# Multi-Objective Optimization Model for an Integrated Disassembly Line Balancing and Green Vehicle Routing Problem

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**Abstract**

Today, serious environmental problems arise with overconsumption. To obtain maximum benefit from the recycling activities depends on the effective and robust design of the disassembly lines. In addition to this, the distribution plan of products to be recycled is as important as the disassembly process. Therefore, it is important to handle these two problems simultaneously. This paper includes the integrated optimization of the disassembly line balancing problem and the multi-objective green vehicle routing problem for the first time. The integrated problem is formulated as a Multi-Objective Mixed Integer Linear Programming. The objectives of the model consist of minimization of total $CO_2$ emission and minimization of the total cost. This proposed model could provide to decision makers flexible solutions for simultaneous optimization regarding environmental and economic aspect by considering potential situations that take into account in supply chain management and help to make strategic decisions as well.

**Keywords**
Disassembly Line Balancing, Green Vehicle Routing Problem, Multi Objective Optimization, Environmental Considerations, Sustainable Logistics.

## 1. Introduction

With the rapid development of science and technology, the amount of consumption is increasing constantly. The increase in the amount of consumption also enhances the number of end-of-life (EOL) products. EOL products contain a substantial amount of renewable resources. For this reason, it is thought that the most effective way to protect nature and prevent pollution is to recycle these products with the right planning. Incorporating recycling in the existing supply chain structures provides various benefits such as recoverable raw materials, energy and economic savings. Disassembly line balancing problem (DLBP) ensures that remanufacture valuable components or recycle of materials (Tang et al. 2002; Zussman and Zhou 1999). To gain the maximum benefit from the recycling activities depends on the design of the disassembly lines.

The valuable components are separated from waste products with the disassembly process. Two commonly considered complications in the scope of DLBP are complete and partial disassembly. While all components and parts are disassembled in the complete disassembly process, the hazardous or high-value parts are disassembled in the partial disassembly process. For this reason, the environmental impacts are minimized while the disassembly profit is maximized in the partial mode (Wang et al., 2019). Thus and so, the disassembly operation enables the economic and environmental efficiency of the recycling activities, ensuring high quality and decreasing various risks of the process (Glöser-Chahoud et al. 2021).

Components obtained with the disassembly process are accepted as raw materials for different products. The distribution of components to the customers for the purpose of the remanufacturing is as important as the disassembly process. Thus, the vehicle routing problem (VRP) occupies an important position in the distribution plan of products to be recycled (Kenger et al., 2020). In the logistics sector, especially road transportation is a type of transport that causes most of the environmental problems such as gas emissions and fuel consumption. With the rise in environmental awareness, the use of the Green Vehicle Routing Problem (GVRP) in the distribution of disassembled components for recycling has been gain importance.

Planning and improving the recycling processes are required, the same as finding the optimum distribution plans for disassembled parts. This creates the need for the optimization of DLBP and GVRP to be ensured simultaneously. This paper contains the integrated optimization of the Disassembly Line Balancing Problem (DLBP) and the Multi-Objective Green Vehicle Routing Problem (MOGVRP) for the first time. The problem has two objectives for the distribution plan of the disassembled parts. The first objective is the minimization of total $CO_2$ emissions. The second objective is the minimization of the total cost consists of the cost of opening workstations on the disassembly line, disassembly cost of the components and transportation cost.

This paper demonstrates its originality by considering the environmental benefits and taking into account the economic aspect in its integrated structure consisting of disassembly line and the vehicle routes. In this way, a multi-objective mathematical model is proposed by considering both environmental effects and economic purposes. The integrated model is developed as a Mixed-Integer Linear Programming (MILP).

The remainder of the paper is organized as follows. In Section 2, the relevant DLBP and GVRP literature is summarized. Section 3 presents the problem definition and the proposed MILP model. Finally, conclusions are given in Section 4.

## 2. Literature Review

This section contains a summary of studies conducted in two main areas, DLBP and GVRP. The following subsections present a concise review of the related studies in each area.

### 2.1 Disassembly Line Balancing Problem

In the existing literature, most of the investigations on the DLBP are focused on complete disassembly. Güngör and Gupta (2001) introduced the DLBP and proposed a model to decrease the task failure effects. The PDLBP was first handled by Altekin et al. (2003). Altekin et al. (2008) formulated the first MILP for the profit-oriented DLBP. Bentaha et al. (2018) handled the profit-oriented DLBP by considering disassembly, the presence of dangerous parts, and the uncertainty of the processing times of disassembly tasks. The method developed for problem-solving consists of a two-stage stochastic Linear Mixed Integer Program and the Sampling Average Approximation (SAA) and Min-Max formulation and an Upper Bound Mixed Integer Program. Wang et al. (2019) proposed a PDLB that aims to disassemble only hazardous parts. They designed a new Multi-objective Genetic Simulated Annealing algorithm. Zhu et al. (2020) investigated a partially parallel disassembly line to disassemble the different products simultaneously. They proposed a new Multi-Objective Hybrid Group Neighborhood Search algorithm for the problem. Wang et al. (2020) proposed a partial destructive disassembly line balancing model by taking into account the uncertainties of corrosion and deformation of the parts.

