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A Reverse Supply Chain Model to Reduce Waste of Solar Panel in Ho Chi Minh City, Vietnam

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Abstract. *The reverse supply chain (RSC) recently attracted many Vietnamese authorities, enterprises and academia owing to the rise of concern on the environment and regulations of waste process. Along with rapid development, Vietnamese manufacturing network has become tightly strained when the end-of-life (EOL) items are not taken back by their manufacturers but end up being processed disorderly in different local businesses. A distressing example is the waste of imported solar panels in Vietnam. Since the number of solar panels has grown steadily in Vietnam recently, we speculate that the network flows of EOL solar panel of Vietnam will be very large and complex in a few years. In order to help Vietnamese government establish efficiently RSC, our paper will apply the mixed-integer linear programming (MILP) and demonstrate an optimized solution for the RSC of EOL solar panel in Ho Chi Minh City. Indeed, via our collected data from current financial market of Ho Chi Minh city, our MILP shows that the optimal cost-reduction is 11219 USD, even with limited constraints of only two landfills and very few collection facilities in Ho Chi Minh city at the moment. This result of our proposed RSC demonstrates that a significant profit is definitely possible when the number of collection facilities in Ho Chi Minh city increase in the future. Also, our MILP approach is flexible for decision-makers to achieve a satisfactory solution.*

Keywords

End-of-life, solar panel, reverse supply chain, mixed-integer linear programming.

1. Introduction

Solar energy is currently one of the widely used energy sources in Vietnam, in which solar panels are the main technology. By the end of 2020, the total installed capacity of solar power nationwide in Vietnam has reached about 19,400 MWp (equivalent to 16,500 MW) [1]. This number is accounted for about 25% of the total installed capacity of the national power system and will continue to grow strongly in the future, reaching 29.000 MWp in 2030 and 170.000 MWp in

2050 [2]. With an increase in installations, the number of solar panels reaching the end of life (EOL) cycle will steadily increase. On average, a solar power source with a capacity of 1 MWp will generate nearly 70 tons of wastes after about 20-25 years from the beginning of power generation [2]. Thus, according to the forecast of the Solar Energy Development Strategy, the amount of waste solar panels will be about 2 million tons by the end of 2030, which is predicted 12 million tons in 2050 [3].

Nonetheless, under the various categories of e-waste, a solar panel is one of the most critical waste streams, as it contains rare-earth elements, such as selenium, tellurium, gallium, molybdenum, and indium [4]. Disposal of solar batteries, if improperly buried, can cause soil and water pollution by generating heavy metals or toxic emissions. In the event of a fire, the toxic components contained in solar panels have the potential to harm human health [5]. If not managed, collected and recycled, then almost surely with such a large quantity, solar panel's waste will cause serious environmental pollution and huge waste of natural resources [6]. For this situation, many countries require and encourage manufacturers to have a recycling plan for their products. In order to achieve sustainability of a solar panel in large scale deployments, it is important to establish low-cost recycling technologies for the growing solar panel industry, in parallel with rapid commercialization of these new technologies [7].

In addition to the improvement of solar cell recycling technology, we need to pay attention to the reverse supply chain (RSC) for solar panels so that we can promptly prevent factors that adversely affect the environment due to electricity waste and optimize resources for the system [8].

In terms of RSC network design, one of the most prior studies was conducted in [9], which determines how to handle used products and reduce the total cost of network. This research used mixed-integer linear programming (MILP) in the model and its results are confirmed through a case study of a copier company in Venlo, Netherlands.

Similarly, a national recovery network for the e-waste in Portugal was investigated in [10]. They applied the MILP model to seek the most optimal locations for collection and sorting facilities. In [11], a reverse logistics system with different collecting scenarios for electronic waste in Turkey was built using the MILP model. This study aimed to minimize the total cost of the RSC system. Noticeably, the model included various categories of storage and recycling centers. Recently, in [12], MILP was applied to maximize profit in an RSC system for used refrigerators.

In literature, the uncertain parameters have been recognized as the key properties of RSC systems, e.g. in [13–17]. The conclusion indicates that the uncertain parameters of quantity and quality of returned products have influence on the practical applications of RSC systems. Authors in [16] applied a stochastic programming model to an RSC system to maximize the profit in the case study regarding the electronic waste recycling industry in Turkey. The considered uncertain parameters were transportation costs and the quantity and quality of returned products.

In this study, we will propose a novel RSC model that contributes to reducing e-waste in the environment and helps reusing, remanufacturing, recycling and disposal of EOL solar panels. Note that, since the waste of EOL solar panel is an emerging problem, our custom RSC model is a prospective model for a problem occurring in future. Hence, to our knowledge, our RSC model is the first RSC model for EOL solar panels in Ho Chi Minh city.

Also, for simplicity, we neglected the remarketing cost from our RSC in this paper, since our aim is to focus on the industrial process of EOL solar panels in our prospective RSC model.

Since MILP is a popular method for RSC in literature, this paper will apply MILP and propose an optimized solution for an RSC of end-of-life (EOL) solar panel in Ho Chi Minh City. This MILP method has emerged as a potential method for efficient RSC optimization because of its flexibility in the processing of uncertain information from managers or experts.

The rest of the paper is organized as follows. Section 2 discusses the design of an RSC network. Section 3 introduces the mathematical development for uncertain parameters. Section 4 illustrates the applicability of the model in practice with the case study of solar panels in Ho Chi Minh City. Section 5 then draws a conclusion.

2. Model development

In this section, let us study an RSC model for collecting EOL solar panels in Ho Chi Minh city, as illustrated in Fig. 1 and Fig. 2. In short, there are four main stages in our RSC network:

(i) Collection stage: the elements of EOL solar panels will be accumulated from many sources, e.g. electronic stores, factories, houses, etc.

(ii) Tranferring stage: the EOL elements will be transferred to disassembly centers and categorized into smaller parts.

(iii) Refurbishment stage: the reusable parts will be transported to spare markets or repair centers.

(iv) Disposal stage: the irreparable and toxic parts will be transported to disposal areas.

In our RSC model, the key elements are decision variables and parameters, as defined in Subsections 2.2 and 2.3 below.

2.1. RSC's index

The notation of RSC's index in Fig.1 are given below.

c index of collection facilities, $c = 1, \dots, C$

d index of prospective disassembly facilities, $d = 1, \dots, D$

r index of prospective repairing facilities, $r = 1, \dots, R$

l index of prospective recycling facilities, $l = 1, \dots, L$

s index of fixed spare markets, $s = 1, \dots, S$

n index of fixed primary markets, $n = 1, \dots, N$

o index of fixed landfill site, $o = 1, \dots, O$

p index of end-of-life products, $p = 1, \dots, P$

u index of reusable items, $u = 1, \dots, U$

w index of renewable items, $w = 1, \dots, W$

m index of recycling materials, $m = 1, \dots, M$

t index of toxic waste, $t = 1, \dots, T$

2.2. RSC's decision variables

The notation of RSC's decision variables in Fig.1 are given below.

