the stability analysis of the SALBP-2. For an optimal line balance, its stability is investigated with respect to simultaneous independent variations of the processing times of the assembly operations. Necessary and sufficient conditions when optimality of a line balance is stable with respect to sufficiently small variations of operation times were proven. It was shown how to calculate lower and upper bounds on the stability radius, i.e., the maximal value of simultaneous independent variations of the processing times, keeping the optimality of the line balance at hand. The algorithm was developed for selecting the set of all stable line balances (for each stable line balance, the stability radius is strictly positive).

The article [139] is devoted to the uncertain SALBP-2. In this problem, it is assumed that the given set of operations includes two types of assembly operations: manual and automated. For the assembly line, it is necessary to minimize the cycle time for processing a partially ordered set of operations on the linearly ordered workstations. The number of workstations and the initial processing times of the assembly operations are given. However, for a set of the manual operations, it is impossible to fix the processing times for the whole lifecycle of the assembly line. On the other hand, for each automated operation, the processing time is fixed. The stability of an optimal line balance of the assembly line with respect to independent variations of the processing times of the manual operations is investigated. It is shown how to calculate the stability radius of the optimal line balance, i.e., the maximal value of simultaneous independent variations of the processing times of the manual operations, keeping the optimality of this line balance. The criterion for the stability of the optimal line balance for the SALBP-2 is proven. Published results on the stability radius of an optimal line balance for a dual SALBP-1 were also surveyed, which minimized the number of workstations for the fixed cycle time.

For the simple assembly line, it is required to minimize the number of workstations for processing a partially ordered set of the operations within a fixed cycle time (SALBP-1). A dual assembly line balancing problem SALBP-2 is to minimize the cycle time, provided that the number of the workstations is fixed. An initial vector of the processing times of the assembly operations is given for both problems, SALBP-1 and SALBP-2. For a subset of the manual operations, the processing times may vary since operators may have different skills, levels of fatigue, experience and motivation. For each automated operation, the processing time cannot vary. In [140], the stability of an optimal line balance for the assembly line is investigated with respect to variations of the processing times of the manual operations (a line balance is stable, if it is optimal for any sufficiently small variation of the processing times). The enumerative algorithms are developed for constructing feasible and stable optimal line balances for the problems SALBP-1 and SALBP-2. Computational results for the stability of the assembly line balances showed that there are a lot of unstable optimal line balances for the tested benchmark assembly lines. The simulation for the benchmark assembly line showed that the stable optimal line balance considerably outperforms the unstable ones. The complexity analysis of the assembly line balancing problems with different partial orders given on the operation set has been developed.

The SALBP-E with interval durations of the manual assembly operations was investigated in [141]. The authors consider the SALBP-E, in which each assembly operation of the partially ordered set of assembly operations needs to be assigned to one workstation of the set of available workstations used for processing the assembly operations. The

objective of the SALBP-E is to minimize the product of the number of workstations used in the considered line balance and the cycle time of this line balance among all admissible line balances. This objective is equivalent to maximization of the efficiency, E, which is determined by Equality (1). A feasible line balance is a partition of assembly operations into at least two available workstations, without violating the set of given precedence relations among the assembly operations. It is assumed that during the long lifespan of this existing assembly line, the duration of each manual operation may deviate from an initially estimated real value, while the real duration of each automated operation is deterministic during the lifespan of the assembly line. Sufficient and necessary conditions have been proven for the optimal line balance to be stable (i.e., the stability radius of the optimal line balance is strictly positive). It was shown that the stability radius of an optimal line balance could be infinitely large. Sufficient and necessary conditions were proven for the existence of an infinite optimal line balance. Several lower and upper bounds for a finite stability radius were proven. The formula was proven for obtaining the stability radius of an optimal line balance existing for the SALBP-E.

The book chapter [142] presents a survey of sequencing and scheduling problems with inaccurate data, which can be solved by a stability method. It was assumed that the job processing times (and other given numerical parameters) may take any real values from the given closed intervals. For different possible types of sequencing and scheduling problems, the known mathematical models were discussed along with proven mathematical results and developed algorithms, which are based on the stability analysis of the optimal solutions (i.e., optimal operation sequences or optimal semi-active schedules) with respect to possible variations of input data. The stability method combines a stability analysis, a multi-stage scheduling framework (i.e., off-line planning stages and online scheduling stages) and the solution concept of a minimal dominant set of the semi-active schedules [39,40] (e.g., job or operation sequences), that optimally covers all possible scenarios in the sense that for any feasible scenario, such a dominant set contains at least one optimal solution (optimal operation sequence or optimal semi-active schedule). The mathematical results discussed in this book chapter have been obtained in the period from 1988 to 2013.

