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Balancing disassembly line under hazardous parts with precise and fuzzy goals

Kesin ve bulanık hedeflerle tehlikeli parçaları dikkate alan demontaj hatlarının dengelenmesi

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Abstract

Disassembly is one of the steps of the recovery activities. Since it includes expensive processes, disassembly shoul be performed with the system that provides efficient and effective outputs. A disassembly line is the most suitable system for disassembly of the returned products. A disassembly line balancing problem (DLBP) is assigning disassembly tasks to consecutive workstations by satisfying a series of constraints and optimizing one or more than one goal. In this paper, the DLBP with multiple conflicting goals which takes into account the negative zone (DLBP-Z) constraints has been proposed. Negative zone constraint is related to hazardous parts. If there are hazardous part/parts in the product and they need to be removed, they may damage the othetr parts and disassembly line. Therefore, these parts must be assigned to different stations from the other parts. Goal programming (GP) and fuzzy goal programming (FGP) approaches have been proposed in order to optimize three conflicting goals, namely total net recovery profit value, the number of parts to be removed for recycling and cycle time. Through a numerical example, the proposed approaches have been tested and goal programming formulations have been shown to be valid and useful. To the best of the authors knowledge, the proposed GP and FGP models are the first multi citeria decision making (MCDM) approaches for DLBP-Z.

Keywords: Disassembly, Disassembly lines, Fuzzy goals, Goal programming, Line balancing.

Özet

Demontaj, geri kazanım faaliyetlerinin adımlarından biridir. Pahalı süreçler içermesi nedeniyle, demontajın etkin ve verimli çıktılar üreten sistemlerde gerçekleştirilmesi gerekmektedir. Bir demontaj hattı, ürünlerin demontajı için en uygun sistemdir. Demontaj hattı dengeleme problemi (DHDP) belirli kısıtların sağlanması koşuluyla bir ya da daha fazla hedefe ulaşmak için görevlerin ardışık olarak sıralanmış istasyonlara atanmasıdır. Bu çalışmada negatif bölge kısıtına göre, birbirleriyle çelişen hedeflerin optimize edilmesine odaklanan DHDP (DHDP-Z) önerilmiştir. Negatif bölge kısıtı tehlikeli parçalarla ilgilidir. Eğer bir üründe çıkarılması gereken tehlikeli parça/parçalar varsa, bu parçaların diğer parçalara ve sisteme zarar vermemesi amacıyla farklı bir istasyonda çıkarılmaları gerekmektedir. Birbirleriyle çelişen hedefler toplam net gerikazanım karı, geri dönüştürülecek parçaların sayısı ve çevrim zamanıdır. İlgili hedeflerin en iyilenmesi için hedef programlama (HP) ve bulanık hedef programlama (BHP) yaklaşımları önerilmiştir. Küçük boyutlu bir örnekle, yaklaşımların geçerli ve faydalı olduğu gösterilmiştir. DHDP literatürü gözlemlendiğinde, DHDP-Z'nin çözümü için çok kriterli karar verme (ÇKKV) yaklaşımlarının uygulanmadığı gözlemlenmiştir

Anahtar kelimeler: Bulanık hedefler, Demontaj, Demontaj hatları, Hat dengeleme, Hedef programlama

Introduction

As the world population dramatically increases, the requirements of people also continuously increase, leading to serious environmental and economic problems. The amount of solid waste and the damage to the environment increase with growing resource consumption, the natural balance deteriorates. At this point, the importance of recovery becomes apparent.

Product recovery is to reclaim valuable materials and parts from outdated or old products to minimize the ultimate quantities of waste sent to landfills by means of recovery actions such as remanufacturing, reusing or recycling [1, 2]. Product recovery reduces waste, saves costs, increases profits and creates new jobs, and so achieves sustainability [3].

All recovery actions require one or more than one process and disassembly is the common process used in all these actions. Disassembly is to separate a product into its constituent parts/subassemblies and materials from the products via a series of technical operations [4, 5]. Disassembly also allows selective extraction of desired parts and materials [3]. Many different problems are encountered during the design and execution of the disassembly process [6, 7]. One of these problems is disassembly line balancing problem (DLBP). A disassembly line consists of consecutive workstations connected by a material handling system. DLBP is assigning disassembly tasks to consecutive workstations by satisfying a series of constraints and optimizing one or more than one performance measure while meeting the demand for the parts. An example layout of a disassembly line is given in Figure 1.

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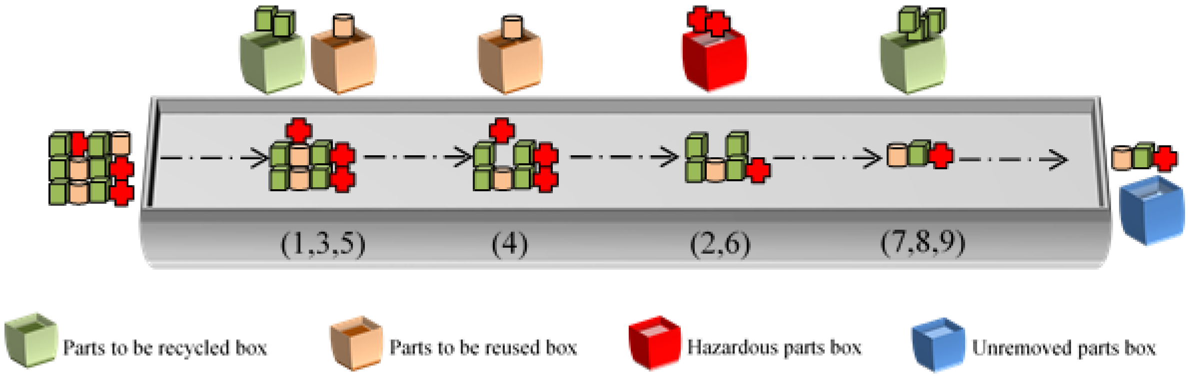

Figure 1. An example illustration of a disassembly line

The disassembly line consists of a total of four workstations and nine tasks in Figure 1. The part or parts removed at each station are placed in boxes separated according to where they will be used later.