### 2.2 Green Vehicle Routing Problem

An important study, which can be considered as one of the firsts on GVRP, was carried out by Erdoğan and Miller-Hooks (2012). The authors combined alternative fuel vehicles with the VRP. To solve the problem, two heuristic algorithms, Adapted Savings Algorithm, introduced by Clarke and Wright (1964), and Density Based Clustering Algorithm, are proposed. Many articles taken place in the scope of GVRP consider a single objective. In progress of time, the studies that involve multi-objective optimization in which more than one objective function is considered, have gained importance. Demir et al. (2014) created a model by considering two conflicting objective functions, fuel consumption and driving time. This model is one of the first examples of the MOGVRP. The authors proposed an Adaptive Large Variable Neighborhood Search (ALNS) algorithm for the problem. Habibi et al. (2017) integrated the problem of pick-up product and DLBP into the reverse logistics network design. Budak (2020) handled the DLBP and the sustainable logistics network design problem as a whole in her study.

No MOGVRP study which takes into account the disassembly of recycled products and deals with the distribution of the obtained components has been encountered in the literature. There is only one study related to the integrated DLBP and VRP in the literature. Kenger et al. (2020) modelled the integration of the complete DLBP and VRP as single-objective optimization in their study. However, in their paper, there is no MOGVRP approach designed by considering environmental effects. Thus, this paper is proposed a practical mathematical model which considers both environmental effect and economic contribution for supply chain managers. Logistic companies may use the proposed model by manipulating their own data in their distribution plans. The aim of this paper is that present the proposed integrated mathematical model to solve DLBP and GVRP simultaneously.

## 3. Problem Definition and Mathematical Formulations

In this paper, an integrated DLBP and GVRP is proposed. The process starts with the assignment of parts of the waste product to the workstations in the disassembly center reasonably. These parts need to be transported to the collection centers by homogeneous vehicles that travel between the collection centers and then go back to the distribution center. The tasks that come from the disassembly center to the collection centers go remanufacturing centers or disposal. Our model deals with the distribution from the disassembly center to the collection centers. Figure 1 shows which part of the network the proposed mathematical model focuses on.

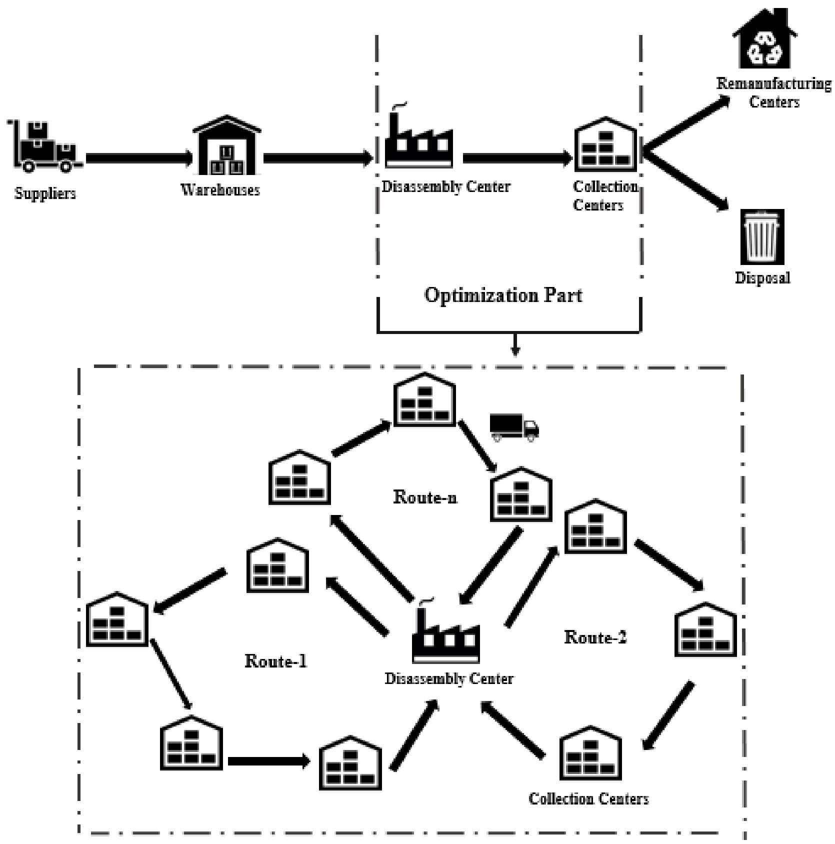


Figure 1: The illustration of the proposed integrated problem

### 3.1 Assumptions of the Integrated Model

In the model, two objectives are determined to minimize the total CO2 emissions and the total costs. In line with these objectives, the proposed model is designed as a Multi-Objective MILP model. Assumptions of the model are given as follows:

- A task cannot be split among two or more workstations.
- A single type of discarded product is disassembled.
- All disassembled products are distributed to the collection centers.

