A novel hybrid network optimization model for printed circuit boards recycling: a circular economy perspective

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Abstract
The recycling of printed circuit boards, which accounts for a considerable monetary value in waste electrical and electronic equipment, has long been ignored due to the serious challenges in collection, dismantling, and recycling processes. In this study, the open-loop and closed-loop supply chain involving circular economy objectives is designed in order to increase the recyclability of valuable metals including gold, silver, copper, and palladium. In this regard, a mixed-integer linear programming model, which aims at maximizing the profit from the flow in the supply chain network, is developed. The model is tested with actual data obtained from a printed circuit board firm in Turkey that aims an optimal distribution in its supply chain. The results reveal that the product/material flows, which have an impact on the revenues, are among the most important factors affecting the profitability. According to results, the circular economy objectives increase the revenue obtained in the hybrid open-loop and closed-loop supply chain. Besides, the boundaries of the proposed model are tested with sensitivity analyses, and the results are discussed extensively with conclusions on managerial implications.

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Keywords Circular Economy · Open-Loop Supply Chain · Closed-Loop Supply Chain · Mixed Integer Linear Programming · Sustainability · Printed Circuit Board

List of Abbreviation

ANP  Analytical Network Process
CE  Circular Economy
EEE  Electrical and Electronic Equipment
GSCM  Green Supply Chain Management
WEEE  Waste Electrical and Electronic Equipment
LCA  Life Cycle Assessment
PCB  Printed Circuit Boards
WPCB  Waste Printed Circuit Boards
MINLP  Mixed Integer Linear Programming
OF  Objective Function
PI  Performance Indicators
PV  Photovoltaic
RQ  Research Question

Introduction

Environmental concerns, fast deterioration of natural resources, high level of urbanization, and industrialization have recently made waste management, which aims at minimizing environmental impact while maximizing economic utility, more crucial (Deveci 2016). Electronic cards, which are found in the structure of several electrical and electronics equipment, are considered to be the main cause of the rapid growth in the amount of waste generated across the world (Pérez-Belis et al. 2015). As such, it was reported in (Baldé et al. 2017) 44.7 million metric tons of electronic waste has been generated until 2016, and only 20% was recycled properly (Baldé et al. 2017). In this regard, electronic waste is a substantial issue for the whole world due to its adverse environmental impacts and its potential to form substances that are harmful to human health. To this end, developed countries aim to minimize the environmental damage with a waste management approach that involves
recycling, consumption, collection, sorting, and disposal of waste electrical and electronic equipment (WEEE) (Ismail and Marlia 2020).

One of the most striking examples of WEEE is waste printed circuit boards (WPCBs), and since WPCBs include precious materials such as ferrum, copper, silver, gold and palladium, recycling of WPCB is mainly focused on the recovery of these materials (Awasthi et al. 2017; Jad-hao et al. 2020). However, WPCBs contain not only such valuable materials but also some hazardous ones, including lead, mercury, arsenic, cadmium, selenium, chromium (+ 6) and flame retardant, that threaten to human health and the environment since the waste of these products to gain the property of hazardous waste (Özkan 2018). Hence, recycling of WPCBs does not only protect the environment but also provide the sustainability of non-renewable resources.

Besides, as WPCBs are found in the structure of every piece of electrical and electronic equipment, they have a large share in the circular economy. The first characteristic of the examined network of printed circuit boards (PCBs), which are the most fundamental form of electronic cards, has been designed from production to consumption and from collection to recycling in the scope of circular economy (Wagner et al. 2019). In this network, the second-hand materials that are obtained from the first dismantling of PCBs are sent to factories or various users for them to reprocess for selling in the internal market, forming an open-loop supply chain. Open-loop supply chain design provides reusable second-hand materials to different actors and alternative supply chain networks (Kalverkamp 2018; Ene and Öztürk 2014).

The second characteristic of the examined network is that it is an integrated closed-loop supply chain network that makes a contribution to the circular economy by using the raw materials obtained from the second layer of recycling within the same loop, which in turn reduces the resource usage. In other words, the circular economy objectives are considered and integrated into the developed supply chain network, providing a sustainable contribution to the circular economy due to its environmental, social and economic dimensions.