The products may be disassembled completely or partially in order to provide economically and environmentally requirements. In complete disassembly, all parts of the product are disassembled, and in partial disassembly, the parts are generally disassembled up to the level that will ensure profitability. Disassembling the product completely, even if all parts have revenue, is often not profitable due to high-cost operations. Therefore, in general, partial disassembly is preferred [6, 8]. Disassembly operations are carried out with one of the two main actions: destructive and non-destructive, regardless of performing partial or complete disassembly. Non-destructive action focuses on part recovery rather than material recovery, and destructive action focuses on material recovery instead of part recovery [9] . Which action will be applied to which part may vary according to the damage status of the parts, the precedence relations between the parts, the demand status of the parts and the goals set by the product recovery facility. For example, non-destructive actions are preferred if parts are to be used in remanufacturing and are easy to disassemble, while destructive actions are performed if parts cannot be removed or they are to be used for recycling [10]. During the performance of the relevant actions, special situations may occur that complicate or restrict the disassembly process. One of these situations is related to parts containing hazardous materials. Some products may have such parts. For example, fuel tanks containing gasoline, diesel etc., cathode ray tubes containing gas such as iron and platinum can be examples of hazardous parts. Disassembly of these parts requires special attention and handling. Otherwise, hazardous materials contained in the parts may harm the worker health and the environment. These materials may also contaminate non-hazardous parts, causing the recovery process of these parts to be canceled. Therefore, these parts should be disassembled at the first stations on the disassembly line as much as possible or at different stations from other parts [6].

The traditional version of DLBP is the straight, single product-type, complete and non-destructive DLBP which was first described by Gungor and Gupta [6, 11]. McGovern and Gupta [12, 13] provided NP-completeness proof of the decision version of DLBP and showed unary NP-completeness. As the interest in DLBP increased, the problem has been developed by modifying the basic assumptions. Some of the assumptions considered are parallel line layout [14, 15], U-shaped layout [8, 16–18], partial [19–24], destructive [10, 18] and hazardous [6, 13, 18, 20, 25–28].

In studies related with hazardous parts, it has been assumed that the relevant parts are assigned to the earliest stations where they can be assigned and they bring additional costs to the stations where they are assigned, as they require special equipment and labor hazardous [6, 13, 18, 20, 25–28].

Different approaches have been proposed and developed to solve the DLBP. Some researchers have developed mathematical programming techniques to solve DLBP optimally [5, 19, 29–31]. However, the fact that DLBP is NP-hard has caused medium and large sized problems to not be solved in a reasonable time. Therefore, metaheuristic approaches have been proposed [13, 21, 31–43].

In recent years, the studies have focused on real-life conditions. One of these conditions is related to uncertainties regarding the quality of the product, the number of parts it contains, or the duration of the operation. Effective solution approaches have been developed for problems that take into account the relevant situation such as stochastic programming [8, 14, 36, 44–51] and fuzzy programming [32, 41, 42, 52–55]. Other conditions are related to robotics [31, 35, 56–59], green objectives, and sustainability [60–66].

When the DLBP literature is examined in terms of the aims to be achieved, it has been observed that some of the studies focused on a goal [15, 19–22, 27, 29, 30, 57, 67–70]. In practice, however, the managers of the disasembly line may want to achieve compromising solutions between several conflicting goals rather than optimizing a single goal. This means that, they wish to meet high-priority goals before low-priority goals. The goals and priority levels of a DLBP can be different in terms of a disassembly line manager, who is the decision maker (DM), and the decision-making environment. This has motivated researchers to develop multi-criteria (multi objective and multi attritubute) approaches for the DLBP. The DLBP literature contains several studies that consider balancing disassembly lines with multi-criteria [6, 14, 18, 25, 33, 36–38, 41, 45, 47, 53, 56, 68, 71–77]. One of the most common methods used to solve multi-criteria decision making problems is GP method [78].

Goals are precisely defined in GP. For example, one of the exact goals of the DM may be that the cycle time should not exceed 10 minutes. If the cycle time does not exceed 10 minutes, the manager is 'satisfied', otherwise he is 'unsatisfied'. However, the level of dissatisfaction with the 15-minute cycle time ('unsatisfactory level') may be less than the level of dissatisfaction with the 20-minute cycle time ('unsatisfactory level'). The dissatisfaction level of the DM is directly proportional to the amount of deviation variable from the goal value. However, in some cases precise determination of the desired goal values may not be easy, or the disassembly manager may not want to specify the relevant values precisely. After balancing a disassembly line with uncertain goal levels, the manager may be "fully satisfied", 'partially satisfied' or 'fully dissatisfied'. In real life applications, the managers want to be fully satisfied with all conflicting goals, but this may not always be possible. Therefore, the DM should set priorities for various conflicting goals and try to maximize the overall satisfaction level for all goals. Traditional GP fails in being applied for goal values that are not clearly specified [79]. Fuzzy set theory has been adapted to traditional GP to define uncertain request levels and the problem has been transformed into FGP [79–81]. In the DLBP literature, GP and FGP approaches have been applied in the studies of [14, 54], respectively to DLBP problems successfully. Karadag and Turkbey [14] used GP approach to show the effectiveness of the proposed GA. The proposed GP approach has been applied to find the best task assignments for workstations with minimum cost and optimized line balance. Paksoy et. al [54] proposed FGP with multiple conflicting objectives that are minimising the number of disassembly workstations and the cycle time, and providing balanced workload per workstation.

It is noted here that a more comprehensive and detailed review of the DLBP papers can be found in [82] and [83].

When the DLBP literature is examined, it is observed that the number of studies on assumptions and approaches towards real life is increasing. Accordingly, DLBP, which takes into account some realistic properties, has been presented in this paper and solution approaches have been developed to solve this problem. We are inspired by recycling and disposal of waste cathode ray tube (CRT) of the TV sets. CRTs contain hazardous substances such as lead and phosphorus and they must be disassembled separately from the other parts that are not contian hazardous substances. The purpose of the disassembly of CRT is to obtain valuable materals while separate the parts with hazardous substances. However, disassembly of all parts of the CRT may be resulted in environmental and line contamination, and long cycle time (namely expensive line cost). For this reason, a solution method is required to make a trade-off between cycle time, parts to be recycled and line profit.

The features taken into account also express the contribution of this paper to the literature. These features have been determined in line with the determinations obtained from the literature and summarized below:

- Although non-destructive actions have been observed to be studied more, an increasing number of studies that take into account destructive actions have been conducted in recent years. Because, situations that require destructive action arise in the disassembly of almost every product. Therefore, besides non-destructive actions, destructive actions that are an undeniable reality of the disassembly process and seriously affect the cost of the line, must be taken into account.
- Although the number of studies on hazardous parts (hazardous tasks) is high, it has been observed that the zone constraint is not used for these parts. Zone constraint is about assigning tasks to the same or different stations. It is divided into two as positive and negative zone constraints. Positive zone constraint is that some tasks (requiring the same equipment, requiring the same special action, etc.) are assigned to the same station, while negative zone constraint is that some tasks should not be assigned to the same station. For example, hazardous tasks and non-hazardous tasks should not be assigned to the same stations so that non-hazardous parts are not damaged. In this paper, negative zone constraint has been taken into account. Assigning hazardous tasks to different stations can increase the cost of the line. However, in cases where it is necessary to remove these parts, negative zone restriction is one of the best precautions that can be taken to prevent negative situations in which the line fails or stops, or solid parts are damaged, etc. In addition, considering the negative zone constraint, the possible increase in the cost of the line will not be more than the sum of the cost items caused by the negative situations that arise when this constraint is not applied [25–28, 33, 42, 50, 62, 67, 76, 84–88].
- When DLBP is examined, it has been observed that there are few studies applying GP and FGP approaches**.** However, the uncertainties arising from the nature of disassembly and the focus on more than one goal indicate that goal programming approaches should be applied more and the goals should be diversified.