$X1_{c,d,p} = \{X1_{1,1,1}, ..., X1_{C,D,P}\}$ units of end-of-life product p to be transferred from c to d

$X2_{d,r,w} = \{X2_{1,1,1}, ..., X2_{D,R,W}\}$ units of renewable item w to be transferred from d to r

$X3_{d,o,t} = \{X3_{1,1,1}, ..., X3_{D,O,T}\}$ units of toxic waste t to be transferred from d to o

$X4_{d,s,u} = \{X4_{1,1,1}, ..., X4_{D,S,U}\}$ units of reusable item u to be transferred from d to s

$X5_{d,l,m} = \{X5_{1,1,1}, ..., X5_{D,L,M}\}$ units of recycling material m to be transferred from d to l

$X6_{l,o,t} = \{X6_{1,1,1}, ..., X6_{L,O,T}\}$ units of toxic waste t to be transferred from l to o

$X7_{l,n,m} = \{X7_{1,1,1}, ..., X7_{L,N,M}\}$ units of recycling material m to be transferred from l to n

$X8_{r,s,w} = \{X8_{1,1,1}, ..., X8_{R,S,W}\}$ units of renewable item w to be transferred from r to s

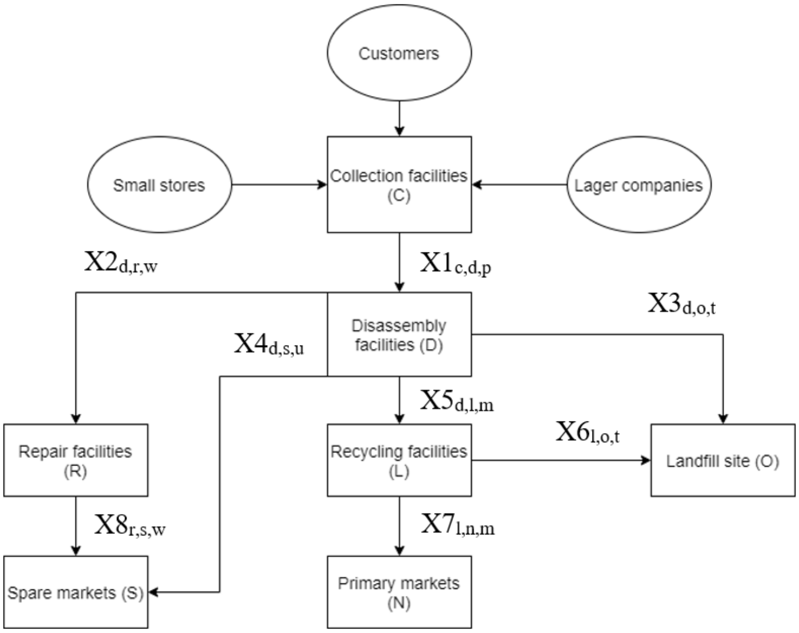
Z_d is a binary variable: $Z_d = 1$ if a disassembly facility is built at the place d and $Z_d = 0$ otherwise.

Z_r is a binary variable: $Z_r = 1$ if a repair facility is built at the place r and $Z_r = 0$ otherwise.

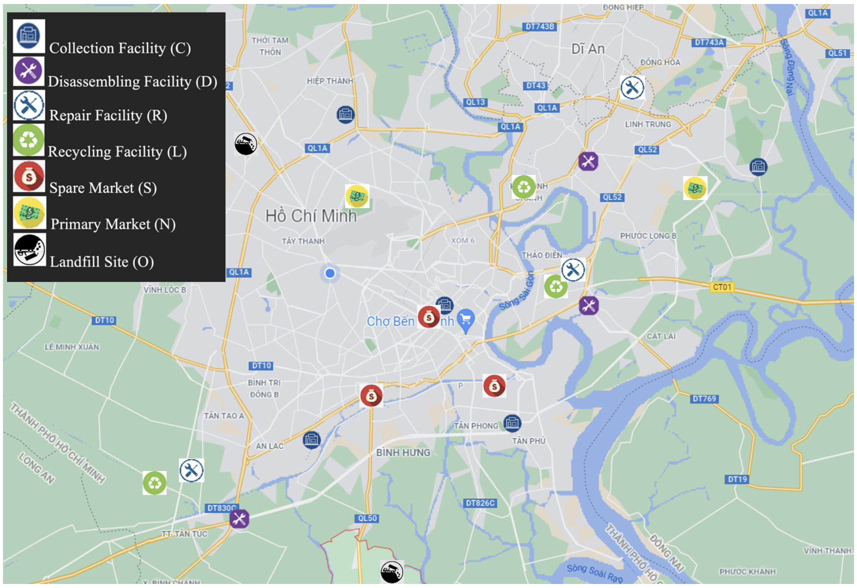
Z_l is a binary variable: $Z_l = 1$ if a recycling facility is built at the place l and $Z_l = 0$ otherwise.

2.3. RSC's parameters

The notation of RSC's parameters in Fig.1 are given below.



Hình 1: Diagram of solar panel RSC network.



Hình 2: Prospective facilities [18] for the case of solar panel RSC network in Ho Chi Minh city. The details are given in Tabs. 11 and 12.

$\widetilde{T}_p$ unit transportation cost ($USD) of end-of-life product $p \in P$

$\widetilde{T}_u$ unit transportation cost ($USD) of reused item $u \in U$

$\widetilde{T}_w$ unit transportation cost ($USD) of renewable item $w \in W$

$\widetilde{T}_m$ unit transportation cost ($USD) of recycling material $m \in M$

$\widetilde{T}_t$ unit transportation cost ($USD) of toxic waste $t \in T$

$\widetilde{P}_{p,d}$ unit processing cost ($USD) of end-of-life product p at disassembly facility d

$\widetilde{P}_{w,r}$ unit processing cost ($USD) renewable part w at repair facility r

$\widetilde{P}_{m,l}$ unit processing cost ($USD) of recycling material m at recycling facility l

$\widetilde{D}_t$ unit disposal cost ($USD) of toxic waste t

$\widetilde{C}_p$ unit collection cost ($USD) of end-of-life product p at collection facility c