The paper [143] is devoted to the calculation of the stability radius of an optimal semi-active schedule for a general shop scheduling problem, where the objective is to minimize the mean (total) flow time. The stability radius denotes the largest quantity of independent variations of the durations of the operations, such that an optimal semi-active schedule of the considered general shop scheduling problem remains optimal. The authors of this paper derived formulas for calculating the stability radius and necessary and sufficient conditions when the stability radius is equal to zero. Computational results on the calculation of the stability radius for randomly generated job-shop scheduling problems were also discussed.

The paper [144] addresses the calculation of the stability radius of the semi-active schedule for a job-shop scheduling problem, when the objectives are to minimize either mean or maximal flow times. The proposed approach may be regarded as a posteriori analysis, in which an optimal semi-active schedule has already been constructed and the main question is to determine such possible changes in the durations of operations so as to not destroy the optimality of the semi-active schedule. The stability radius of the optimal semi-active schedule denotes the largest quantity of independent and simultaneous variations of the durations of the operations, such that an optimal semi-active schedule of the job-shop scheduling problem remains optimal. In scheduling theory [39–41], mainly deterministic problems have been considered, and the durations of jobs and operations are supposed to be provided in advance. Such deterministic scheduling problems do not very often arise in practice. Even if the operation (or job) durations are known before applying a scheduling algorithm, OR workers are forced to consider possible changes and errors within the practical realization of the constructed schedule, e.g., due to additionally arrived jobs, machine breakdowns and the precision of equipment, which are used to calculate the operation durations (or job durations) and so on. In other words, usually in practice, a semi-active schedule has to be realized under uncertain conditions. The influence of

errors and changes of the operation durations on the optimality of a semi-active schedule is investigated in [144]. The extensive numerical experiments with randomly generated job-shop scheduling problems were performed and discussed. The developed software provides the possibility of comparing the values of the stability radii, the numbers of optimal semi-active schedules for two criteria: minimization of maximal job completion times and minimization of the sum of job completion times. How large the stability radius was for the tested randomly generated problems was investigated.

6.3. A Stability Approach to Job-Shop Scheduling Problems with Uncertain Parameters

In [142–144], the stability radius of the optimal semi-active schedule for shop scheduling problems was investigated. The developed algorithms can be used to solve a set of uncertain scheduling problems arising in optimization of the assembly and disassembly lines. The authors of these articles present the necessary and sufficient conditions for the existence of a zero-stability radius of the optimal semi-active schedule, as well as formulas for calculating the stability radii in a general case.

The uncertain scheduling problem, $Im||C_{max}$, is studied in [145]. A set of jobs has to be processed on identical machines. Every job may be processed on any available machine without preemptions. The criterion is to minimize the makespan (the completion time of the last job in the schedule). During the realization of a schedule, durations of some jobs may deviate from the initial values estimated before scheduling. Other jobs have fixed durations that are known before scheduling and do not change in the realization of any feasible semi-active schedule. For this uncertain scheduling problem, $Im||C_{max}$, which is NP-hard even for the simplest deterministic case with $m = 2$, a stability analysis of the optimal semi-active schedule was conducted. The necessary and sufficient conditions for an optimal semi-active schedule were proven to be unstable with respect to infinitely small variations of the non-fixed job durations (in this case, the stability radius of the unstable semi-active schedule is equal to zero). It was shown that the stability radius of an optimal semi-active schedule could be infinitely large. The necessary and sufficient conditions for an infinitely large stability radius were proven. Several lower and upper bounds on the stability radius have been established. A formula was proven, and the algorithm was developed for calculating the exact stability radius in a general case of the uncertain problem, $Im||C_{max}$.

