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TRADITIONAL AND FUZZY GOAL PROGRAMMING APPROACHES FOR RESOURCE DEPENDENT ASSEMBLY LINE BALANCING PROBLEM

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Abstract. In this study, two goal programming models are proposed for balancing resource dependent assembly lines with precise and fuzzy goals in order to provide flexibility for decision makers based on their decision environment and preferred priorities. Three conflicting goals, namely, total number of utilized workstations, cycle time and total cost of additional resources (equipment and assistant workers) are considered. The proposed models are validated on illustrative examples and scenario analyses are performed with different priority levels of the goals. The results show that the proposed goal programming formulations are valid and useful for balancing resource dependent assembly lines.

1. **Introduction.** A product composing of smaller parts is usually produced through an assembly line where various tasks are executed in a series of workstations. Tasks are assigned to workstations according to given precedence relations and each single task is assigned to exactly one workstation. This assignment effort of tasks and workstations subject to some specific constraints (e.g. sum of processing times of tasks in each workstation does not exceed a given cycle time) to optimize one or several performance measures (e.g. minimization of the number of workstations utilized over the line) is referred to as Assembly Line Balancing (ALB) problem.

Since the first presentation of the ALB problem in Salveson [34], it has piqued the interest of many researchers. The literature review studies of Baybars [4], Ghosh and Gagnon [14], Erel and Sarin [11], Becker and Scholl [5], Scholl and Becker [35], Battaïa and Dolgui [3], Sivasankaran and Shahabudeen [36], Hazir et al. [16] and Li et al. [25] are useful for the interested readers.

In most of the ALB studies it is assumed that each task has a single fixed processing time. However, this is always not the case, particularly when different

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production resource choices such as specific equipment or an auxiliary worker are available to complete tasks with varying processing times. In practice, some activities cannot be completed by one worker alone and may require the assistance of another worker or the use of specialized equipment as additional resources. Even if additional resources are not required, the assistance of another person or the usage of a certain equipment can speed up the completion of a task. Moreover, different resource combinations may also be used[19].

Faaland et al.[12] have defined this problem as resource dependent assembly line balancing problem (RDALB). In their problem setting, they simultaneously assign tasks to workstations and resources (additional workers and/or equipment) to tasks. Each different resource usage combinations results different processing times and costs. The authors also proposed three different solution methodologies (one exact and two heuristics methods) to solve their model. Later, Kara et al.[19] have addressed the problem from a wide point of view and have adapted the RDALB approach to U-shaped assembly lines (RDULB) with some new practice-oriented assumptions. The objective is the minimization of a total cost function, which is comprised of three different terms: the cost of workstation utilisations, the employment cost of additional workers and the operating costs of equipment. They showed that the total cost reduces when a U-shaped line is applied instead of a straight line. Bukchin and Tzur[6] consider several equipment options to process each task for their equipment selection and task assignment problem. Each different equipment has a different cost and influence on task times, and each workstation can process with only one piece of equipment. They design a branch and bound method and heuristic procedure to reduce overall equipment cost. Corominas et al.[9] developed a general model for assigning heterogeneous resources that optimizes the total cost of workstation processes and resource usage. Combinations of resource types may be used simultaneously similar to the RDALB problem. However, task times do not change depending on the resource combinations, i.e., it does not include resource dependent task times. Their model is a generalization of resource-constrained assembly line balancing (RCALB) problem of Ağpak and Gökçen[1] which differs from the RDALB problem since task times are not resource dependent. Jayaswal and Agarwal[17] adopted the RDULB of Kara et al.[19] and proposed a simulated annealing (SA) algorithm to solve the model. The proposed SA solved small to moderate sized instances optimally and result a good feasible solution in a reasonable time where CPLEX is unable to provide one. Moon et al.[27] deal with an assembly line problem which also includes a selection of multi-functional workers with varying wages based on their skills. They try to minimize the total workstation costs and total worker salaries. Zhang et al.[46] considers balancing of resource-dependent straight or U-shaped assembly lines and preventive maintenance operations at the same time. For this purpose, they propose two integrated models and a memetic algorithm to solve them.