In the light of the above, in this paper, the DLBP with multiple conflicting goals which takes into account the negative zone (DLBP-Z) constraints has been proposed. GP and FGP approaches have been developed in order to solve the related problem. It should be kept in mind that the proposed approaches (GP and FGP) are not competitors. They are alternatives to each other. To the best of the authors knowledge, the proposed goal programming approaches are the first MCDM approaches to DLBP-Z.

The remainder of this paper is organized as follows: In Section 2 the DLBP-Z is defined and a 0-1 integer linear programming formulation is developed. Section 3 and Section 4 detail GP and FGP for DLBP-Z, respectively. An illustrative example is presented in Section 5. Some concluding remarks and future perspectives are given in Section 6.

Material ve method

2.1. Characteristics of DLBP-Z

Partial disassembly is performed in the proposed problem. The products are disassembled for their materials or parts depending on the type of demand. Here, if a part is subject to reuse or storage, non-destructive action is taken into account, and if it is to be used for recycling, destructive action is applied. All or some parts of the product have demand and therefore revenue. However, it is not necessary to remove every part demanded. A part is disassembled as a result of a task. With the solution of the problem, which stations will be opened, which tasks will be assigned to which stations, which part / parts will be removed, which action and therefore which recovery action (reuse or recycling) will be applied to the parts to be removed are determined depending on the goals of the DM. If there are hazardous parts in the product and they need to be removed, these parts must be assigned to different stations from the other parts. Other assumptions about the proposed problem are as follows:

- The configuration of each part is known in advance.
- The supply is unlimited.
- Part-based precedence relationship diagram and AND / OR precedence relationshipa are taken into consideration.
- Precedence relationships are known in advance.
- Precedences between parts also show precedences between tasks.
- Each task has cost and duration.
- A task can be carried out by applying only destructive action, by applying only non-destructive action, or by selecting either action.
- Revenue, cost and duration for the task where both actions are likely to be applied vary depending on the type of action.
- If both destructive and non-destructive actions can be applied for a task, the duration, cost and revenue of the destructive action are generally lower than the non-destructive one [85, 89]. Therefore, in order to optimize the goal, either destructive action with less time and cost or non-destructive action with higher revenue can be chosen.
- Since hazardous parts require special attention and handling, the time and cost required to remove these parts may be higher than other parts [88].
- The unit revenue of a part is calculated according to the unit weight if this part is to be used in recycling, and according to one piece if it is to be reused.
- The cost of transport required for transporting non-disassembled parts to the necessary areas for later evaluation has been taken into account.
- Weights and recyclable percentage rates of parts removed for recycling are known in advance.
- All parameters are deterministic and known in advance.
- Both destructive and non-destructive actions can be performed at a workstation.
- Idle time of the operators is not taken into account.

In this paper, traditional GP and FGP formulations were proposed for the solution of DLBP-Z whose assumptions were given above. It was aimed to optimize three conflicting goals with the relevant formulations. The goals are related to the total net profit, the number of parts to be used for recycling and the cycle time. In addition, a 0-1 integer mathematical formulation was presented. Proposed goal programming formulations were structured according to this formulation. The notation used in all proposed formulations was given as follows:

Indices

i, l	:	task (part), $i, l = 1,2,\ldots,N$
j, v	:	workstation, $j, v = 1,2,\ldots,M_{max}$;
k	:	action, $k = 1, 2$ (if acton is nondestructive, k=1; otherwise k=2)

Parameters

I	:	set of all tasks;
J	:	set of workstations;
H	:	set of hazardous tasks;
K	:	set of actions;
M_{max}	:	maximum number of workstations;
N	:	total number of tasks;
ZN	:	set of task pairs that cannot be performed on the same workstation.
$PA(i)$	:	set of AND predecessors of task i;
$PO(i)$	:	set of OR predecessors of task i;
d_i	:	demand of part i (monthly)
w_i	:	weight of part i
t_{ik}	:	task time of i if it is processed with action k (min)
r_{ik}	:	unit revenue of i if it is processed with action k
pr_i	:	recyclable percentage of part i if it is processed with action k=2
ct_{ik}	:	operation cost of task i if it is processed with action k (monthly)
tc	:	average transportation cost from facility to storage (monthly)
cw	:	utilization cost of a workstation (worker + fixed costs) (monthly)
C	:	cycle time
TRC	:	the number of recycled parts
TNP	:	the total net recovery profit
$\underline{C}$	:	lower bound for C
$\overline{C}$	:	upper bound for C
$\underline{TRC}$	:	lower bound for TRC
$\overline{TRC}$	:	upper bound for TRC
$\underline{TNP}$	:	lower bound for TNP

$\overline{TNP}$: upper bound for TNP
L^0 : linearisation parameter for C goal;
P^0 : linearisation parameter for TNP;
S^0 : linearisation parameter for TRC
μ : A big number

Variable decisions

x_{ijk} : 1, if task i is assigned to workstation j with action k; 0, otherwise
y_i : 1, if task i is not done; 0, otherwise.
z_j : 1, if workstation j is utilized; 0, otherwise
e^- : under achievement of the total net recovery profit
e^+ : over achievement of the total net recovery profit
g^- : under achievement of the number of parts to be recycled
g^+ : over achievement of the number of parts to be recycled
h^- : under achievement of the cycle time goal (for FGP);
h^+ : over achievement of the cycle time goal (for traditional GP);
h_j^- : under achievement of the cycle time goal (for traditional GP)
h_j^+ : over achievement of the cycle time goal (for FGP)