In [146], a two-machine shop scheduling problem was studied, provided that only lower and upper bounds on processing times of the jobs are known before scheduling. An exact value of the job processing time remains unknown until completion of this job. The objective is to minimize the makespan (schedule length). The authors of this paper address the issue of how to best execute a semi-active schedule if the job processing time may take any real value from the given segment. Scheduling decisions consist of two phases: an off-line phase and an online phase. Using available information on the lower bounds and upper bounds for each job processing time that are available in the off-line phase, a scheduler can determine a minimal dominant set of semi-active schedules (DS for short) based on sufficient conditions for a schedule domination. The DS optimally covers all possible scenarios of the uncertain job processing times in the sense that, for each scenario, there is at least one semi-active schedule in the DS which is optimal. The DS enables a scheduler to quickly make an online scheduling decision whenever additional information on completing some jobs is available. A scheduler can choose a semi-active schedule, which is optimal for the most scenarios. An algorithm for testing a set of conditions for schedule dominance was developed. The developed algorithm is polynomial in the number of jobs. Computational experiments have shown the effectiveness of the algorithms. If there were no more than 600 jobs, then all 1000 tested instances in each tested series were solved in 1 s. A problem instance with 10,000 jobs was solved in 0.4 s on average. The most problem instances from nine tested problem classes were optimally solved. If the maximum relative error of the job processing time was not greater than 20%, then more than 80% of the tested instances were optimally solved. If the maximum relative error was equal to 50%, then 45%

of the tested instances from the nine problem classes were optimally solved despite the processing time uncertainty.

The paper [147] addresses the issue of how to best execute a schedule in a two-phase scheduling decision framework by considering a two-machine flow-shop scheduling problem, in which the uncertain duration of a job on a machine may take any real value between the lower and upper bounds. The scheduling objective is to minimize the makespan. There are two phases in the proposed scheduling process: the off-line phase (the schedule planning phase) and the online phase (the schedule execution phase). The available information of the lower and upper bounds for uncertain job duration is available at the beginning of the off-line phase, while the local information on the realization (the actual value) of the uncertain duration is available once the corresponding operation of the job on the machine is completed. In the off-line phase, a scheduler prepares a minimal dominant set (DS) of semi-active schedules, which is derived based on a set of sufficient conditions for a semi-active schedule domination that was developed in [146,147]. This dominant set of schedules enables a scheduler to quickly make an online scheduling decision whenever additional local information on the realization of uncertain job durations is available. This DS of schedules optimally covers all feasible realizations of the uncertain job durations. The proposed algorithm enables a scheduler to best execute a semi-active schedule and may end up executing the optimal schedule in instances according to the extensive computational experiments, which was based on randomly generated data up to 1000 jobs. The algorithm for testing the set of sufficient conditions of schedule domination was not only theoretically appealing (polynomial in the number of jobs) but also empirically fast, as the computational experiments indicated.

In [148], a scheduling problem is investigated, provided that input data are uncertain (the duration of a job can take any real value from the closed interval). The criterion is to minimize the total weighted completion time for the jobs. As a solution concept to such an uncertain scheduling problem with uncertain job durations, it is reasonable to consider a minimal dominant set (DS) of job permutations containing an optimal one for each possible realization of the job durations. To find an optimal or approximate permutation to be realized, the authors look for a job permutation with the largest stability box, being a subset of the stability region. A branch-and-bound algorithm was developed for constructing a job permutation with the largest stability box. If several permutations have the same volume of the stability box, one of them was selected due to simple heuristics. The efficiency of the constructed job permutations (how close they are to the optimal permutation) and the efficiency of the developed software, i.e., average CPU time used for an instance, were demonstrated on a wide set of randomly generated instances.

The book chapter [149] addresses a two-stage, minimum-length scheduling problem with n jobs to be processed on two specified machines, where the job processing times are uncertain (only lower and upper bounds for the random processing times are provided before scheduling). For such an uncertain scheduling problem, usually, there is not a single semi-active schedule that remains optimal for all possible realizations of the job processing times. Therefore, it is required to look for a minimal set of semi-active schedules that is dominant. Such a minimal dominant set (DS) of schedules may be represented by a dominance circuit-free digraph. Some useful properties of such a digraph are investigated. To the uncertain scheduling problem under consideration, the stability method is applied, combining a stability analysis, a multi-stage decision framework and the solution concept of a minimal dominant set of semi-active schedules.

7. New Settings of Simple Assembly Line Balancing Problems and Unresolved Issues

As determined by Smith [5], advantages of the division of manual labor can be considered not only as a specialization of human operators, to perform a variety of assembly operations assigned to them, but also as the need to remove workplaces on the assembly line from one another. The need for such a division of manual labor arises in connection with the spread of coronavirus infection (COVID-19) when the financial costs of preventing,

treating and coping with the consequences of the disease for workers who have had COVID-19 have become comparable to other costs of an inefficient use of the assembly line. The necessary removal of workstations from one another can be achieved as a result of changing (increasing or, conversely, reducing) the number of actually used workstations (it is assumed that such a workstation is used by one human operator).