$\widetilde{F}_d$ fixed cost ($USD) of disassembly facility d

$\widetilde{F}_r$ fixed cost ($USD) of repair facility r

$\widetilde{F}_l$ fixed cost ($USD) of recycling facility l

$\widetilde{S}_u$ unit selling price ($USD) of reusable item u

$\widetilde{S}_w$ unit selling price ($USD) of renewable item w

$\widetilde{S}_m$ unit selling price ($USD) of recycling material m

$\tilde{D}_{c,d}$ distance driven (km) from c to d

$\tilde{D}_{d,s}$ distance driven (km) from d to s

$\tilde{D}_{d,r}$ distance driven (km) from d to r

$\tilde{D}_{d,l}$ distance driven (km) from d to l

$\tilde{D}_{d,o}$ distance driven (km) from d to o

$\tilde{D}_{r,s}$ distance driven (km) from r to s

$\tilde{D}_{l,n}$ distance driven (km) from l to n

$\tilde{D}_{l,o}$ distance driven (km) from l to o

$\widetilde{N}_{p,c}$ the number of end-of-life products p (unit) at collection facility c

$\widetilde{\theta1}_{u,p}$ the ratio of reused items u obtained from p

$\widetilde{\theta2}_{w,p}$ the ratio of renewable items w obtained from p

$\widetilde{\theta3}_{m,p}$ the ratio of recycling materials m obtained from p

$\widetilde{\theta4}_{t,p}$ the ratio of toxic waste t obtained from p

$\widetilde{\gamma}_t$ the ratio of toxic waste t obtained from l

$\widetilde{\gamma}_m$ the ratio of recycling materials m obtained from l

$\widetilde{U}_{u,s}$ capacity (maximum value of u) at s

$\widetilde{U}_{w,s}$ capacity (maximum value of w) at s

$\widetilde{U}_{m,n}$capacity (maximum value of m) at n

$\widetilde{U}_{p,d}$ capacity (maximum value of p) at d

$\widetilde{U}_{w,r}$ capacity (maximum value of w) at r

$\widetilde{U}_{m,l}$ capacity (maximum value of m) at l

$\widetilde{U}_{t,o}$ capacity (maximum value of t) at o

The parameters topped with a tilde ($\tilde{}$) are unforeseen parameters. Since it is hard to collect accurate data from a fluctuating financial market at a specific time, this paper use approximated values of current market in Ho Chi Minh city. The value of RSC's parameters will be given in the Appendix section and references there-in.

3. A mathematical model

In this section, let us apply MILP to minimize the total expense of the RSC model for EOL solar panels.

3.1. Objective function

The total expense will be determined by the sum of all expenses, such as collection expenses, processing expenses, fixed expenses, transportation expenses, and disposal expenses minus the income gained from selling recovered materials or items, as shown in Eq. (1)

$$Total\,expense(E) = collection\,expenses(E1)+ processing\,expenses(E2)+fixed\,expenses(E3)+ transportation\,expenses(E4)+ disposal\,expenses(E5) - income\,(E6), \quad (1)$$

in which:

- Collection expenses (E1) is the expense that the collectors have to pay for collecting the EOL solar panels.
- Processing expenses (E2) is the expense of processing products (i.e. EOL products at disassembly facilities, renewable products at repair facilities and recycling materials at recycling facilities).
- Fixed expenses (E3) is the expense of facility maintenance in three facilities (i.e. repair facilities, recycling facilities and disassembly facilities).
- Transportation expenses (E4) is the expense of transportation in supply chain network (e.g. from collection facilities to disassembly facilities, etc.).
- Disposal expenses (E5) is the expense of toxic waste disposal at landfill sites.
- Income (E6) is the profit via selling renewable items, reusable items and recycling material.

All the expenses in Eq. (1) will be given in Eqs. (2)-(8) below. The first element of the total expenses in Eq. (1) is collection expenses (E1) that are calculated as follows:

$$E1 = \sum_{c\in C}\sum_{d\in D}\sum_{p\in P} X1_{c,d,p} \times \tilde{C}_p \quad (2)$$

The processing expenses (E2) is then influenced by many factors such as labor expenses, operating expenses and other expenses during the treatment process at some relevant facilities (i.e. disassembly facilities, repairing facilities and recycling facilities). This costs (E2) is demonstrated in the Eq. (3):

$$E2 = \sum_{c\in C}\sum_{d\in D}\sum_{p\in P} X1_{c,d,p} \times \tilde{P}_{p,d} + \sum_{d\in D}\sum_{r\in R}\sum_{w\in W} X2_{d,r,w} \times \tilde{P}_{w,r} + \sum_{d\in D}\sum_{l\in L}\sum_{m\in M} X5_{d,l,m} \times \tilde{P}_{m,l} \quad (3)$$

Thirdly, one of the most important indicators in total expenses is fixed expenses incurred in the foundation of repair facilities, recycling facilities and disassembly facilities, which is defined in Eq. (4):

$$E3 = \sum_{r\in R} Z_r \times \tilde{F}_r + \sum_{l\in L} Z_l \times \tilde{F}_l + \sum_{d\in D} Z_d \times \tilde{F}_d \quad (4)$$

The next indicator of total expenses is transportation expenses. This is a crucial expense in any supply chain network, which largely relies on transferring different kinds of goods from many various locations in a chain, as given below:

$$\begin{aligned} E4 = {} & \sum_{c\in C}\sum_{d\in D}\sum_{p\in P} X1_{c,d,p}\times\tilde{D}_{c,d}\times\tilde{T}_p + \\ & \sum_{d\in D}\sum_{r\in R}\sum_{w\in W} X2_{d,r,w} \times \tilde{D}_{d,r} \times \tilde{T}_w + \\ & \sum_{d\in D}\sum_{o\in O}\sum_{t\in T} X3_{d,o,t} \times \tilde{D}_{d,o} \times \tilde{T}_t + \\ & \sum_{d\in D}\sum_{s\in S}\sum_{u\in U} X4_{d,s,u} \times \tilde{D}_{d,s} \times \tilde{T}_u + \\ & \sum_{d\in D}\sum_{l\in L}\sum_{m\in M} X5_{d,l,m} \times \tilde{D}_{d,l} \times \tilde{T}_m + \\ & \sum_{l\in L}\sum_{o\in O}\sum_{t\in T} X6_{l,o,t} \times \tilde{D}_{l,o} \times \tilde{T}_t + \\ & \sum_{l\in L}\sum_{n\in N}\sum_{m\in M} X7_{l,n,m} \times \tilde{D}_{l,n} \times \tilde{T}_m + \\ & \sum_{r\in R}\sum_{s\in S}\sum_{w\in W} X8_{r,s,w} \times \tilde{D}_{r,s} \times \tilde{T}_w \end{aligned} \quad (5)$$

Subsequently, the highest impact on the environment is disposal expenses. The Eq. (6) below represents the formula of the disposal expenses:

$$E5 = \sum_{d\in D}\sum_{o\in O}\sum_{t\in T} X3_{d,o,t}\times\tilde{D}_{d,o}\times\tilde{D}_t + \sum_{l\in L}\sum_{o\in O}\sum_{t\in T} X6_{l,o,t} \times \tilde{D}_{l,o} \times \tilde{D}_t \quad (6)$$