The proposed integer mathematical programming model is given as follows:

$$\max \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} r_{ik}d_iw_ipr_ix_{ijk} - \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ik}x_{ijk} - \sum_{i\in I} tcy_i - \sum_{j\in J} cwf_j \quad (1)$$

$$\sum_{j\in J}\sum_{k\in K} x_{ijk} \le 1 \qquad \forall i \in I \quad (2)$$

$$\sum_{k\in K} x_{ijk} \le \sum_{v=1}^{j}\sum_{k\in K} x_{ilk} \quad \forall i \in I,\ \forall l \in PA_i, \forall j \in J \quad (3)$$

$$\sum_{k\in K} x_{ijk} \le \sum_{v=1}^{j}\sum_{l\in PO_i}\sum_{k\in K} x_{ilk} \quad \forall i \in I, \quad \forall j \in J \quad (4)$$

$$\sum_{i\in I}\sum_{k\in K} t_{ik}x_{ijk} \le Cz_j \quad \forall j \in J \quad (5)$$

$$\sum_{k\in K} x_{ijk} + \sum_{k\in K} x_{ljk} \le 1 \quad \forall (i,l) \in ZN, \forall j \in J \quad (6)$$

$$y_i = 1 - \sum_{j\in J}\sum_{k\in K} x_{ijk} \quad \forall i \in I \quad (7)$$

$$x_{ijk}, y_i, z_j \in \{0,1\} \text{ for } i,j,k \quad (8)$$

The objective function (1) maximizes the total net recovery profit associated with the total revenue earned from parts to be reused, total revenue earned from parts to be recycled, operation cost, transportation cost and workstation utilization. Equation (2) enables that a task can be assigned to at most one work station. In Equations (3) and (4) precedence relations among tasks are satisfied. Equation (3) ensures that task i cannot be assigned until its AND predecessors are assigned to station 1 through j. Equation (4) ensures that task i cannot be assigned to station j until at least one of its OR predecessors is assigned to workstation 1 through j. Equation (5) guarantees that the workload of a workstation does not exceed the cycle time. negative zoning constraint is ensured by the Equation (6). Equation (7) determines the parts which are not disassembled. Equation (8) indicates that all variables are binary variables.

2.2. DLBP-Z with precise goals

The GP is a modelling technique for MCDM problems. GP was introduced by [78] and has been developed by many researchers. GP aims to optimize the several conflicting goals precisely transforming a multi-objective problem to a single-objective problem. There are two basic GP approaches in the literature [74]: (1) weighted (non-preemptive) GP; and (2) pre-emptive GP. In both approaches negative and positive deviational variables are added to the goal equations. According to directions of the equations some of these variables are minimized.

All different deviational variables are formulated with weights to represent their importance level of the corresponding goals in the objective function of a weighted GP model. On the other hand, in a preemptive GP, a priority order of goals is determined. Firstly, the deviational variable of the first goal is minimized and this solution is fixed. Then, the model is solved again by minimizing the devaitions of the second goal. This process is repeated until the all goals are solved in the model [79, 90]. The GP model shows whether a goal has been met.

In the GP approaches, it is assumed that the values of all goals can be clearly defined by DM. Determining these values is a difficult task for DM. The DM should set the values of the goals considering account the specific conditions of the problem. No calculations are needed to determine the values of $\underline{TNP}$, $\underline{TRC}$ and $\overline{C}$. These values are determined entirely by the DM, taking into account the special cases of the problem [90].

In this section, after three precise goals are determined, a pre-emptive GP model is proposed for balancing the disassembly lines using these three precise goals. In the context of this paper the proposed pre-emptive GP model is also referred to as the proposed GP. The goals of DLBP may vary according to the features of the returned products and recovery systems and the preferences of DM. Due to the high costs of disassembly action, it is important for DM to gain profit as a result of the disassembly process. Accordingly, there is a greater tendency to remove parts that have more revenue. Therefore, there is a desire to remove parts to be reused. However, the disassembly manager may need to partially or completely meet the demand of the parts to be used in recycling in order to satisfy the consumers by meeting their demands and to fulfill some legal obligations. It also is desirable that the cycle time be as little as possible to increase efficiency. However, it is not possible to achieve these goals at the same time. For example, the total net profit may decrease when the cycle time decreases. On the other hand, increasing the number of parts to be recycled may reduce the number of parts to be reused and cause the total net profit not to be at the desired levels. Therefore, related goals are conflicting goals, and conflicting goals coexist in practical applications. In this case, a balanced level is tried to be found between them for achieving the goals. This paper focuses on three conflicting goals, namely total net recovery profit value, the number of parts to be removed for recycling and cycle time, and these goals are tried to be optimized. The goals are formulated as follows:

Precise Goal (1) : *Total net recovery profit value* ($\underline{TNP}$)

If the total net recovery profit is equal or greater than an aspiration level ($\underline{TNP}$) is desired by the DM, the following equation can be written as below:

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} r_{ik}d_i w_i pr_i x_{ijk} - \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ik}x_{ijk} - \sum_{i\in I} tcy_i - \sum_{j\in J} cwf_j \geq \underline{TNP} \quad (9)$$

Then, the goal constraint of the total net recovery profit value can be formulated by adding deviational variables as below:

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} r_{ik}d_i w_i pr_i x_{ijk} - \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ik}x_{ijk} - \sum_{i\in I} tcy_i - \sum_{j\in J} cwf_j - \underline{TNP} + e^- - e^+ = 0 \quad (10)$$

Precise Goal (2): *The total number of parts to be recycled* ($\underline{TRC}$)

The DM wants the total number of parts to be recycled to be equal to or higher than an aspiration level ($\underline{TRC}$). This can be formulated with the following equation:

$$\left(\sum_{i\in I}\sum_{j\in J} d_i w_{ik} pr_{ik} x_{ijk}\right) \geq \underline{TRC} \qquad i \in (I-H), \quad k=2 \quad (11)$$

Then, the goal constraint of the total number of parts to be recycled can be formulated by adding deviational variables as below:

$$\left(\sum_{i\in I}\sum_{j\in J} d_i w_{ik} pr_{ik} x_{ijk}\right) - \underline{TRC} + g^- - g^+ = 0 \qquad i \in (I-H), \quad k=2 \quad (12)$$

In Equations (10) and (12), negative deviational variables e^- and g^- represent the amount of under achievement of the total net recovery profit and total number of parts to be recycled, respectively. In the solution of the model, if results of these deviational variables are zero then the goals are achieved, otherwise it is not achieved.

Precise Goal (3): *Cycle time* ($\bar{C}$)

The last goal considered in this paper is related to the cycle time. The cycle time of a workstation has to be equal or less than upper bound of cycle time ($\bar{C}$). Then the following equation can be written as below:

$$\left(\sum_{i\in I}\sum_{k\in K} t_{ik}x_{ijk}\right) \leq \bar{C}f_j \qquad \forall j \in J \quad (13)$$

Then, by adding deviational variables, the goal constraint of the cycle time can be formulated as follows:

$$\left(\sum_{i\in I}\sum_{k\in K} t_{ik}x_{ijk}\right) - \bar{C}f_j + h_j^- - h^+ = 0 \qquad \forall j \in J \quad (14)$$

The minimisation of h^+ will minimise the cycle time of disassembly line. When h^+ is found to be zero, the cycle time goal is achieved.

Accordingly, the pre-emptive GP model proposed for DLBP-Z with precise goals is formulated as follows:

$$Min\ \{d^-, e^-, h^+\} \quad (15)$$

Subject to

Goal equations : (10), (12) and (14)

System equations : (1) to (8)

$$\sum_{i\in I}\sum_{k\in K} x_{ijk} - \mu z_j \leq 0 \qquad \forall j \in J \quad (16)$$

Non-negativity equations :

$$e^-,\ e^+, g^-,\ g^+, h_j^-,\ h^+ \geq 0 \quad (17)$$

Note that Equation (16) determines whether workstation j is opened.