- Demand quantities for the collection center for a component are deterministic and must be fully satisfied.
- All workstations can process any of the tasks and all have the same associated costs.
- A disassembly task may result in the removal of one or more parts (or subassemblies).
- Task times and costs are deterministic and independent of the station at which tasks are performed.
- Homogeneous fleet is used.
- Precedence relations of disassembly tasks are predefined with precedence matrix.
- Each vehicle starts and ends the route at the disassembly center and each collection center can be visited by a specific vehicle.
- The total demand of collection centers allocated to a route should not surpass the vehicle capacity.
- The distances between the disassembly center and collection centers are deterministic.

## 3.2 Mathematical Model

The mathematical model is presented below.

**Sets and Indices**:

*CC:* set of collection centers $CC = \{2,3, \ldots., K\}$
*W:* set of workstations
*V:* set of vehicles
*N:* node size N={1,2,….,K+1} (1 and K+1 indicate the disassembly center)
*P:* the disassembly precedence relationship matrix for the disassembly tasks, if the task i immediately precedes the task j, $p_{ij}$=1, else, $p_{ij}$=0
*i,j:* disassembly task index i,j={1,2,…,I}
*s:* station index s={1,2,…,S}
*k,r:* collection center index k,r={2,…,K}
*v:* vehicle index v={1,2,…,V}

**Parameters**:

$t_i$: the task time of the disassembly task i
*U:* number of workstations (upper bound)
$d_k$: demand for collection center k
*V:* the maximum number of vehicles that can be used
$dis_{rk}$: distance between disassembly center and collection center or between collection centers r and k
$\varepsilon_{rk}$: $CO_2$ emission (in kg)between collection centers r and k per km
*M:* A sufficiently large number
*F:* fixed cost to open a workstation in the disassembly line
*T:* transportation cost from collection center r to collection center k
$c_i$: cost of the disassembly task i
*Q:* the loading capacity of each vehicle
*WT:* total working time
*CT:* cycle time

**Decision Variables:**

$L_{kv}$: load of the vehicle v upon leaving collection center k

$Y_{is}$: $\begin{cases} 1, & \text{if the disassembly task i is assigned to the workstation s} \\ 0, & \text{otherwise} \end{cases}$

$Z_{rkv}$: $\begin{cases} 1, & \text{if vehicle v travels from collection center to collection center or between collection centers} \\ 0, & \text{otherwise} \end{cases}$

$G_s$: $\begin{cases} 1, & \text{if the workstation s is opened} \\ 0, & \text{otherwise} \end{cases}$

**Objective Functions**:

$$\min \sum_{\substack{r,k\in N \\ r\neq k}} \sum_{v\in V} \varepsilon_{rk} * dis_{rk} * Z_{rkv} \quad (1)$$

$$\min \sum_{s=1}^{S} F*G_s + \sum_{i=1}^{I} \sum_{s=1}^{S} c_i*Y_{is} + \sum_{\substack{r,k\in N \\ r\neq k}} \sum_{v\in V} T*dis_{rk}*Z_{rkv} \quad (2)$$

**Constraints:**

1. **Precedence Constraints**

$$\sum_{s=1}^{S} (s*Y_{is}) - \sum_{s=1}^{S} (s*Y_{js}) \leq 0 \qquad \forall p_{ij}=1 \ i,j\in P \quad (3)$$

2. **Task Assignment Constraints**

$$\sum_{s=1}^{S} Y_{is} = 1 \ \forall i \quad (4)$$

3. **Workstation Constraints**

$$G_s \geq G_{s+1} \quad \forall s, s=1,2,\dots S-1 \quad (5)$$

$$Y_{is} \leq G_s \quad \forall i\in\{1,2,\dots,I\}, \forall s \in\{1,2,\dots,S\} \quad (6)$$

$$\sum_{s=1}^{S} G_s \geq \frac{\left(\sum_{i=1}^{I} \sum_{s=1}^{S} t_i*Y_{is}\right)}{CT} \quad (7)$$

$$\sum_{s\in W} G_s \leq U \quad (8)$$

4. **Cycle Time Constraints**

$$\sum_{i=1}^{I} (t_i*Y_{is}) \leq CT*G_s \quad \forall s\in\{1,2,\dots,S\} \quad (9)$$

$$CT = \left( WT / \left( \sum_{k=2}^{K} d_k \right) \right) \quad (10)$$

5. **VRP Assignment Constraints**

$$\sum_{v\in V} \sum_{\substack{k=2 \\ r\neq k}}^{K+1} Z_{rkv} = 1 \ \forall r\in CC \quad (11)$$