Finally, the financial benefit of total RSC network gains from sales and resales of used products and recovered components at spare markets and primary markets in Fig. 1 will be described as follows:

$$E6 = \sum\nolimits_{d\in D}\sum\nolimits_{s\in S}\sum\nolimits_{u\in U} X4_{d,s,u} \times \tilde{S}_u + \sum\nolimits_{l\in L}\sum\nolimits_{n\in N}\sum\nolimits_{m\in M} X7_{l,n,m} \times \tilde{S}_m + \sum\nolimits_{r\in R}\sum\nolimits_{s\in S}\sum\nolimits_{w\in W} X8_{r,s,w} \times \tilde{S}_w. \quad (7)$$

From above components, let us summarize the final total expense as follows:

$$E = E1 + E2 + E3 + E4 + E5 - E6 \quad (8)$$

3.2. Constraints

Another key factor is the constraints of the MILP model. First of all, the constraint in Eq. (9) with the purpose of balancing the amount of EOL items acquired from customers, small electronic stores and large companies must be accumulated at collection facilities:

$$\sum\nolimits_{d\in D} X1_{c,d,p} = \tilde{N}_{p,c}, \ \forall c, p \quad (9)$$

The following constraints, as illustrated from Eqs. (10)-(13), track distinct materials such as reusable items, damaged components, recyclable ingredients and toxic waste items, which are demolished, inspected and categorized into many different parts at disassembly facilities in order to transfer them to appropriate destinations. For instance, the number of reusable items transported to spare markets is verified in Eq. (10). The constraint in Eq. (11) indicates that the defective components are transported to repair facilities. The other constraints in Eq. (12-13) adequately ensure that the scale of recyclable materials and the number of toxic waste items are sent to recycling facilities and landfill sites, respectively:

$$\sum\nolimits_{s\in S} X4_{d,s,u} = \sum\nolimits_{p\in P} (\tilde{\theta 1}_{u,p} \times \sum\nolimits_{c\in C} X1_{c,d,p}), \forall c, u \quad (10)$$

$$\sum\nolimits_{r\in R} X2_{d,r,w} = \sum\nolimits_{p\in P} (\tilde{\theta 2}_{w,\,p} \times \sum\nolimits_{c\in C} X1_{c,d,p}), \forall c, w \quad (11)$$

$$\sum\nolimits_{l\in L} X5_{d,l,m} = \sum\nolimits_{p\in P} (\tilde{\theta 3}_{m,p} \times \sum\nolimits_{c\in C} X1_{c,d,p}), \forall d, m \quad (12)$$

$$\sum\nolimits_{o\in O} X3_{d,o,t} = \sum\nolimits_{p\in P} (\tilde{\theta 4}_{t,p} \times \sum\nolimits_{c\in C} X1_{c,d,p}), \forall d, t \quad (13)$$

Similarly, the constraints in Eqs. (14)-(16) below guarantee no lack of products from "sender" to "receiver". That means the number of repaired items at repairing facilities is precisely equivalent to the scale of segments delivered to spare markets in Eq. (14). In addition, Eq. (15) indicates that the multiplication between the number of recyclable components and operation efficiency $(\tilde{\gamma}_m, \tilde{\gamma}_t)$ at recycling facilities is exactly equivalent to the scale of parts transported to primary markets. Likewise, Eq. (16) shows the equivalent relationship between the inflows at recycling plants and the outflows at landfill sites:

$$\sum\nolimits_{d\in D} X2_{d,r,w} = \sum\nolimits_{s\in S} X8_{r,s,w}, \forall r, w \quad (14)$$

$$\sum\nolimits_{n\in N} X7_{l,n,m} = (\tilde{\gamma}_m \times \sum\nolimits_{d\in D} X5_{d,l,m}), \forall l, m \quad (15)$$

$$\sum\nolimits_{o\in O} X6_{l,o,t} = (\tilde{\gamma}_t \times \sum\nolimits_{d\in D}\sum\nolimits_{m\in M} X5_{d,l,m}), \forall l, t \quad (16)$$

Apart from the given constraints, the next constraints demonstrated in Eqs. (17)-(20) shows the limited size of distinct locations. Firstly, Eq. (17) indicates that the maximum size of EOL products at disassembly facilities. Secondly, Eq. (18) verifies that the capacity restriction of defective segments at repair plants. Thirdly, Eq. (19) emphasizes the capacity limit of recycled ingredients at recycling facilities. Last but not least, Eq. (20) expresses the maximum size of toxic waste items at landfill sites:

$$\sum\nolimits_{c\in C} X1_{c,d,p} \leq Z_d \times \widetilde{U}_{p,d}, \forall d, p \tag{17}$$

$$\sum\nolimits_{d\in D} X2_{d,r,w} \leq Z_r \times \widetilde{U}_{w,r}, \forall w, r \tag{18}$$

$$\sum\nolimits_{d\in D} X5_{d,l,m} \leq Z_l \times \widetilde{U}_{m,l}, \forall l, m \tag{19}$$

$$\sum\nolimits_{d\in D} X3_{d,o,t} + \sum\nolimits_{l\in L} X6_{l,o,t} \leq \widetilde{U}_{t,o}, \forall t, o \tag{20}$$

In order not to exceed market demands, the imposed constraints in Eqs. (21)-(23) are practical confirmation. Eq. (21) represents that the number of reusable items sent to spare markets should be no exceed than its market size, whereas Eq. (22) implies that the number of renewable components delivered to spare markets should be less than or equal to its demands. Likewise, Eq. (23) indicates that the number of recyclable parts transferred to primary markets should be satisfied with its market demands:

$$\sum\nolimits_{d\in D} X4_{d,s,u} \leq \widetilde{U}_{u,s}, \forall u, s \tag{21}$$

$$\sum\nolimits_{r\in R} X8_{r,s,w} \leq \widetilde{U}_{w,s}, \forall w, s \tag{22}$$

$$\sum\nolimits_{l\in L} X7_{l,n,m} \leq \widetilde{U}_{m,n}, \forall m, n \tag{23}$$

The final constraints of the mathematical model display the binary and non-negative values of decision variables shown in Eq. (24) and Eq. (25), respectively:

$$Z_d, Z_r, Z_l \in \{0, 1\} \tag{24}$$

$$X1_{c,d,p}, X2_{d,r,w}, X3_{d,o,t}, X4_{d,s,u}, X5_{d,l,m}, X6_{l,o,t}, X7_{l,n,m}, X8_{r,s,w} \geq 0 \tag{25}$$

4. Case study of EOL solar panels

In this section, we will present a practical situation of solar panel RSC network in Ho Chi Minh (HCM) city, Vietnam. It will clarify our mathematical RSC model and MILP approach.