2.3. DLBP-Z with fuzzy goals

In the proposed GP model, it is assumed that the DM determines the values of the goals precisely and deterministically. However, in many decision-making cases, DM encounters fuzzy, ambiguous or stochastic goals and objectives. That is, they may not be able to determine the goal values precisely. One of the methods used to express the related goals is the fuzzy goal programming method (FGP). FGP is a method used in cases where there are imprecise goals created by applying fuzzy set theory into GP. In FGP, the goals that are used to indicate the demand levels of the purpose include expressions containing uncertainty such as ‘around’ or ‘nearly’ used in fuzzy logic instead of ‘precise’ expressions like in classical logic. In other words, the FGP model determines the success degree of each goal. It provides high flexibility to DM to set goals [79–81, 90, 91].

Zimmerman [80] adapted fuzzy set theory to classical linear programming (LP) problems with several objectives. Later, studies that paved the way for the use of fuzzy logic in LP models followed each other [72, 81, 91–95]. One of these studies belongs to Chang [96], who proposed the binary fuzzy goal programming (BFGP) model, and the BFGP model has been used in the optimization of many operational research problems to date.

In this paper, the BFGP model has been adapted for DLBP-Z with fuzzy goals. It can be considered that the proposed BFGP model is an alternative to the proposed GP model. The BFGP aims to optimize the same goals as the GP model, namely total net profit, the number of parts to be disassembled for recycling and cycle time goals. In the model, these goals have been formulated as fuzzy parameters. The BFGP model suggested by Chang [96] is given below:

$R_p(x)$: the function of resource constraints for the pth goal, $p = 1,2,3,\dots,n$;

c_p : aspiration level set of the goals, $p = 1,2,3,\dots,n$;

b_p : binary decision variable for the pth goal, $p = 1,2,3,\dots,n$; its behaviour (i.e., 0 or 1) is bounded by $R_p(x)$:

$$f_p(x).b_p \gtrsim c_p.b_p \text{ or } (f_p(x).b_p \lesssim c_p.b_p), \quad p = 1,2,\dots,n. \tag{18}$$

subject to: $x \in F$ (F is a feasible set);
$b_p \in R_p(x),\ p = 1,2,\dots,n.$
Minimise:

$$d_p^-,\ p = 1,2,\dots,n. \tag{19}$$

Subject to:

$$L_p f_p(x) b_p - L_p^0 b_p + d_p^- - d_p^+ = 1,\quad p = 1,2,\dots,n \text{ for } f_p(x) \gtrsim c_p \tag{20}$$

$$I_p^0 b_p - I_p f_p(x) b_p + d_p^- - d_p^+ = 1,\quad p = 1,2,\dots,n \text{ for } f_p(x) \lesssim c_p \tag{21}$$

$x \in F$ (F is a feasible set)
$b_p \in R_p(x),\ p = 1,2,\dots,n.$
where:

$$L_p = \frac{1}{c_p - l_p};\ L_p^0 = L_p l_p;\ I_p = \frac{1}{u_p - c_p};\ I_p^0 = I_p u_p,$$

where l_p is lower limit and u_p is upper limit for the pth goal, respectively; d_p^- is under achievement and d_p^+ is over achievement of pth goal, respectively.

In this paper, the goals given in Section 3 have been formulated as fuzzy, and the fuzzy goal constraints can be written as below:

Fuzzy Goal (1): *Total net recovery profit value* ($\overline{TNP}$)

In a disassembly facility, the DM can desire that the total net recovery profit is approximately greater than or equal to $\overline{TNP}$ as formulated in Equation (22).

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} r_{ik} d_i w_i pr_i x_{ijk} - \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ik} x_{ijk} - \sum_{i\in I} tcy_i - \sum_{j\in J} cwf_j \gtrsim \overline{TNP} \tag{22}$$

Then, the total net recovery profit goal constraint can then be obtained as follows:

$$P\Big(\sum_{i\in I}\sum_{j\in J}\sum_{k\in K} r_{ik} d_i w_i pr_i x_{ijk} - \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ik} x_{ijk} - \sum_{i\in I} tcy_i - \sum_{j\in J} cwf_j\Big) - P^0 + e^- - e^+ = 1 \tag{23}$$

Where $P = 1/\overline{TNP} - \underline{TNP}$ and $P^0 = P\underline{TNP}$.

The minimization of e^- will maximize the total net recovery profit. If e^- is calculated as zero,the total net recovery profit is fully-achieved. Or else, it can be level-achieved or not achieved completely.

Fuzzy Goal (2): The total number of parts to be recycled ($\overline{TRC}$)

Equation (24) implies that the total number of parts to be recycled is approximately greater than or equal to $\overline{TRC}$.

$$\left(\sum_{i\in I}\sum_{j\in J} d_i w_i pr_i x_{ijk}\right) \gtrsim \overline{TRC} \quad i \in I - H,\ k = 2 \tag{24}$$

The the total number of reused parts goal constraint can be shown as follows:

$$S\left(\sum_{i\in I}\sum_{j\in J} d_i w_i pr_i x_{ijk}\right) - S^0 + g^- - g^+ = 1 \quad (25)$$

$$i \in I - H, \quad k = 2$$

Where $S = 1/\overline{TRC} - \underline{TRC}$ and $S^0 = S\underline{TRC}$.

The minimization of g^- will maximize the total number of parts to be recycled. If g^- is found to be zero, the total number of of parts to be recycled is fully-achieved. Or else, it can be level-achieved or not achieved completely.

Fuzzy Goal (3): *Cycle time* ($\underline{C}$)

Cycle time is approximately less or equal to $\underline{C}$ and it can be given as below:

$$\left(\sum_{i\in I}\sum_{k\in K} t_{ik} x_{ijk}\right) \lesssim \underline{C} f_j \quad \forall j \in J \quad (26)$$

Then, the fuzzy cycle time goal constraint can be formulated as follows:

$$L^0 - L\left(\sum_{i\in I}\sum_{k\in K} t_{ik} x_{ijk}\right) + h^- - h_j^+ = 1 \quad 0 \ \forall j \in J \quad (27)$$

where $L = 1/\overline{C} - \underline{C}$ and $L^0 = L\overline{C}$.

If h^- is found to be zero, the cycle time is fully-achieved. Or else, it can be level-achieved or not achieved completely.