Depending on the specific conditions of assembly production and the market's needs for the products to be harvested, an enterprise can either reduce the number of workplaces actually used (i.e., some workplaces will temporarily not be used) or create new workplaces if there is space for this in the assembly shop. Such changes in the composition and location of the assembly line will increase the distance between the human operators of the assembly plant.

One can find other reasons for the need to modernize the composition and configuration of the assembly line during the exploitation of the assembly plant. For example, during the holiday period (in summertime), there is a periodic need to replace qualified assembly line operators with seasonal workers, which may lead to an increase in the duration of some assembly operations. In this case, the required value of the cycle time of the assembly line can be provided, for example, by increasing the number of workstations and the subsequent solution of the SALBP-2 with an increased number of workstations. The division of SALBP into three classes: SALBP-1, SALBP-2 and SALBP-E, proposed in [2], does not provide for the re-designing or optimal modernization of the assembly line during its exploitation. In the most complex simple assembly line balancing problem, SALBP-E, special cases of which are both problems SALBP-1 and SALBP-2, the efficiency of the assembly line is determined by the equality: $E = t_{sum}/(m \cdot c)$, see (1), which does not allow for differentiating the financial costs of commissioning new workstations and the financial losses associated with an increase in the cycle time of the assembly line.

Next, we introduce new settings of simply assembly line balancing problems.

7.1. Maximization of the Effectiveness of Assembly Line Modifications

Due to a significant change in the conditions of assembly production, it may be necessary to solve the following optimization problem, which we denote SALBP-E_α^β. Suppose there is a set, $S = \{S_1, S_2, \ldots, S_m\}$, of workstations that can be used in assembly production. The duration, $t_i, i \in V$, of the assembly operations and the partial strict order of their execution, defined by the digraph $G = (V, A)$, are also specified. The average costs $\alpha \geq 0$, for using one workstation from the selected workstation subset of the set, $S = \{S_1, S_2, \ldots, S_m\}$, of the workstations available at the enterprise. This cost, $\alpha \geq 0$, includes depreciation of one workstation, energy costs, creation and exploiting of a new workstation, and commissioning of a previously reserved workstation.

The average cost $\beta \geq 0$ of assembling one product on the assembly conveyor is usually known before solving the problem. In the SALBP-E_α^β, it is necessary to find an optimal line balance, $b = (V_1^b, V_2^b, \ldots, V_m^b)$, of assembly operations, V, and the cardinality, m, of a subset of workstations used on the assembly conveyor. Using the optimal line balance is required to minimize the following weighted costs:

$$E_\alpha^\beta = \alpha \cdot m + \beta \cdot c \tag{2}$$

for the exploitation of the assembly conveyor and the assembly of the final products of the assembly conveyor. Recall that the SALBP-E proposed in [2] requires maximizing the efficiency of the assembly line, which is determined by the Equality (1).

If the relative costs of the exploitation of the assembly line and the production of assembly products are considered and the equality $\alpha + \beta = 1$ is assumed, then the problem SALBP-E_α^β turns into the problem SALBP-1 with the equality $\beta = 0$, and into the problem SALBP-2 with the equality $\alpha = 0$. If the absolute cost of the exploitation of the assembly

line and the production of assembly products are considered, then the objective function of the SALBP-E_α^β takes the form:

$$E_\alpha^\beta = \alpha \cdot \left(\sum_{i=1}^{m} E_i + \sum_{j=m+1}^{m+k} E_j \right) + \beta \cdot c, \tag{3}$$

in the case of increasing the set of workstations of the assembly line by including $k \geq 1$ new workstations in the assembly production.

The objective function of the SALBP-E_α^β is of the form:

$$E_\alpha^\beta = \alpha \cdot \left(\sum_{i=1}^{m} E_i - \sum_{j=k}^{m} E_j \right) + \beta \cdot c \tag{4}$$

if it is needed to reduce the set of workstations of the existing assembly line by excluding $(m-k+1)$ workstations from the assembly production.

In the Formula (4), the value of E_i determines the total cost of the exploitation of a workstation S_i from a set of the workstations, $S = \{S_1, S_2, \ldots, S_m\}$, used on an operating assembly line. The Formula (3) defines the values of E_i for all the workstations, $S_i \in S$. For workstations of the set, $\{S_{m+1}, S_{m+1}, \ldots, S_{m+k}\}$, the value of $E_j, j \in \{m+1, m+2, \ldots, m+k\}$, in addition to the total cost of operating a workstation S_j includes the cost of creating a workstation, if it is a new workstation, and the cost of putting it into operation, if the workstation S_j was previously reserved.