4.1. The input parameters of solar panel RSC

As defined in section 2.3. , all prospective facilities of disassembly and collection places are given in Tab. 10. In order to meet high customer's demand in HCM city, the collection facilities are located in suitable plants through urban districts. Meanwhile, the disassembly facilities are divided into three plants, which are built along the vertical axis of HCM city with the purpose of transporting items feasibly from the collection facilities to other places.

Table 11 represents the fixed locations such as repairing facilities, recycling facilities, spare markets, primary markets and disposal areas. These places are established logically to reduce transporting time, as well as cost contributing to the foundation system. The data of distance are listed fully in Tab. 12, which represents how far to transfer merchandise from one facility to another. Table 13 demonstrates the transportation expenses, which consisted of transferring cost of various items per kilometer. While Tab. 14 describes the disposal cost for treatment centers, Tab. 15 and Table 19 represents the distinct expenses incurred during the production (i.e. collection expenses, fixed expenses, disposal expenses, etc.). Also, Tab. 16 provides information on treatment expenses at three main facilities in the solar panel RSC model: disassembly, recycling, and repairing facilities.

Beside the given data tables, Tab. 17 and Tab. 18 provides data on the number of EOL solar panels at collection facilities and the income gained from trading in reusable, recycling and renewable components per unit, respectively. Table 20 shows the maximum capacity demand at all facilities. Table 21 shows the ratio of renewable, recycling items obtained from EOL products and Tab. 22 presents the ratio of toxic waste and recycling materials obtained from recycling facilities.

4.2. The output solution of MILP

For our solar panel RSC, let us apply the popular branch and bound method [19] via Microsoft Excel solver for MILP problem. The MILP's optimized values of decision variables in subsection 2.2 are given as follows:

Table 1. Expenses of the our solar panel RSC model ($USD)

Table 2. Units of recycling materials to be transferred from disassembly facilities to recycling facilities

Table 3. Units of recycling materials to be transferred from recycling facilities to primary markets

Table 4. Units of renewable items to be transferred from disassembly facilities to repair facilities

Table 5. Units of renewable items to be transferred from repair facilities to spare markets

Table 6. Units of reusable items to be transferred from disassembly facilities to spare markets

Table 7. Units of end-of-life products to be transferred from collection facilities to disassembly facilities

Table 8. Units of waste items to be transferred from recycling facilities to landfill sites

Table 9. Units of waste items to be transferred from disassembly facilities to landfill sites

Since the optimized total expense in Tab.1 is negative, our solar panel RSC is a profitable model to the market size of HCM city.

5. Conclusions and further work

This paper has introduced a reverse supply chain (RSC) model for collecting the waste of solar panels in Ho Chi Minh city, Vietnam. Normally, the decision-makers for a supply chain is a multi-objective problem. In order to facilitate this issue, we regard this problem as a single optimized problem subject to multiple constraints. Hence, RSC must balance between two opposite problems: the higher the constraint satisfaction, the lower the prospective number of optimal solutions.

To clarify the effectiveness of the our solar panel RSC model, we have applied the mixed-integer linear programming (MILP) method and demonstrated that our designed RSC is a profitable model for a realistic scenario of solar panels in Vietnam. The result of this study indicates that the RSC model can yield a superior solution for a network of recycling solar panel and reduce the total cost.

For further development, the RSC model may be upgraded with cloud computing, which provides the decision-makers convenient means to access cloud databases. The MILP approach via cloud computing has a lot of attractive improvement, which yields higher speed of computation and provides real-time process for logistic network. Hence, our designed RSC model could be studied further from this point forward.

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References

[1] EVN (2021). Khi điện mặt trời bùng nổ. *Tạp chí Điện lực Chuyên đề Quản lý & Hội nhập.*

[2] Thong, D.T. (2020). Rác thải từ các tấm pin mặt trời - Những vấn đề môi trường cần quan tâm. *Tạp chí môi trường.*

[3] Đình Tuấn, P. (2021). Pin mặt trời hết hạn: Một vấn đề cần quan tâm. *Tạp chí khoa học công nghệ việt nam.*

[4] Fiandra, V., Sannino, L., Andreozzi, C., Corcelli, F., & Graditi, G. (2019). Silicon photovoltaic modules at end-of-life: Removal of polymeric layers and separation of materials. *Waste Management*, *87*, 97–107.

[5] Quyền, B. (2020). Dự án điện mặt trời: Nguy cơ ô nhiễm từ những tấm pin rác. *Tạp chí thương hiệu và công luận.*

[6] Garrido-Hidalgo, C., Olivares, T., Ramirez, F.J., & Roda-Sanchez, L. (2019). An end-to-end Internet of Things solution for Reverse Supply Chain Management in Industry 4.0. *Computers in Industry*, *112*, 103127.

[7] Tran, V.H. & Coupechoux, M. (2017). Cost-constrained Viterbi algorithm for resource allocation in solar base stations. *IEEE Transactions on Wireless Communications*, *16*(7), 4166–4180.

[8] Xu, Y., Li, J., Tan, Q., Peters, A.L., & Yang, C. (2018). Global status of recycling waste solar panels: A review. *Waste Management*, *75*, 450–458.

[9] Krikke, H.R., van Harten, A., & Schuur, P.C. (1999). Business case Oce: Reverse logistic network re-design for copiers. *OR-Spektrum*, *21*, 381–409.

[10] Gomes, M.I., Barbosa-Povoa, A.P., & Novais, A.Q. (2011). Modelling a recovery network for WEEE: A case study in Portugal. *Waste Management*, *31*(7), 1645–1660.

[11] Kilic, H.S., Cebeci, U., & Ayhan, M.B. (2015). Reverse logistics system design for the waste of electrical and electronic equipment (WEEE) in Turkey. *Resources, Conservation and Recycling*, *95*, 120–132.

[12] John, S.T., Sridharan, R., Kumar, P.N.R., & Krishnamoorthy, M. (2018). Multi-period reverse logistics network design for used refrigerators. *Applied Mathematical Modelling*, *54*, 311–331.

[13] Kara, S.S. & Onut, S. (2010). A two-stage stochastic and robust programming approach to strategic planning of a reverse supply network: The case of paper recycling. *Expert Systems with Applications*, *37*(9), 6129–6137.

[14] Lee, D.H. & Dong, M. (2009). Dynamic network design for reverse logistics operations under uncertainty. *Transportation Research Part E: Logistics and Transportation Review*, *45*(1), 61–71.

[15] Prakash, C. & Barua, M.K. (2016). A multi-criteria decision-making approach for prioritizing reverse logistics adoption barriers under fuzzy environment: case of Indian electronics industry. *Global Business Review*, *17*, 1107–1124.