According to the fuzzy goal constraints described above, the proposed BFGP model for DLBP-Z with fuzzy goals is presented below:

$$Min\,\{\,e^-, g^-, h^-\} \quad (28)$$

Subject to

System constraints : (1) to (8), 16

Goal constraints : (23), (25) and (27)

Non-negativity constraints

$$: e^-,\ e^+,\ g^-,\ g^+,\ h^-,\ h_j^+ \geq 0 \quad (29)$$

Findings and discussion

3.1. Illustrative example

In this section, the proposed GP and BFGP approaches are illustrated on a small-scaled numerical example problem created by the authors. The related problem has been generated according to the data obtained from some studies in the disassembly literature [6, 9, 85, 89]. The example disassembly facility consists of a disassembly line with eigth tasks. The precedence relationships among the tasks are illustrated in Figure 2. The knowledge data of the example problem, including *cw* = 2500 unit and *tc* = 850 currency unit, are given in Table 1.

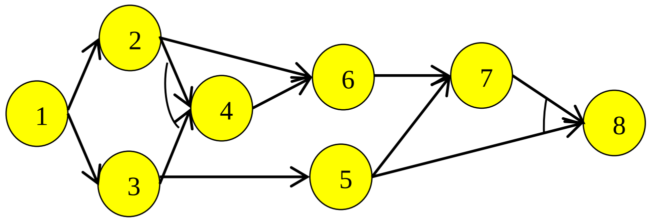

Figure 2. The precedence relationships diagram of the example

Table 1 consists of nine rows and columns. The first column shows the task / part number, the second column shows the actions, and the other columns show the duration of the task required to disassemble part i, unit revenue, task cost, recyclable percentage rate, weight of the part, the amount of demand for the part and the hazard status of the part, respectively.

Table 1. The knowledge data of the example problem

i	k	t_{ik}	r_{ik}	ct_{ik}	pr_i	w_i	d_i	Haz.cont.*
1	1	9	18	2080	-	-	620	No
	2	7	12	1440	1	0.8		
2	2	8	11	1120	0.9	0.6	585	No
3	1	6	13	2060	1	-	420	No
4	2	10	-	2240	-	-	-	Yes
5	1	9	14	1760	-	-	760	No
	2	8	8	960	1	0.8		
6	2	7	11	1140	0.7	0.9	800	No
7	1	9	8	2100	-	-	210	No
8	2	6	10	960	0.8	0.7	160	No

* Hazardous content

Part i is performed with task i. For example, part 1 is performed with task 1, part 2 is performed with task 2. Tasks 1 and 5 are performed with either non-destructive or destructive action. Tasks 3 and 7 are performed using only non-destructive actions, while tasks 2, 6 and 8 are performed using only destructive actions. Task 4 requires special handling as it is applied to remove the hazardous part. It has no demand and no revenue. However, in order to solve the mathematical model in less time, it is taken as $k = 2$ for hazardous parts. Only the duration and the cost of the task are taken into account for these parts. If task 1 is performed with non-destructive action ($k = 1$), the task duration is 9 min, the unit revenue is 18 units / part and the task cost is 2080 currency unit. If the destructive action ($k = 2$) is applied, the duration of the task is 7 min, the unit revenue is 12 units / part, and the task cost is 1440 currency unitg. Since the part will be recycled in non-destructive action, weight and recyclable percentage rates should be known when calculating the total revenue. The weight of the part 1 is 0.8 kg, and the recyclable percentage of this weight is 1 kg. In other words, all 0.8 kg is recyclable. The total revenue for both actions is calculated according to the amount of demand, which is 620 units.

Based on the priority levels, the state-of-the-art LP/MIP solver CPLEX (version 10.2) is used to solve the formulations on Intel(R) Core(TM) i3-5005U CPU, 2.00 GHz equipped (with 8 GB RAM).

Firstly, the results obtained from the proposed GP approach and then the proposed FGP were given.

3.2 The results of the proposed pre-emptive GP

For the proposed GP approach, it was assumed that the disassembly manager determined the priorities among goals and priority values as follows:

Precise goal 1: The total net recovery profit value should be equal or greater than 6000 currency unit ($\underline{TNP} = 6000$).

Precise goal 2: The total number of parts to be recycled ($\underline{TRC}$) should be equal or greater than 1200 unit $(\underline{TRC} = 1200)$.

Precise goal 3: The cycle time should not exceed 12 min ($\bar{C} = 12$); Considering 20 working days and the highest amount of demand, C was calculated according to the formulation given in Güngör and Gupta, 2002). The values of e^-, g^-, h^+ can be illustrated in Figure 3.

The example problem was solved primarily for the first goal, i.e. to maximize the TNP, and e^- was found to be zero. It means that TNP is larger than 6.000 currency unit (TNP =6702.900) and this goal is achieved. $e^-$was fixed at zero by using a new constraint. Then, the model is solved again with the objective of maximizing the total number of parts to be recycled.

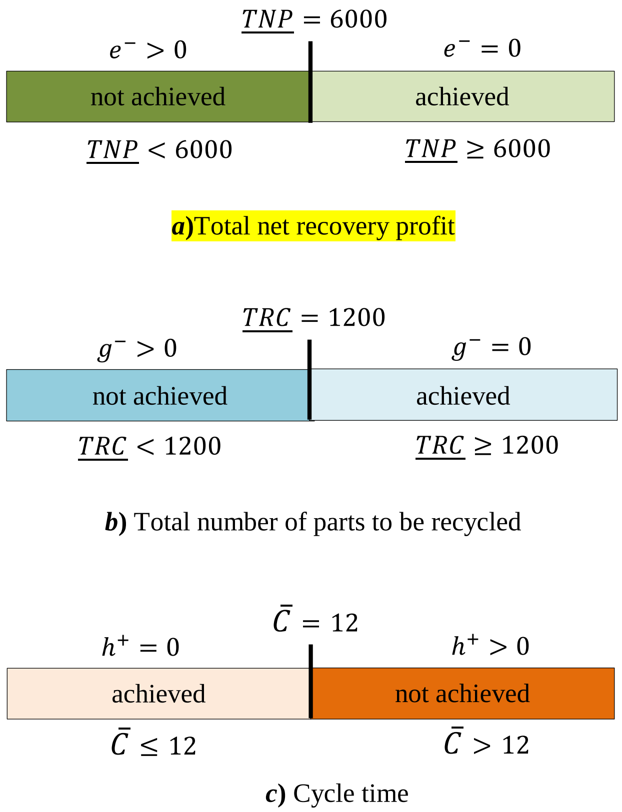

Figure 3. Achievement of three precise goals, separetely.

The negative deviational g^- was calculated as be zero in the solution. This shows that the second goal was achieved as well as the first goal, that is, the TRC is greater than 1200 ($TRC = 1427.900$). g^- was fixed at zero by using a new constraint. The model is solved again to minimise the sum of h^+ of the cycle time.

In the final solution, the objective value was found to be one and the third goal is not achieved. The disassembly line will be run at 12+1=13 min. Task and action assignments obtained with the last solution of the model are given in Table 2. According to the Table 2, the layout of the disassembly line is shown in Figure 4.