**6. Flow Conservation Constraints**

$$\sum_{k \in RC} (Z_{1kv}) = 1 \quad \forall v \in V \tag{12}$$

$$\sum_{\substack{r=1 \\ r \neq h}}^{K} Z_{rhv} - \sum_{\substack{k=2 \\ k \neq h}}^{K+1} Z_{hkv} = 0 \quad \forall h \in CC, \ \forall v \in V \tag{13}$$

$$\sum_{r \in RC} Z_{r,K+1,v} = 1 \quad \forall v \in V \tag{14}$$

$$\sum_{v=1}^{V} \sum_{k=2}^{K} Z_{1kv} \leq V \tag{15}$$

**7. Capacity Constraints**

$$L_{rv} + d_k * Z_{rkv} - Q*(1 - Z_{rkv}) \leq L_{kv} \quad \forall r, r=1,2,\ldots,K, \ \forall k, k=2,\ldots,K+1, \ r \neq k, \ \forall v \in V \tag{16}$$

$$L_{kv} \leq Q \quad \forall k \in CC, \forall v \in V \tag{17}$$

$$L_{1v} = 0 \quad \forall v \in V \tag{18}$$

$$L_{kv} \geq 0 \quad \forall k \in CC, \ \forall v \in V \tag{19}$$

$$Y_{is}, G_s, Z_{rkv} \in \{0,1\} \quad \forall i,s,r,k,v \tag{20}$$

Equations (1) and (2) represent objective functions. Eq. (1) minimizes the total $CO_2$ emission. Eq. (2) minimizes the total cost. The first term of Eq. (2) is the total opening cost of disassembly workstations. The second term is the total cost of performing the assigned disassembly tasks. The third term is the total travelling cost of vehicles. Eq. (3) indicates the precedence constraints among all tasks in the disassembly line. Eq. (4) imposes the assignment of a disassembly task to one workstation, exactly. Equations (5) - (8) indicate workstation constraints. Eq. (5) provides that workstations are opened in sequence and that an empty workstation is not allowed. Eq. (6) ensures that a workstation opens if and only if a task is assigned to that workstation at least. Eq. (7) gives a theoretical lower bound on the total number of workstations to be used. Eq. (8) guarantees that the total number of workstations to be opened cannot exceed the maximum number of workstations. Cycle time constraints are included in Equations (9) and (10). Eq. (9) ensures that the disassembly time of each station in the disassembly line does not exceed the cycle time. Eq. (10) indicates the calculation of the cycle time. The cycle time in disassembly centers is calculated by dividing the total working time by the total demand for collection centers. Since the working time and total demand are known. Eq. (11) is general assignment constraints for the VRP. It guarantees that each collection center must be visited exactly once by one vehicle. Eq. (12) - (14) give the flow constraints that ensure that each vehicle leaves the disassembly center 1, departs from a collection center it visited and finally returns to the disassembly center given by node K+1. Eq. (15) specifies that up to V routes go out of the disassembly center. Eqs. (16) and (17) are the capacity constraints. Eq. (18) initializes the load variables, $L_{kv}$ to zero for all vehicles at the disassembly center. Eq. (19) states that decision variables cannot be negative. Eq. (20) represents the binary variables.

## 4. Conclusion

With increasing consumption amount continuously, recycling is gaining more and more importance. For this reason, disassembly, which is one of the most important stages of recycling, comes to the fore. After the disassembly process, planning the distribution of the obtained components is also very important for supply chain companies. It is thought that modelling and solving complex optimization problems can provide significant benefits to such decision makers.

With the growing importance of sustainable supply chains, companies have considered green logistics activities. For this reason, strategic decisions should be made by simultaneously considering economic and environmental aspects. With this paper, the opportunities of the integrated DLBP and GVRP structure, which is created by considering both economic factors and environmental effects, are revealed for decision makers. This study focuses on Integrated DLB and GVRP for the first time. The model respectively determines: (i) the total number of opened workstations in disassembly center (ii) optimal task assignments to workstations in disassembly centers (iii) total workstation times and idle times of each workstation (iv) optimal distribution routes for all vehicles.

This paper provides a recent and robust perspective for to be done scientific researches in the future. On the basis of the results obtained, various multi-objective solution methods such as Nondominated Sorting Genetic Algorithm (NSGA), NSGA II and Particle Swarm Optimization (PSO) can be developed for large-size instances. A heterogeneous fleet can be considered to evaluate the model under different circumstances.

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