In practice, assembly line managers may prefer to obtain compromise solutions among several conflicting objectives rather than optimising a single objective. The objectives and the priority levels of these objectives may be different with regard to the decision maker and decision making environment[18]. Then this problem is a kind of multi-objective optimization problem, more specifically, multi-objective assembly line balancing problem. In accordance with the very large application areas of multi-objective optimization [22, 23, 28, 33, 39, 40, 41, 45] the multi-objective assembly line balancing problem exists in various studies.

Pekin and Azizoglu[30], developed a bicriteria assembly line balancing model where there are several equipment alternatives for each task. The two criteria they considered are: the total number of workstations and total equipment cost. They proposed a branch and bound algorithm to find non-dominated solutions. Rekiek et al.[32] proposed a multi-objective line balancing model that also includes equipment-workstation assignment decisions. The three objectives were the minimization of total cost, maximization of the line availability and balancing the workload among the workstations. Rekiek et al.[31] propose a generic multi-objective strategy that takes into account decision maker's preferences. Workload balancing and cost minimization are used as the two criteria. To solve the problem, a grouping genetic algorithm was devised, which was combined with a branch-and-cut algorithm and the PROMETHEE II. Their algorithm is applied on a real-world example. Yoosefelahi et al.[43] formulates a multi-criteria assembly line balancing problem involving equipment decisions and present multi-objective evolution strategies to solve it. The equipment are robots in their study. The model minimizes the cycle time, robot setup cost and robot costs. Triki et al.[42] presented a new multi-objective resource dependent line balancing and resource assignment problem. Their model aims to minimize both the cycle time and the total cost of resources used and it is solved by a multi-objective genetic algorithm.

Goal programming (GP) approaches are widely used in multi-objective ALB problems [15, 18, 20, 26, 29]. Atasagun and Döyen[2] have proposed a traditional pre-emptive GP model for RDALB as a conference paper. This paper is an extended and improved version of Atasagun and Döyen[2] with an additional fuzzy GP approach included. Traditional and fuzzy GP approaches are proposed for RDALB in order to provide flexibility for decision makers based on their preferred priorities. The proposed approaches are validated on illustrative examples and the results are presented.

The remainder of the paper is structured as follows: the proposed traditional and fuzzy GP models are presented in Section 2. Illustrative examples and scenario analyses are presented in Section 3. Finally, some concluding remarks are given in Section 4.

2. **Traditional and fuzzy GP models for RDALB.**

The goal programming (GP) concept was introduced by Charnes and Cooper[8]. It has been used as an important modelling technique for a wide range of multi-objective decision making problems [37, 10, 13, 18, 21, 24, 38]. In GP approaches, positive and negative deviational variables are added to the goal equations and some of these deviational variables are minimized according to the directions of the equations. Either weighted sum of these deviational variables can be minimized (weighted GP), or a priority order of the objectives can be defined, and the deviational variables can be minimized in a pre-emptive manner (pre-emptive or lexicographic GP). In the weighted GP approaches, each deviational variable is weighted according to the importance level of the related goal and the weighted sum of the deviational variables is tried to be optimized as an objective function. So that, the problem is transformed to a single objective problem. On the other hand, in the pre-emptive (lexicographic) GP approaches, the deviational variable(s) of the highest priority goal is minimised at the first step. The yielded value of this variable is fixed, and the model is re-solved for minimizing the deviational variable(s) of the goal with the second priority. This process continues consecutively for all goals until the deviational variables of all goals are minimized.

In this section, the traditional pre-emptive GP model of Atasagun and Döyen[2] is given and a fuzzy GP model for RDALB is proposed by adhering to the assumptions of Kara et al.[19] for RDALB. Both of the proposed models are structured on Kara et al.[19]s mathematical formulation. Three conflicting goals are included to both models such as Goal 1 (G1): total number of utilized workstations, Goal 2 (G2): cycle time and Goal 3 (G3): total cost of additional resources (operating cost of equipment and employment cost of assistant workers).