It is worth mentioning that in this study, the environmental and economic effect, provided by recycling, is analyzed with real data. In this context, this study focuses on network design recycling of PCBs, the open-loop and closed-loop supply chain approach from a circular economy perspective. Besides, the factors that affect profitability in the developed hybrid open-loop and closed-loop supply chain network over electronic card recycling are investigated. In particular, in the proposed open-loop supply chain model, the effects of factors such as capacity, recycling rates, and customer demand on profitability are examined within the scope of costs and revenues.

Based on the above-mentioned research directions, the main purpose of this study is to design open-loop and closed-loop supply chain networks toward recycling of electronic cards with the circular economy perspective (i.e., suppliers, manufacturers, customers, end users, recycling centers, collection centers and dismantler centers) (Mairizal et al. 2021; Rene et al. 2021; Pokhrel et al. 2020). As such, a mixed-integer linear programming (MILP) model is developed for this network design, and the results are mathematically analyzed with real data acquired from a PCB firm in Turkey. Moreover, the investigation of the affecting factors such as demand, recycling ratios, transportation costs, and facility capacities, on profitability in the open-loop supply chain network, constitutes another significant part of the study. Additionally, analyses of different operational scenarios are important in terms of measuring the sensitivity of the developed model. For this reason, in the study, several parameters are taken to consideration, and scenario analyses with the combinations of these parameters are presented.

To the best of the authors’ knowledge, the number of studies in the literature on the hybrid open-loop and closed-loop supply chain approach in recycling of electronic cards is limited. Furthermore, existing studies are predominantly on a theoretical level. In this regard, this study has the quality to fill in the gap in the literature, in that, it is not only focuses on an actual case but also discusses electronic card recycling. The network structure will provide significant contributions to the literature, as it has strong potential of being an inspiration for new studies on circular economy.

As a novelty of this study, even though the circular economy is considered in a perspective, the simultaneous open-loop and closed-loop supply chain network design and 10R targets were tested, and furthermore, the analysis and applicability of their economic and environmental impacts were investigated on a real case. From an originality aspect, despite the existence of the hybrid open-loop and closed-loop supply chain articles in the literature (Özceylan, 2016; Huysman et al. 2015), this it is a pioneering study as it reflects the circular economy perspective on a real case.

The remainder of the article is structured as follows. In section ‘Literature review’, the literature review is presented in three different parts, namely sections ‘Methodology, Results, and Discussion’. A simultaneous optimization of the hybrid open-loop and closed-loop network design within the circular economy perspective is modeled in section ‘Methodology’ with a case study. In section ‘Results,’ the obtained results of the model are presented, while in section ‘Discussion,’ the obtained solutions are discussed, the scenario analyses and managerial implications of the model design in terms of circular economy targets are presented. Lastly, section ‘Conclusion’ concludes the article with concluding remarks along with suggestions for future studies.
Literature review

In this section, the related literature will be extensively reviewed under three subsections; namely circular economy, open-loop and closed-loop supply chain, integration of open-loop and closed-loop supply chain with circular economy. Regarding the open-loop recycling network design model developed in a circular economy perspective for recycling of PCBs, a search was conducted on Scopus, ScienceDirect, and ResearchGate databases by using the key phrases of “circular economy”, “recycling”, “open-loop supply chain”, “closed-loop supply chain”, “waste electric electronic equipment”, and “printed circuit board”, and the accessed articles are thoroughly discussed in the relevant following paragraphs. Firstly, the articles that are related to the proposed study are shortlisted, and then, 66 of that are then selected by taking into account their qualities and possible contributions to this study. Then, these 66 articles are classified into three categories and it was aimed to find answers to the research questions.

In this context, in the first part of the literature review, the concept of circular economy and related studies are discussed. In addition to the advantages and disadvantages of circular economy, potential problems encountered in practice are revealed, and recommendations are given. In the second part, the studies conducted on open-loop and closed-loop supply chain are examined, and by focusing on examples of mathematical models, the infrastructure of the model to be developed is formed. In the third part, the articles accessed as a result of the search made by using the key phrases of circular economy perspective and open-loop and closed-loop supply chain are analyzed, followed by determining the issues that would reveal the distinguishing points of the proposed study. As such, it is aimed to emphasize the contribution of the study to the literature. Each subsection includes a summary table created based on the relevant key phrases, and the last section defines the research questions of the study based on the GAP analysis revealed as a result of the literature review.