Table 2. Task and action assignments with precise goals

Worksation	Task	Action	Workload
1	1	1	9
2	2	2	8
3	4	-	10
4	3, 6	1, 2	13
5	5	2	8

As shown in Table 2 and Figure 4, the disassembly line consists of five workstations. Tasks 7 and 8 have were not performed, so parts 7 and 8 were not removed. The product enters the disassembly line as a whole and is divided into part / parts at each station. Provided that three precise goals are met, information on which task will be assigned to which station and with which action the tasks will be carried out are obtained as a result of the solution of the proposed GP model. For example, task 1 with two alternative actions at station one is performed with non-destructive action. At station five, task 3 is performed with non-destructive action and task 6 with destructive action.

Three precise goals can be prioritized according to 3! = 6 different scenarios, and the DM can solve each scenario with the proposed pre-emptive GP model to perform a sensitivity analysis. The sample problem has been solved for 6 different scenarios. It is obtained as the average CPU time of the problems is less than 1 second. The results are summarized in Table 3. Table 3 consists of eight rows and eight columns. The rows show the scenarios. The first column shows the scenario number, the following three columns show priority rows, the fifth column shows the unsatisfied goal, and the following three columns show the TNP, TRC and C values obtained from the scenarios, respectively. In each row, the names of the prioritized goals, and below each goal, the deviation values obtained as a result of the solution are given.

According to Table 3, only TNP in two scenarios, only TRC in two scenarios and only C goals in two scenarios are unsatisfied. The DM has to choose one of the scenarios with less total net recovery profit, fewer total number of parts to be recycled, or longer cycle time, depending on the situation.

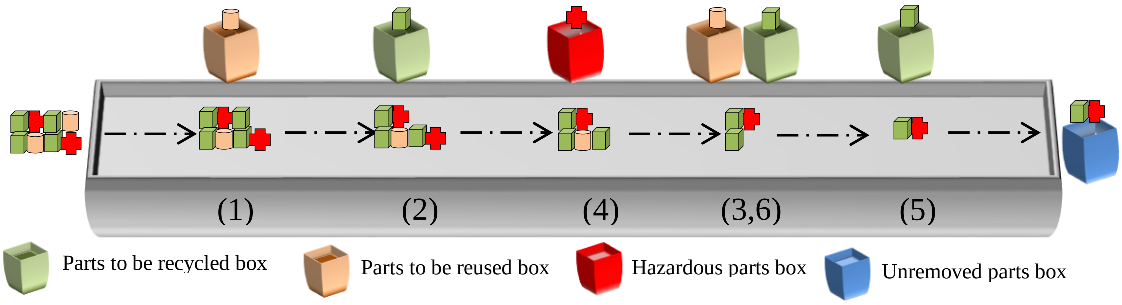

Figure 4. The layout of the disassembly line of the example problem with precise goals

Table 3. Sensitivity analysis according to the priority order of the precise goals

Scenario	Priority 1	Priority 2	Priority 3	Not achived	TNP	TRC	C
1	TNP $e^-=0$	TRC $g^-=0$	C $h^+=1$	C	6702.9	1427.9	13
2	TNP $e^-=0$	C $h^+=0$	TRC $g^-=90.5$	TRC	7464.9	909.5	12
3	TRC $g^-=0$	TNP $e^-=0$	C $h^+=1$	C	6702.9	1427.9	13
4	TRC $g^-=0$	C $h^+=0$	TNP $e^-=1389.1$	TNP	4610.9	1315.9	12
5	C $h^+=0$	TNP $e^-=0$	TRC $g^-=90.5$	TRC	7464.9	909.5	12
6	C $h^+=0$	TRC $g^-=0$	TNP $e^-=1389.1$	TNP	4610.9	1315.9	12

3.3 The results of the proposed FGP

The same disassembly manager now wants to balance the disassembly line with uncertain goals and defines the following fuzzy goals and priorities:

Fuzzy goal 1 : The total net recovery profit value should be approximately greater than or equal to $\overline{TNP} = 8000$ with a lower tolerance limit of $\underline{TNP} = 2000$.

Fuzzy goal 2: The total number of parts to be recycled value should be greater than or equal to $\overline{TRC} = 1400$ with a lower tolerance limit $\underline{TRC} = 300$ unit.

Fuzzy goal 3: The cycle time value should be with a lower bound limit $\underline{C} = 10$ and with an upper tolerance limit function 0 indicates that the purpose is not met in any way and 1 indicates that it is completely met. Achievement levels of the goals can be showed in Figure 5, Figure 6 and Figure 7.

The results obtained by solving the proposed FGP approach by considering the above priorities are given in Table 4 and the placement of the disassembly line in Figure 8. $\bar{C} = 16$.

The variables are defined on a scale between 0 and 1. The membership function values are found according to the values of the variables (1-variable value). Membership function 0 indicates that the purpose is not met in any way and 1 indicates that it is completely met.

The results obtained by solving the proposed FGP approach by considering the above priorities are given in Table 4 and the placement of the disassembly line in Figure 8.

According to Table 4 and Figure 8, the disassembly line consists of four stations, tasks 7 and 8 have not been performed as in the proposed pre-emptive GP, and these parts have not been removed. Under achievement variables e^- ve g^- are calculated as zero which represent full-achievement of the total net recovery profit goal and total number of parts to be recycled goal, respectively. So, TNP is greater than 8000 and TRC is greater than 1400 ($TNP > 8000$ and $TRC > 1400$). However, under achievement variable h^- is calculated as 0.833 which means the cycle time goal is level achieved with the membership value of 0.167 (1-0.0.833). The cycle time is 15 min.

As in Preemptive GP, three goals are listed according to 3! = 6 different scenarios. Each scenario have been solved with the proposed pre-emptive FGP model in order to perform sensitivity analysis. According to the results, the average CPU time of the problems is less than 1 second. The results obtained are given in Table 5.

Table 5 is arranged like Table 4 and only the expression 'level-achieved' goal is used instead of 'not achieved' According to Table 5, it is observed that all goals are fully achieved in four scenarios and level achieved in two scenarios. TNP is fully achieved in the scenarios where it has the first and second priority (1st, 2nd, 3rd, and 5th scenarios). Accordingly, in two scenarios, it has the third priority and is level achieved with a membership function value of 0.367. When TRC has the first and second priority in the 1st, 3rd, 4th and 6th scenarios, it is fully-achieved, and when it has the third priority in the second and fifth scenarios, it is the level achieved with the 0.473 membership function. When C has the first and second priority in four scenarios, it is fully achieved, and when it has the third priority in two scenarios, it is level achieved with 0.167 membership function.

The upper and lower bounds for goals of the illustrative example provide the DM to accept either greater total net recovery profit and total number of parts to be recycled, longer cycle time, or greater total net recovery profit, shorter cycle time, less total number of parts to be recycled or greater total number of parts to be recycled, shorter cycle time, less total net recovery profit. On the other hand, the DM can re-set the lower and upper limit values of the goals to obtain better alternatives. This is completely related to the policy that the DM will follow according to the circumstances, and it may change.