2.1. **Notation.**

Indices, Parameters and Sets

i, r, s : task
j : workstation
T^0_{ie} : completion time of task i with equipment e without assistant
T^1_{ie} : completion time of task i with equipment e with assistant
I : set of tasks
E : set of equipment
E_i : set of equipment which can be used to process task i
NE_e : available number of equipment e
NA : available number of assistants
J : set of workstations
PR : set of precedence relations
$(r, s) \in PR$: a precedence relation; task r is an immediate predecessor of task s
M : a big number
CA : employment cost of an assistant
CE_e : operating cost of equipment e
GWL : lower bound for the total number of workstations
GWU : upper bound for the total number of workstations
CTL : lower bound for the cycle time
CTU : upper bound for the cycle time
CRL : lower bound for the total cost of additional resources
CRU : upper bound for the total cost of additional resources
A^0 : linearisation parameter for the number of workstations goal
B^0 : linearisation parameter for the cycle time goal
C^0 : linearisation parameter for the total cost of additional resources goal

Variables

x_{ij} : 1, if task i is assigned to workstation j; 0, otherwise
p_{ije} : 1, if task i is assigned to workstation j with equipment e without assistant; 0, otherwise
q_{ije} : 1, if task i is assigned to workstation j with equipment e with assistant; 0, otherwise
z_{je} : 1, if equipment e is assigned to workstation j; 0, otherwise
u_j : 1, workstation j is utilized; 0, otherwise
k_j : 1, if an assistant is assigned to workstation j; 0, otherwise
d^- : under achievement of the number of workstations goal
d^+ : over achievement of the number of workstations goal
f^-_j : under achievement of the cycle time goal (for traditional goal

programming)
f^+ : over achievement of the cycle time goal (for traditional goal programming)
h^- : under achievement of the cycle time goal (for fuzzy goal programming)
h_j^+ : over achievement of the cycle time goal (for fuzzy goal programming)
g^- : under achievement of the total cost of additional resources goal
g^+ : over achievement of the total cost of additional resources goal

2.2. **Mathematical formulation for traditional GP.** Traditional GP formulation of Atasagun and Döyen[2] for RDALB is given below:

$$Min\ d^+ \tag{1}$$

$$Min\ f^+ \tag{2}$$

$$Min\ g^+ \tag{3}$$

$$\sum_{j\in J} x_{ij} = 1 \qquad \forall i \in I \tag{4}$$

$$\sum_{e\in E_i} (p_{ije} + q_{ije}) = x_{ij} \qquad \forall i \in I; \forall j \in J \tag{5}$$

$$\sum_{j\in J} (\|J\| - j + 1)(x_{rj} - x_{sj}) \geq 0 \qquad \forall (r,s) \in PR \tag{6}$$

$$\sum_{i\in I} x_{ij} \leq \|I\|\, u_j \qquad \forall j \in J \tag{7}$$

$$\sum_{i\in I} (p_{ije} + q_{ije}) \leq M z_{je} \qquad \forall e \in E_i; \forall j \in J \tag{8}$$

$$\sum_{j\in J} z_{je} \leq NE_e \qquad \forall e \in E \tag{9}$$

$$\sum_{i\in I}\sum_{e\in E_i} q_{ije} \leq M k_j \qquad \forall j \in J \tag{10}$$

$$\sum_{j\in J} k_j \leq NA \tag{11}$$

$$\sum_{j\in J} u_j + d^- - d^+ = GWU \tag{12}$$

$$\sum_{i\in I}\sum_{e\in E_i} (T^0_{ie} p_{ije} + T^1_{ie} q_{ije}) + f_j{}^- - f^+ = CTU \qquad \forall j \in J \tag{13}$$

$$\sum_{j\in J} CA k_j + \sum_{j\in J}\sum_{e\in E} CE_e z_{je} + g^- - g^+ = CRU \tag{14}$$