If the set of workstations in use is increased to a set, $S^+ = \{S_1, S_2, \ldots, S_m, S_{m+1}, \ldots, S_{m+k}\}$, it is necessary to renumber all the workstations in use so that when the workstations are indexed again, the inequality, $u < v$, implies that the workstation S_u precedes the workstation S_v in the modified assembly line, $S^+ = \{\ldots, S_u, \ldots, S_v \ldots\}$.

Similarly, one should renumber the workstations of the set, $S^- = \{S_1, S_2, \ldots, S_{k-1}\}$, which is obtained after removing the set of $(m-k+1)$ workstations from the original set of workstations, $S = \{S_{i_1}, S_{i_2}, \ldots, S_{i_m}\}$, of the existing assembly conveyor. Note that to simplify the symbols in the Equality (4), a new numbering of workstations that remained in the assembly line reduced on $(m-k+1)$ workstations was used. The numbering of workstations used in (4) may not correspond to the previous indexing of workstations of the set S, which is consistent with the linear order of the workstations on the assembly line, $S = \{S_{i_1}, S_{i_2}, \ldots, S_{i_m}\}$.

The above problem, SALBP-E_α^β, and its variants, with various objective Functions (2)–(4), are intended for frequent modifications of existing assembly lines, which have become popular due to the accelerated development of technologies and frequent changes in the consumer market, which necessitates the assembly of new product models instead of obsolete assembly products.

7.2. Assembly Line Balancing Problems with Uncertain (Interval) Durations of Assembly Operations

The ALBP with interval durations of assembly operations are not sufficiently investigated in the OR literature. In the articles [136–140], for the problems SALBP-1 and SALBP-2, an analysis of the stability of the optimal line balances of the assembly line was carried out. In the future research, it is planned to study the uncertain problems SALBP-1, SALBP-2, SALBP-E and SALBP-E_α^β, provided that only lower bounds $l_i \geq 0$ and upper bounds $l_i \geq u_i$ with $u_i < \infty$ are known for possible durations of the assembly operations.

To solve the uncertain problems SALBP-1, SALBP-2, SALBP-E and SALBP-E_α^β with interval durations of the assembly operations, one can apply a stable method, similar to the use of this method for solving different scheduling problems with uncertain (interval) durations of the jobs and operations [146–149]. This method is based on the stability analysis of the optimal line balance to interval variations in the durations of assembly operations and uses the following concept of the minimum dominant set. The set of line

balances, B, is called the minimum dominant set (DS) for the SALBP, with interval durations of the assembly operation, if for any possible set of operation durations, the set B contains at least one optimal line balance $b \in B$, and the set B has the minimum cardinality among all the dominant sets existing for the SALBP.

8. Conclusions

The simple assembly line balancing problems are fundamental versions of the general ALBP, which has attracted the attention of practitioners and researchers of OR. With respect to the objective functions, the SALBP was classified into SALBP-1, SALBP-2 and SALBP-E. These deterministic problems are not always applicable for real assembly and production lines, since in practice the durations of the assembly operations and other parameters may depend on many factors and are not constant values throughout the lifecycle of the assembly and production lines.

This survey covered most of the papers dealing with the assembly and disassembly line design and balancing under uncertainty. Deterministic models for assembly lines have also been discussed, provided that they are subject to some deviations from normally fixed manufacture conditions. The survey showed that for non-deterministic assembly line design and balancing, most of the referenced papers modeled the assembly operation durations as independent with known probability distributions. Most frequently, such optimization problems have been addressed by heuristic and meta-heuristic approaches. Since the design of assembly and production lines is a strategic problem of high importance, defining the optimal line balances over a large planning horizon, more effort needs to be devoted to the development of efficient exact methods. In the case of the disassembly lines, more attention needs to be paid to the high uncertainty of end-of-life product quantity and quality, as well as to the environmental impact of such lines.

This review focused on assembly and production lines with stochastic, fuzzy and uncertain parameters. We surveyed both the progress in academic knowledge and the current needs of the practitioners. Reviewing the previous studies and studying the needs of the industry led us to propose new settings for the SALBP and highlight the research areas that are worth further investigation. To reduce the financial costs associated with the modification of the existing assembly line, a new formulation, SALBP-E_{α}^{β}, of the SALBP, balancing the assembly line with three variants of the objective Functions (2)–(4), was proposed for further research. These problems, SALBP-E_{α}^{β}, with various objective functions, are intended for frequent modifications of existing assembly lines and production lines due to the accelerated development of technologies and frequent changes in the consumer market, which necessitates the assembly of new product models instead of obsolete assembly products.

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