[16] Ayvaz, B., Bolat, B., & Aydin, N. (2015). Stochastic reverse logistics network design for waste of electrical and electronic equipment. *Resources, Conservation and Recycling*, *104*, 391–404, green Sourcing: Taking Steps to Achieve Sustainability Management and Conservation of Resources.

[17] Trochu, J., Chaabane, A., & Ouhimmou, M. (2018). Reverse logistics network redesign under uncertainty for wood waste in the CRD industry. *Resources, Conservation and Recycling*, *128*, 32–47.

[18] Nhan, B.T. (2020), Design of supply chain for factories (undergraduate thesis), Ton Duc Thang university.

[19] Fylstra, D., Lasdon, L., Watson, J., & Waren, A. (1998). Design and Use of the Microsoft Excel Solver. *Interfaces*, *28*(5), 29–55.

[20] (2021), https://chuyenhakienvang.com/bang-gia-cuoc-van-chuyen-xe-tai.html.

[21] (2020), http://phuhuu-quan9.hochiminhcity.gov.vn/thu-vien-hinh-anh/-/asset_publisher/lJKKcqQtEQKh/content/thong-bao-muc-gia-thu-gom-van-chuyen-va-tan-suat-thu-gom-rac-uoc-ap-dung-tu-thang-9-nam-2020.

[22] (2018), https://tapchitaichinh.vn/nghien-cuu-trao-doi/nghien-cuu-dieu-tra/gia-cung-ung-dich-vu-quan-ly-chat-thai-nguy-hai-duoi-goc-do-phap-luat-moi-truong-140671.html.

[23] (2021), https://shopee.vn/Thanh-Nhôm-Cứng-2x50cm-i.50091114.2354754601.

[24] (2021), https://thanhnien.vn/tp-hcm-co-muc-luong-trung-binh-cao-nhat-toan-quoc-post738105.html.

[25] (2021), https://phelieuthienloc.com/tin-tuc/thu-mua-thuy-tinh-kinh-vun-phe-lieu-gia-cao-uy-tin-tai-binh-duong-tp-hcm-dong-nai_369.html.

[26] (2021), https://vietnamese.alibaba.com/product-detail/silicon-rubber-scrap-62023304611.html.

[27] tam pin nang luong mat troi 150w mono MN22 (2021), https://www.sendo.vn/tam-pin-nang-luong-mat-troi-150w-mono-29778989.html.

[28] (2021), https://shopee.vn/Tấm-Pin-Năng-Lượng-Mặt-Trời-Usb-Kép-Linh-Hoạt-18v-50w-i.85470937.5556432660.

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Appendix

Tab. 1: Expenses of the suggested solar panel model ($USD), as explained in Subsection 3.1.

Expense	Suggested model
Collection expenses (E1)	5050
Processing expenses (E2)	1708
Fixed expenses (E3)	9600
Transportation expenses (E4)	4225
Disposal expenses (E5)	57
Income (E6)	31859
Total expenses (E)	-11219

Tab. 2: Units of end-of-life products ($X1_{c,d,p}$) to be transferred from collection facilities to disassembly facilities.

CD Routes		Used Solar Panels	Value
O	D		
C1	D1	Silicon solar panel	200
C1	D1	Thin-film solar panel	0
C2	D1	Silicon solar panel	100
C2	D1	Thin-film solar panel	0
C3	D1	Silicon solar panel	110
C3	D1	Thin-film solar panel	0
C4	D1	Silicon solar panel	80
C4	D1	Thin-film solar panel	0
C5	D1	Silicon solar panel	100
C5	D1	Thin-film solar panel	0
C1	D2	Silicon solar panel	0
C1	D2	Thin-film solar panel	100
C2	D2	Silicon solar panel	0
C2	D2	Thin-film solar panel	120
C3	D2	Silicon solar panel	0
C3	D2	Thin-film solar panel	100
C4	D2	Silicon solar panel	0
C4	D2	Thin-film solar panel	50
C5	D2	Silicon solar panel	0
C5	D2	Thin-film solar panel	50
C1	D3	Silicon solar panel	0
C1	D3	Thin-film solar panel	0
C2	D3	Silicon solar panel	0
C2	D3	Thin-film solar panel	0
C3	D3	Silicon solar panel	0
C3	D3	Thin-film solar panel	0
C4	D3	Silicon solar panel	0
C4	D3	Thin-film solar panel	0
C5	D3	Silicon solar panel	0
C5	D3	Thin-film solar panel	0

Tab. 3: Units of renewable items ($X2_{d,r,w}$) to be transferred from disassembly facilities to repair facilities.

DR Routes		Renewable Solar Panels	Value
O	D		
D1	R1	Silicon solar panel	118
D1	R1	Thin-film solar panel	0
D2	R1	Silicon solar panel	84
D2	R1	Thin-film solar panel	0
D3	R1	Silicon solar panel	0
D3	R1	Thin-film solar panel	0
D1	R2	Silicon solar panel	0
D1	R2	Thin-film solar panel	59
D2	R2	Silicon solar panel	0
D2	R2	Thin-film solar panel	42
D3	R2	Silicon solar panel	0
D3	R2	Thin-film solar panel	0
D1	R3	Silicon solar panel	0
D1	R3	Thin-film solar panel	0
D2	R3	Silicon solar panel	0
D2	R3	Thin-film solar panel	0
D3	R3	Silicon solar panel	0
D3	R3	Thin-film solar panel	0

Tab. 4: Units of waste items ($X3_{d,o,t}$) to be transferred from disassembly facilities to landfill sites.

DO Routes		Waste items	Value
O	D		
D1	O1	Waste	0
D1	O1	Hazardous substances	0
D2	O1	Waste	12.6
D2	O1	Hazardous substances	4.2
D3	O1	Waste	0
D3	O1	Hazardous substances	0
D1	O2	Waste	11.8
D1	O2	Hazardous substances	11.8
D2	O2	Waste	0
D2	O2	Hazardous substances	0
D3	O2	Waste	0
D3	O2	Hazardous substances	0

Tab. 5: Units of reusable items ($X4_{d,s,u}$) to be transferred from disassembly facilities to spare markets.

DS Routes		Reusable Solar Panels	Value
O	D		
D1	S1	Silicon solar panel	59
D1	S1	Thin-film solar panel	59
D2	S1	Silicon solar panel	0
D2	S1	Thin-film solar panel	0
D3	S1	Silicon solar panel	0
D3	S1	Thin-film solar panel	0
D1	S2	Silicon solar panel	0
D1	S2	Thin-film solar panel	0
D2	S2	Silicon solar panel	42
D2	S2	Thin-film solar panel	42
D3	S2	Silicon solar panel	0
D3	S2	Thin-film solar panel	0
D1	S3	Silicon solar panel	0
D1	S3	Thin-film solar panel	0
D2	S3	Silicon solar panel	0
D2	S3	Thin-film solar panel	0
D3	S3	Silicon solar panel	0
D3	S3	Thin-film solar panel	0

Tab. 6: Units of recycling materials ($X5_{d,l,m}$) to be transferred from disassembly facilities to recycling facilities.