$$x_{ij}, p_{ije}, q_{ije}, u_j, k_j, z_{je} \in \{0,1\} \qquad \forall i \in I; \forall j \in J; \forall e \in E \tag{15}$$

$$f_j^- \geq 0 \qquad \forall j \in J \tag{16}$$

$$d^-, d^+, f^+, g^-, g^+ \geq 0 \tag{17}$$

The objective functions defined in (1), (2) and (3) minimizes the over achievements of the goals 1, 2 and 3 respectively. As an example, the goal of total number of workstations (G1) is achieved when d^+ is found to be zero in the solution of the model. If d^+ is greater than zero, it means that the G1 is not achieved. Equation (4) ensures that each task is assigned to exactly one workstation. Equation (5) determines the resources (equipment type and assistant) allocated to a workstation. Precedence relationships among tasks are satisfied by the set of constraints given in equation (6). Equation (7) determines whether workstation j is utilized or not. Equation (8) determines whether equipment e is allocated to workstation j or not. Equation (9) restricts the allocated number of equipment type e by the available number of this equipment type. Equation (10) determines whether an assistant is assigned to workstation j or not. Equation (11) ensures that the number of assistants assigned to workstations does not exceed the available number of assistants. Equations (12), (13) and (14) are the goal constraints for the goals 1, 2 and 3 respectively. Finally, equations (15) to (17) are sign constraints.

2.3. **Mathematical formulation for fuzzy GP.** The traditional GP approaches assume that the decision maker(s) can determine the goal values precisely. However, in some cases it cannot be easy to determine a goal value precisely. Moreover, in traditional GP approaches, it is assumed that if a goal is achieved then the decision maker is satisfied, otherwise unsatisfied. But in the case that the goal is not achieved, the unsatisfactory level of the decision maker may not be equal for different deviation values of the related goal. Therefore, an assembly line manager may be unable to state exact aspiration levels and may desire to state imprecise (vague) aspiration levels to the goals. Fuzzy set theory of Zadeh[44] is a useful tool to introduce imprecision to problems. Fuzzy goal programming (FGP) is basically the application of fuzzy set theory to traditional GP. Chang[7] proposed an FGP model called binary fuzzy goal programming (BFGP), which is appropriate for optimisation problems such as ALB[18].

In this section, Chang[7]'s BFGP model is adopted for balancing resource dependent assembly lines with fuzzy goals. The proposed model is presented below:

$$Min\ d^- \tag{18}$$

$$Min\ h^- \tag{19}$$

$$Min\ g^- \tag{20}$$

Equations (4) - (11) and Equation (15) are exactly valid in fuzzy GP model.

$$A^0 - A\left(\sum_{j\in J} u_j\right) + d^- - d^+ = 1 \quad \text{where } A = 1/(GWU - GWL) \text{ and } A^0 = A \times GWU \tag{21}$$

$$B^0 - B\left(\sum_{i\in I}\sum_{e\in E_i}(T^0_{ie}p_{ije} + T^1_{ie}q_{ije})\right) + h^- - h^+_j = 1 \qquad \forall j \in J \quad \text{where } B = 1/(CTU - CTL) \text{ and } B^0 = B \times CTU \tag{22}$$

$$C^0 - C\left(\sum_{j\in J} CAk_j + \sum_{j\in J}\sum_{e\in E} CE_e z_{je}\right) + g^- - g^+ = 1 \tag{23}$$

where $C = 1/(CRU - CRL)$ and $C^0 = C \times CRU$

$$h_j^+ \geq 0 \qquad \forall j \in J \tag{24}$$

$$d^-, d^+, h^-, g^-, g^+ \geq 0 \tag{25}$$

The objective functions defined in (18), (19) and (20) minimizes the under achievements of the goals 1, 2 and 3 respectively. As an example, the goal of total number of workstations (G1) is achieved when d^- is found to be zero in the solution of the model. If d^- greater than zero, it means that the G1 is level achieved or not achieved completely. Equation (21), (22) and (23) are the adaptations of Chang[7]'s BFGP for goal 1 (total number of workstations), goal 2 (cycle time) and goal 3 (total cost of additional resources), respectively. Finally, equations (24) and (25) are non-negativity constraints.