With the literature review, in the scope of the CE, WEEE and open-loop supply chain, and closed-loop supply chain concepts, answers will be sought for the questions of:

1. What types of studies were previously conducted in the literature, how methodologies were applied, how objectives were reached, what the related studies were and for which problem solutions were searched,
2. On which sectors and by using which methods studies were conducted,
3. How circular economy perspective was adapted to different sectors, especially the WEEE industry.

Table 1  Methodologies and application areas of circular economy studies

| Authors | Methodology | Green design | Production | Recycling | Business |
|---------|-------------|--------------|------------|----------|----------|
| Moktadir et al. (2018) | Graph Theory & Matrix Approach | ✓ | ✓ | | |
| Hanumante et al. (2019) | Simulation Model | | | ✓ | |
| Halonen et al. (2019) | Literature Review | ✓ | | | |
| Panda et al. (2019) | Data Analysis | | | | |
| Hao et al. (2020) | Thermal & Char Analysis | | | | |
| Wu et al. (2021) | Theoretical Model | | | | |
| Mohan and Amin (2021) | Simulation Model | | | | |
| Gautam et al. (2021) | Optimization Model | | | | |
4. In which sectors and how the open-loop recycling approach was practiced,
5. How the concepts of open-loop and closed-loop supply chain networks were discussed together with a circular economy perspective and on which sectors studies were carried out.

**Literature review on circular economy studies**

With environmental concerns and exhaustion of resources, the concept of circular economy has gained recently attention from both academia and industry. In this context, the studies carried out on circular economy are comprehensively reviewed, and the objectives as well as the application areas of these studies are shown in Table 1.

Accorsi et al. (2020) contributed to the related literature by conducting a study based on recycling with a proposal of a circular economy perspective depending on network design. In the study by Moktadir et al. (2018) where the importance of circular economy in supply chains is emphasized, the authors reported that with the help of sustainable production practices and circular waste management carried out at leather production industries, energy and material usage decreased, and resource usage was optimized. Hanumante et al. (2019) emphasized that assessment of the systematic effects of circular economy on the global scale with a comprehensive perspective is an important instrument for transition to a sustainable future. For this purpose, they proposed a holistic model where the human, environment and industrial components were assessed together and examined the potential challenges regarding this model. Consequently, they stated that adoption of CE would provide significant benefits, but an aggressive transition process may lead to big problems in terms of the unprepared system.

Halonen et al. (2019) examined different circular economy approaches in the literature. Afterward, by evaluating the suitability of these approaches in processes of transition to circular economy by firms with the purpose of strategic development, they provided synthesized guidelines to help firms in their decision-making processes.

Parida et al. (2019) investigated the level of this benefit. They argued that this process would reach success and be possible by the participation of all members within the supply chain ecosystem, and the transition consisted of the preparation and transformation stages. Hao et al. (2020) reported that the anthropogenic material level used in wind energy brings about negativities regarding the environment. For the purpose of reducing this negative effect, they focused on how anthropogenic materials in the form of carbon fibers could be reused at the highest quality possible in a circular economy system. In the scope of the study, the economic outputs provided by the concept of circular economy were discussed over an application.

In their study on the plastic waste industry of Taiwan in the industrialization process, Wu et al. (2021) investigated how an industrial-level circular economy was structured by using an adaptive corporate governance framework and a network-based bricolage. Accordingly, they reported that developing nations could accumulate intrinsic social capacities, facilitate the emergence of network-based collective bricolages, a transition to green-related sectors may carry economic development even further, and new initiatives, firms and job opportunities could be created by establishing a circular economy. Mohan and Amit (2021) focused on recycling markets of vehicles that completed their lifespan, actors in these markets and the economic model formed by actors in these markets. In this context, official dismantler centers and unofficial dismantler centers involved in the recycling process of vehicle that completed lifespan were discussed. As a result of the study which examined the competition emerging in dismantling processes and the economic value brought by this competition, they proposed that healthier recycling in terms of the environment could be achieved if high-capacity vehicle manufacturers established dismantling units connected to themselves and management systems compatible with suitable policy instruments. Gautam et al. (2021) aimed to maximize resource productivity by establishing a supply chain network design based on circular economy to manage e-waste caused by solar photovoltaic (PV) panels that completed their lifespan. For this, by using a prediction model projecting the waste amounts of solar PV panels that completed their lifespan and system balance, they aimed to reveal the size of the problem for India in particular, and they made managerial inferences by predicting the amounts of raw materials gained after recycling in the context of circular economy via the developed model.