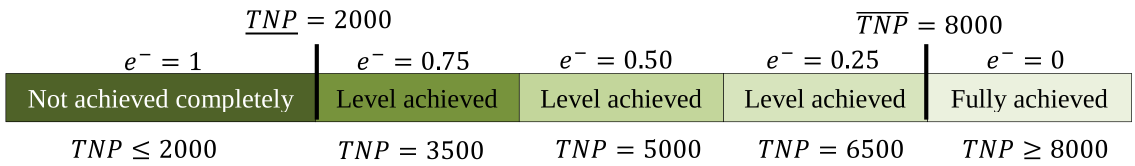

Figure 5. Achievement levels of the total net recovery profit goal.

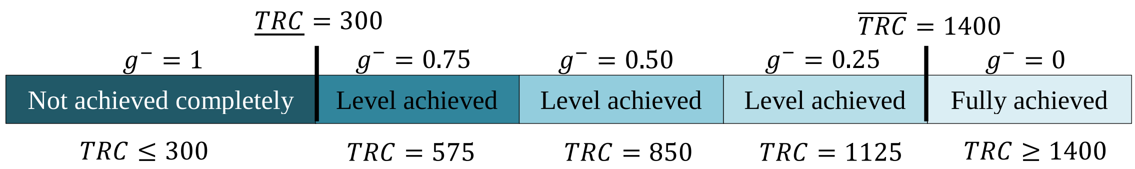

Figure 6. Achievement levels of the total number of parts to be recycled goal.

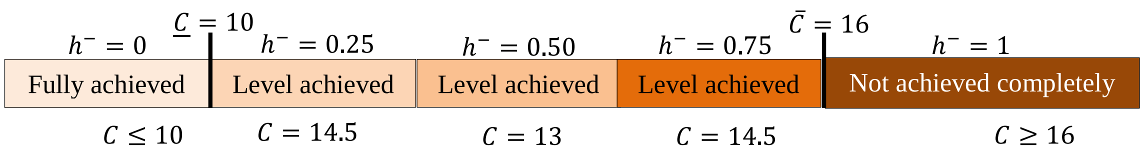

Figure 7. Achievement levels of the cycle time goal.

Table 4. Task and action assignments of the illustrative example with fuzzy goals

Worksation	Task	Action	Workload
1	1	1	9
2	2, 3	2, 1	14
3	4	-	10
4	5, 6	2	15

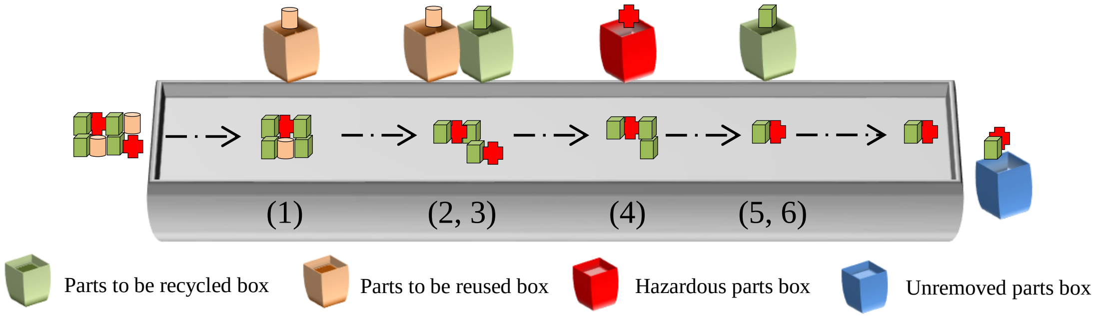

Figure 8. The layout of the disassembly line of the example problem with precise goals

Table 5. Sensitivity analysis according to the priority order of the fuzzy goals

Scenario	Priority 1	Priority 2	Priority 3	Level-achieved Goal	TNP	TRC	C
1	TNP $e^-=0$	TRC $g^-=0$	C $h^-=0.833$	C	9200	1427.5	15
2	TNP $e^-=0$	C $h^-=0$	TRC $g^-=0.527$	TRC	9176	820.3	10
3	TRC $g^-=0$	TNP $e^-=0$	C $h^-=0.833$	C	9200	1427.5	15
4	TRC $g^-=0$	C $h^-=0$	TNP $e^-=0.633$	TNP	4202	1427.5	10
5	C $h^-=0$	TNP $e^-=0$	TRC $g^-=0.527$	TRC	9176	820.3	10
6	C $h^-=0$	TRC $g^-=0$	TNP $e^-=0.633$	TNP	4202	1427.5	10

Conclusion

Disassembly is one of the important steps of the recovery process, and the places where it is efficiently carried out are disassembly lines. If there are hazardous parts in the disassembly of the products on the disassembly lines, these parts should be made with special handling and one or more objectives are tried to be optimized. In real-life applications, multiple conflicting goals are taken into account at the same time to achieve effective and realistic solutions. Some goals can easily be set as precise goals by DM. However, some goals should be set as ambiguous goals because these goals can be imprecise, vague, or uncertain. In this paper, first of all, an IP formulation that takes into account the DLBP-Z problem have been proposed. Later, a preemptive GP model for precise goals and an FGP model for imprecise goals have been proposed in solving the problem by adhering to this formulation. The proposed GP and FGP models are the first MCDM approaches applied for this problem. Three conflicting goals have been taken into account.

Through a numerical example, the proposed approaches have been tested and goal programming formulations have been shown to be valid and useful. One of these approaches can be adopted by DM according to the decision environment. The proposed approaches provide flexibility to DM by considering multiple choice of goals and priorities.

This paper may guide recovery facilities in meeting environmental laws declared by the government, such as "take-back policies," and ensuring the efficiency of the facility. However, This paper is limited to some assumptions to balance the straight and single product-type disassembly lines with deterministic parameters such as demand, time, cost. It is also limited to optimize three goals, namely total net recovery profit value, the number of parts to be removed for recycling and cycle time.

According to these limitations, there are several interesting directions for future research about problem as follows: In DLBP-Z, goal programming approaches can be applied by taking into account mixed model products and/or different layouts such as u-type, parallel and two-sided. Parameters such as task times and demand estimates can be evaluated as fuzzy. New goals such as reducing the number of stations or decreasing the total cost of the task or increasing the number of parts to be removed for reused can be added or replaced with existing goals. Resource savings can be achieved by ensuring that tasks performed with common destructive or non-destructive actions are assigned to the same stations. In this way, goals can be improved. Due to the combinatorial structure of DLBP-Z, heuristic approaches can be developed for the solution of medium and large sized problems.

Conflict of interest

Authors decare that there is no conflict of interest.

Similarity rate (iThenticate): %16

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