3. **Illustrative examples and scenario analysis.**

In this section, the proposed GP formulations are validated on an illustrative problem. Firstly, required data of an RDALB problem with 10 tasks is given. Thereafter, the problem is solved using the proposed traditional and fuzzy GP models and results are presented. Finally, scenario analyses are performed by solving the mentioned illustrative problem with six different goal priority orders.

3.1. **Problem data.**

Table 1 presents the precedence relations and the tasks processing times of the illustrative problem with resource alternatives of the tasks. In the Table 1, i and IP_i columns denote the task number and the immediate predecessors of task i, respectively. The other cells of the table are about processing alternatives of the tasks. For example, task #5 has only one processing alternative without any assistance and any equipment. The processing time of the task #5 is 6 minutes. On the other hand, task #4 has two processing alternatives. This task can be completed manually (without any equipment) by one worker in 5 minutes. But the processing time of the task #4 can be reduced to 3 minutes by assistance of an assistant worker. Another example is task #3. As is seen in the Table 1, task #3 has only one processing alternative with assistant and can be completed in 13 minutes. This means that, task #3 cannot be completed without assistance. In addition, Table 1 indicates that, task #2 has four different resource alternatives. Task #2 can be completed by one worker in 10 minutes manually, in 7 minutes using equipment #1 and in 8 minutes using equipment #2. Alternatively, this task can be completed in 7 minutes with assistance of an assistant worker without using any of the equipment.

The other parameters defined in the model are taken as CA=6, c_1=3.3, c_2=1.7 and c_3=1.5 money units. Available number of assistants, equipment #1, equipment #2 and equipment #3 are 2, 1, 1 and 2, respectively. No equipment case is also defined by labelling the equipment type 0. All of the processing alternatives, task times, costs and available number of the resources are generated randomly.

Table 1. Illustrative Problem Data

i	IP_i	**Task Completion Times**					i	IP_i	**Task Completion Times**				
		Assistant	**Equipment**						**Assistant**	**Equipment**			
			No	**1**	**2**	**3**				**No**	**1**	**2**	**3**
1	-	Yes					6	2,5	Yes				
		No	5			4			No	8	6		6
2	-	Yes	7				7	6	Yes				
		No	10	7	8				No	7			
3	-	Yes	13				8	7	Yes				
		No							No	4			3
4	1	Yes	3				9	3,7	Yes	5			
		No	5						No				
5	4	Yes					10	9	Yes				
		No	6						No	13			

3.2. **Solution of the illustrative problem using traditional GP with precise goals.** For traditional GP solution, it is assumed that the assembly line manager desires to achieve the following precise goals with priority order of G1-G2-G3.

- G1: total number of utilized workstations should not exceed four ($GWU = 4$).
- G2: cycle time should not exceed fifteen minutes ($CTU = 15$).
- G3: total cost of additional resources should not exceed sixteen money units ($CRU = 16$).

Based on the priority levels of the goals, the problem is solved in seconds using CPLEX 12.5 on a workstation with an Intel Xeon E5-1650 (6 Core) 3.20 GHz processor with 16 GB RAM.

After the solution of the model with the objective of minimizing the over achievement of G1, the deviational variable d^+ was found to be 0. This means that G1 is achieved. The total number of utilized workstations will be 4.

Then, the yielded value of d^+ was fixed by adding a new constraint to the model such as $d^+=0$ and the model was re-solved with the objective of minimizing the over achievement of G2. In this case, the deviational variable f^+ was found to be 3. This means that G2 is not achieved, and the assembly line will be operated at 15+3=18 minutes of cycle time.