DL Routes		Recycling Materials	Value
O	D		
D1	L1	Glass	0
D1	L1	Plastic	0
D1	L1	Aluminum	47.2
D1	L1	Silicon	0
D1	L1	Metal	0
D2	L1	Glass	0
D2	L1	Plastic	0
D2	L1	Aluminum	25.2
D2	L1	Silicon	0
D2	L1	Metal	0
D3	L1	Glass	0
D3	L1	Plastic	0
D3	L1	Aluminium	0
D3	L1	Silicon	0
D3	L1	Metal	0
D1	L2	Glass	271.4
D1	L2	Plastic	0
D1	L2	Aluminium	0
D1	L2	Silicon	29.5
D1	L2	Metal	0
D2	L2	Glass	289.8
D2	L2	Plastic	0
D2	L2	Aluminium	0
D2	L2	Silicon	0
D2	L2	Metal	0
D3	L2	Glass	0
D3	L2	Plastic	0
D3	L2	Aluminium	0
D3	L2	Silicon	0
D3	L2	Metal	0
D1	L3	Glass	0
D1	L3	Plastic	59
D1	L3	Aluminium	0
D1	L3	Silicon	0
D1	L3	Metal	5.9
D2	L3	Glass	0
D2	L3	Plastic	16.8
D2	L3	Aluminium	0
D2	L3	Silicon	0
D2	L3	Metal	4.2
D3	L3	Glass	0
D3	L3	Plastic	0
D3	L3	Aluminium	0
D3	L3	Silicon	0
D3	L3	Metal	0

Tab. 7: Units of waste items ($X6_{l,o,t}$) to be transferred from recycling facilities to landfill sites.

LO Routes		Waste items	Value
O	D		
L1	O1	Waste	0
L1	O1	Hazardous substances	59
L2	O1	Waste	11.814
L2	O1	Hazardous substances	11.814
L3	O1	Waste	0
L3	O1	Hazardous substances	0
L1	O2	Waste	1.448
L1	O2	Hazardous substances	1.448
L2	O2	Waste	0
L2	O2	Hazardous substances	0
L3	O2	Waste	1.718
L3	O2	Hazardous substances	1.718

Tab. 8: Units of recycling materials ($X7_{l,n,m}$) to be transferred from recycling facilities to primary markets.

LN Routes		Recycling Materials	Value
O	D		
L1	N1	Glass	0
L1	N1	Plastic	0
L1	N1	Aluminum	5.792
L1	N1	Silicon	0
L1	N1	Metal	0
L2	N1	Glass	0
L2	N1	Plastic	0
L2	N1	Aluminum	0
L2	N1	Silicon	0
L2	N1	Metal	0
L3	N1	Glass	0
L3	N1	Plastic	7.58
L3	N1	Aluminium	0
L3	N1	Silicon	0
L3	N1	Metal	0.101
L1	N2	Glass	0
L1	N2	Plastic	0
L1	N2	Aluminium	0
L1	N2	Silicon	0
L1	N2	Metal	0
L2	N2	Glass	258.152
L2	N2	Plastic	0
L2	N2	Aluminium	0
L2	N2	Silicon	1.475
L2	N2	Metal	0
L3	N2	Glass	0
L3	N2	Plastic	0
L3	N2	Aluminium	0
L3	N2	Silicon	0
L3	N2	Metal	0

Tab. 9: Units of renewable items ($X8_{r,s,w}$) to be transferred from repair facilities to spare markets.

RS Routes		Renewable Solar Panels	Value
O	D		
R1	S1	Silicon solar panel	202
R1	S1	Thin-film solar panel	0
R2	S1	Silicon solar panel	0
R2	S1	Thin-film solar panel	0
R3	S1	Silicon solar panel	0
R3	S1	Thin-film solar panel	0
R1	S2	Silicon solar panel	0
R1	S2	Thin-film solar panel	0
R2	S2	Silicon solar panel	0
R2	S2	Thin-film solar panel	101
R3	S2	Silicon solar panel	0
R3	S2	Thin-film solar panel	0
R1	S3	Silicon solar panel	0
R1	S3	Thin-film solar panel	0
R2	S3	Silicon solar panel	0
R2	S3	Thin-film solar panel	0
R3	S3	Silicon solar panel	0
R3	S3	Thin-film solar panel	0

Tab. 10: Locations of collection and disassembly centers in HCM City.

Collection Areas (C)	Locations	Disassembly Areas (D)	Locations
1	201-233 Hai Ba Trung, Ward 6, District 3, Ho Chi Minh city	**1**	Alley 45 Ho Van Tu, Truong Tho Ward, Thu Duc District, Ho Chi Minh city
2	77 Le Van Khuong, Hiep Thanh Ward, District 12, Ho Chi Minh city	**2**	739 Nguyen Van Linh, An Phu Tay Ward, Binh Chanh District, Ho Chi Minh city
3	Long Thanh My, District 9, Ho Chi Minh city	**3**	An Phu area, District 2, Ho Chi Minh city
4	370 Phu Dinh, Ward 16, District 8, Ho Chi Minh city		
5	Nguyen Van Linh, Tan Phu Ward, District 7, Ho Chi Minh city		

Tab. 11: Locations of various RSC centers of solar panels in HCM City.

Repair Areas (R)	Locations	Recycling Areas (L)	Locations
1	Linh Xuan area, Thu Duc District, Ho Chi Minh City	**1**	137 Street 48, Hiep Binh Chanh Ward, Thu Duc District, Ho Chi Minh City
2	Vo Tran Chi Street, Binh Chanh District, Ho Chi Minh City	**2**	Hoang Yen variety store, The Lu Street, Tan Nhut Ward, Binh Chanh District, Ho Chi Minh City
3	Song Hanh area, An Phu Ward, District 2, Ho Chi Minh City	**3**	An Phu An Khanh urban area, Thao Dien Ward, District 2, Ho Chi Minh City
Spare Market (S)	**Locations**	**Primary Market (N)**	**Locations**
1	266-280 Dien Bien Phu, Vo Thi Sau Ward, District 3, Ho Chi Minh City	**1**	26 Street 26, Tang Nhon Phu A Ward, District 9, Ho Chi Minh City
2	Vo Van Kiet Street, Ward 10, District 6, Ho Chi Minh City	**2**	Tan Hung Thuan area, Dong Hung Thuan Ward, District 12, Ho Chi Minh City
3	117/3B Tran Xuan Soan, Tan Kieng Ward, District 7, Ho Chi Minh City		
Landfill Sites (O)	**Locations**		
1	Da Phuoc area, Binh Chanh District, Ho Chi Minh City		
2	Hiep Thanh landfill, Hiep Thanh Ward, District 12, Ho Chi Minh City		

Tab. 12: Travel distances between RSC centers ($\tilde{D}_{c,d}$, $\tilde{D}_{d,s}$, $\tilde{D}_{d,r}$, $\tilde{D}_{d,l}$, $\tilde{D}_{d,o}$, $\tilde{D}_{r,s}$, $\tilde{D}_{l,n}$, $\tilde{D}_{l,o}$) of solar panels (km).