Finally, the yielded value of f^+ was fixed by adding a new constraint to the model such as $f^+=3$ and the model was re-solved with the objective of minimizing the over achievement of G3. In the solution, the deviational variable g^+ was found to be 0.8. This means that G3 is not achieved, and the total cost of additional resources will be 16+0.8=16.8 money units. The final solution of the model is given in Table 2.

Table 2. Final Results of the Illustrative Problem (Traditional GP)

Workstation	**Assigned tasks**	**Workload**	**Assigned equipment**	**Assistant**	**Cost of additional resources**
1	1,3	18	-	Yes	6
2	2,4,5	18	#1	No	3.3
3	6,7,8	16	#3	No	1.5
4	9,10	18	-	Yes	6
		Total cost of additional resources			**16.8**

The final solution of the model is also illustrated in Figure 1.

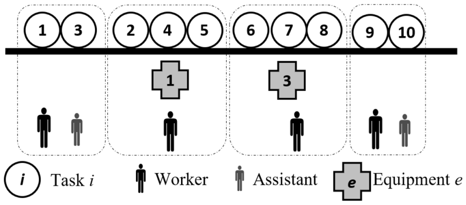

Figure 1. Final Solution of the Illustrative Problem (Traditional GP)

3.3. **Scenario analysis for traditional GP.** The three precise goals of the proposed GP model mentioned above can be ordered in $3! = 6$ different ways depending on their priority levels. The illustrative problem is solved for these six different scenarios and the corresponding results are presented in Table 3.

Table 3. Scenario Analysis by Changing the Priority Levels of the Goals (Traditional GP)

Scenario	**Priority Order**	d^+	f^+	g^+	**Unsatisfied Goals**	**Total Number of Workstations**	**Cycle Time**	**Cost of additional resources**
1	G1-G2-G3	0	3	0.8	G2, G3	4	18	16.8
2	G1-G3-G2	0	4	0	G2	4	19	15
3	G2-G1-G3	1	0	2.3	G1, G3	5	15	18.3
4	G2-G3-G1	2	0	0	G1	6	15	13.5
5	G3-G1-G2	0	4	0	G2	4	19	15
6	G3-G2-G1	2	0	0	G1	6	15	13.5

Table 3 shows that either G1 or G2 is not satisfied in each scenario. G2 is not satisfied in the case that G1 has a higher priority level compared to G2 (Scenarios #1, #2 and #5). Similarly, G1 is not satisfied in the case that G2 has a higher priority level compared to G1 (Scenarios #3, #4 and #6). This means that if the total number of utilized workstations is limited to a smaller value, the assembly line will be operated with a longer cycle time. On the other hand, if the cycle time is limited to a shorter value, a greater number of workstations should be utilized. In addition, as it is seen in Table 3, G3 is not satisfied in two of the scenarios (#1 and #3) where it has the lowest priority level. This means that if the number of workstations and cycle time are both limited, the allocated budget for the additional resources should be increased.

3.4. **Solution of the illustrative problem using fuzzy GP with fuzzy goals.** For fuzzy GP solution, it is assumed that the assembly line manager now desires to achieve the following fuzzy goals for the same problem with priority order of G1-G2-G3.

- G1: total number of utilized workstations should be less than or equal to four with an upper limit of seven ($GWL = 4$, $GWU = 7$).
- G2: cycle time should be less than or equal to fourteen minutes with an upper limit of nineteen minutes ($CTL = 14$, $CTU = 19$).
- G3: total cost of additional resources should be less than or equal to thirteen money units with an upper limit of twenty-three money units ($CRL = 13$, $CRU = 23$).

Having solved the model with the objective of minimizing the under achievement of G1, the deviational variable d^- was found to be 0. This means that G1 is fully achieved.

Then, the yielded value of d^{-} was fixed by adding a new constraint to the model such as $d^{-}= 0$ and the model was re-solved with the objective of minimizing the under achievement of G2. In this case, the deviational variable h^{-} was found to be 0.8. This means that G2 is level achieved with the membership value of 0.2 (1 - 0.8), and the assembly line will be operated at 18 minutes of cycle time.