Dist.	C1	C2	C3	C4	C5	L1	L2	L3	O1	O2	R1	R2	R3	S1	S2	S3
D1	14	15	10	26	20	5	36	9	30	16	5	35	8	15	23	20
D2	18	23	35	10	15	27	6	24	11	27	32	5	25	17	14	18
D3	11	20	15	18	11	13	30	6	27	22	11	29	5	12	20	16

Dist.	N1	N2	O1	O2
L1	11	15	26	17
L2	36	19	18	28
L3	13	19	24	22

Dist.	S1	S2	S3
R1	16	30	22
R2	19	10	24
R3	8	19	11

Tab. 13: Transportation cost per kilometers of solar panel components ($\widetilde{T}_p$, $\widetilde{T}_u$, $\widetilde{T}_w$, $\widetilde{T}_m$, $\widetilde{T}_t$) ($USD), c.f. [20–22].

Items	Cost
Silicon solar panel	0.09
Thin-film solar panel	0.09
Glass	0.07
Plastic	0.07
Aluminum	0.01
Silicon	0.10
Metal	0.01
Waste	0.01
Hazardous substances	0.10

Tab. 14: Disposal cost ($\tilde{D}_t$) for treatment centers ($USD), c.f. [21,22].

Items	Disposal Cost
Waste	0.01
Hazardous substances	0.10

Tab. 15: Fixed cost ($\tilde{C}_p$) of solar panels at collection facility ($USD), c.f. [23].

Items	Collection Cost
Silicon solar panel	5.0
Thin-film solar panel	5.0

Tab. 16: Processing costs at disassembly ($\widetilde{P}_{p,d}$), repair ($\widetilde{P}_{w,r}$) and recycling centers ($\widetilde{P}_{m,l}$) of solar panel items ($USD), c.f. [24].

Items	Disassembly centers		
	D1	**D2**	**D3**
Silicon solar panel	1.1	1.1	1.1
Thin-film solar panel	1	1	1
Items	**Repair centers**		
	R1	**R2**	**L3**
Silicon solar panel	1.6	1.6	1.6
Thin-film solar panel	1.5	1.5	1.5
Items	**Recycling centers**		
	L1	**L2**	**L3**
Glass	0.2	0.2	0.2
Plastic	0.3	0.3	0.4
Aluminum	0.2	0.3	0.2
Silicon	0.3	0.2	0.2
Metal	0.1	0.3	0.1

Tab. 17: Number of end-of-life solar panels ($\widetilde{N}_{p,c}$) at collection facilities (unit).

Items	Recycling centers				
	C1	**C2**	**C3**	**C4**	**C5**
Silicon solar panel	200	100	110	80	100
Thin-film solar panel	100	120	100	50	50

Tab. 18: Income gained from solar panels reusable ($\widetilde{S}_u$), recycling ($\widetilde{S}_m$) and renewable ($\widetilde{S}_w$) materials per unit ($USD), c.f. [25–28].

Items	Recycling	
Glass	2	
Plastic	2	
Aluminum	3	
Silicon	0.2	
Metal	1	
Items	**Reusable**	**Renewable**
Silicon solar panel	70	70
Thin-film solar panel	50	50

Tab. 19: Fixed cost of disassembly facility ($\tilde{F}_d$), repair facility ($\tilde{F}_r$) and recycling facility ($\tilde{F}_l$) ($USD).

Disassembly	Cost	Recycling	Cost	Repair	Cost
D1	3200	**L1**	3000	**R1**	3200
D2	3500	**L2**	3200	**R2**	3300
D3	3500	**L3**	3200	**R3**	3400

Tab. 20: Maximum capacity demand at primary ($\widetilde{U}_{m,n}$), spare markets ($\widetilde{U}_{u,s}$,$\widetilde{U}_{w,s}$), disassembly ($\widetilde{U}_{p,d}$), repair ($\widetilde{U}_{w,r}$), recycling ($\widetilde{U}_{m,l}$) and landfill site ($\widetilde{U}_{t,o}$) of solar panels (unit).

Items	**Spare markets**			**Disassembly centers**			**Repair centers**		
	S1	**S2**	**S3**	**D1**	**D2**	**D3**	**R1**	**R2**	**R3**
Silicon solar panel	500	500	600	600	500	500	500	300	200
Thin-film solar panel	400	600	700	600	600	400	300	200	300

Items	**Recycling centers**			**Primary markets**	
	L1	**L2**	**L3**	**N1**	**N2**
Glass	500	500	500	800	600
Plastic	400	600	600	600	500
Aluminum	500	500	400	700	700
Silicon	400	400	500	600	600
Metal	600	300	400	600	800

	Landfill site	
	O1	**O2**
Waste	2000	2100
Hazardous substances	2200	2300

Tab. 21: The ratio of reused ($\widetilde{\theta}1_{u,p}$), renewable ($\widetilde{\theta}2_{w,p}$), recycling ($\widetilde{\theta}3_{m,p}$), toxic waste ($\widetilde{\theta}4_{t,p}$) obtained from end-of-life products.

	Reused	**Renewable**
Silicon solar panel	0.1	0.2
Thin-film solar panel	0,1	0.1

	Recycling materials					**Toxic waste**	
Items	Glass	Plastic	Aluminium	Silicon	Metal	Waste	Hazardous substances
Silicon solar panel	0.46	0.1	0.08	0.05	0.01	0.02	0.02
Thin-film solar panel	0.69	0.04	0.06	0	0.01	0.03	0.01

Tab. 22: The ratio of toxic waste ($\widetilde{\gamma}_{t,l}$) and recycling materials ($\widetilde{\gamma}_{m,l}$) obtained from recycling facilities.

	Toxic waste		**Recycling materials**				
Items	Waste	Hazardous substances	Glass	Plastic	Aluminium	Silicon	Metal
Silicon solar panel	0.02	0.02	0.46	0.1	0.08	0.05	0.01
Thin-film solar panel	0,03	0.01	0.69	0.04	0.06	0	0.01