Finally, the yielded value of h^{-} was fixed by adding a new constraint to the model, which is $h^{-}= 0.8$, and the model was re-solved with the objective of minimizing the over achievement of G3. In the solution, the deviational variable g^{-} was found to be 0.38. This means that G3 is level achieved with the membership value of 0.62 (1 - 0.38), and the total cost of additional resources will be 16.8 money units. The final solution of the fuzzy GP model is identical to the solution of the traditional GP model given in Table 2 and Figure 1.

3.5. **Scenario analysis for fuzzy GP.**

The illustrative problem is solved by using fuzzy goals for the six different scenarios mentioned above and the corresponding results are presented in Table 4.

TABLE 4. Scenario Analysis by Changing the Priority Levels of the Goals (Fuzzy GP)

Scenario	**Priority Order**	d^{-}	h^{-}	g^{-}	**Total Number of Workstations**	**Cycle Time**	**Cost of additional resources**
1	G1-G2-G3	0	0.8	0.38	4	18	16.8
2	G1-G3-G2	0	1	0	4	19	12.3
3	G2-G1-G3	0.67	0	0.2	6	14	15
4	G2-G3-G1	1	0	0	7	14	12
5	G3-G1-G2	0	1	0	4	19	12.3
6	G3-G2-G1	1	0	0	7	14	12

Table 4 shows that G1 is fully achieved in the scenarios #1, #2 and #5. The commonality between these scenarios is that G1 has higher priority than G2. Additionally, G1 is level achieved in the case that G1 has a lower priority compared to G2 (scenario #3).

A similar case can also be observed for G2 in Table 4. G2 is level achieved in the scenario #1 where G2 has a lower priority compared to G1. And also, G2 is fully achieved in the case that G2 has higher priority than G1 (scenarios #3, #4 and #6). These are expected situations for an ALB problem. When the cycle time increases, the number of utilized workstations decreases. Conversely, when the assembly line will be operated with a shorter cycle time, then the number of utilized workstations should be increased. Table 4 also reveals that G1 is not achieved completely for two scenarios (#4 and #6) in which G1 has the lowest priority. This means that if the cycle time and the allocated budget for the additional resources are both limited, the total number of workstations should be increased. Similarly, G2 is not achieved completely for two scenarios (#2 and #5) in which G2 has the lowest priority. This means that if the number of workstations and the allocated budget for the additional resources are both limited, the assembly line should be operated with a greater cycle time.

Additionally, Table 4 demonstrates that G3 is level achieved in the case that it has the lowest priority level (scenarios #1 and #3) and it is fully achieved in all of the remaining scenarios.

4. **Conclusion.** In this study, traditional and fuzzy goal programming models for the RDALB problem are proposed. Three conflicting goals, which are, total number of utilized workstations, cycle time and total cost of additional resources are considered. The proposed models are validated on an illustrative example and scenario analyses performed for both models with different priority orders of the goals. The results exhibit validity and applicability of the suggested goal programming formulations for balancing resource-dependent assembly lines. The suggested models provide flexibility to the decision-makers by taking into account a variety of goals and varying priority orders of these goals. It should be emphasized that by reassessing the goals' aspirational levels, decision-makers can obtain better solution alternatives.

The proposed GP models for the RDALB problem apply goals with predefined priorities (the so-called pre-emptive or lexicographic goal programming). Instead of using this GP approach, an *a posteriori* multi-objective modelling approach can be adopted in the case that the decision makers are not able to determine priority orders and aspiration levels of the goals prior to the optimization. Thus it is possible to obtain pareto-optimal solutions, the use of which leads decision makers much more flexibility.

Moreover, development of efficient heuristic methods for larger sized problems can be considered as a future research topic due to the NP-hard nature of the RDALB problems.

On the other hand, various types of RDALB problems such as mixed-model RDALB or RDALB with stochastic task completion times can be further studied. Mathematical models and solution approaches such as stochastic programming, chance-constrained programming or robust optimization can be developed for those problems.

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