**Literature review on open-loop and closed-loop supply chain studies**

This part of the literature review discusses the studies on the open-loop and closed-loop supply chain which occurs the structure of the optimization model. Firstly, with a comprehensive analysis, it is understood that open-loop recycling models in the literature have mainly focused on sustainability and green philosophy. The articles examined in the scope of the literature review are classified based on their methodology used and the type of waste recycling focused on, and summary of the review is presented in Table 2. Some articles, which will act as sources for the design of an open-loop recycling network to be integrated into the recycling process of PCB cards, discussed in this study are examined in detail below.

Nicholson et al. (2009) argued that material selection decisions affect the product form, processing technology and supply chain configuration, and this situation has a large
| Authors                  | Methodology                        | Type of waste |
|-------------------------|------------------------------------|---------------|
|                         |                                    | Glass| Composite| Paper| Metal| E-Waste| Plastic| General| Organic| Other |
| Nicholson et al. (2009) | LCA & Allocation Method            | ✓    |           |      |      |         |        |        |        |       |
| Ha (2012)               | Thermal, Spectroscopic Morphological & Chromatographic Analyses | ✓    |           |      |      |         |        |        |        |       |
| Komly et al. (2012)     | Mathematical Modeling               | ✓    |           |      |      |         |        |        |        |       |
|                        | Pareto Analysis                     |      |           |      |      |         |        |        |        |       |
| Milnes and Perrochet (2013) | Numerical Modeling               |      |           |      |      |         |        |        |        | ✓     |
| Nakamura et al. (2014)  | Dynamic material flow analysis      | ✓    |           |      |      |         |        |        |        |       |
| Liu and Hu (2017)       | LCA                                |      |           |      |      |         |        |        |        | ✓     |

Table 2  Methodologies and type of wastes of open-loop supply chain studies
effect on the environmental performance of firms. For this reason, the authors investigated the recycling effects of products that have completed their lifespan, various analytical variations of relevant life cycle assessment (LCA) and the effects of these variations.

Nakamura et al. (2014) emphasized the importance of achieving sustainability in relation to problems such as potential material function losses that could be experienced in open-loop recycling or failure to meet quality requirements. Therefore, for the purpose of achieving sustainability and reducing losses, they developed a model based on dynamic material flow analysis. This way, they aimed to optimize the model by ensuring that the product could be monitored throughout its recycling, and potential losses and quality errors were taken into account.

Emphasizing the necessity of recycling for reducing the dimensions of the damage given to the environment originating from wastes, Liu and Hu (2017) focused on the concept of external economy in an open-loop supply chain. As a result of the study where comparative analyses were conducted by using the lifecycle assessment method, it was concluded that closed-loop supply chains and reverse supply chains are highly important in terms of solution of problems.

Secondly in this part, it is noticed that closed-loop models in the literature have mainly focused on recycling of WEEE and sustainable activities. Some articles that will role as sources for the design of a closed-loop recycling network to be integrated into the recycling process of PCB cards discussed in the scope of this study are examined below with their details.

Zlamparet et al. (2017) assessed the remanufacturing concept which can be embraced by the electronic manufacturing industry. The article uncovers values to decrease the amount of e-waste in the industry and academia in the scope of differential steps. They found that differences between developing and developed country's regions according to the concept of electronic waste remanufacturing. Fornasiero et al. (2016) evaluated the re-production networks to change the state-of-the-art processes in the case of WEEE which requires the configuration related to new manufacturing systems to improve the ability of a type of waste. They suggested a modular approach which is the EOL process for this configuration. Tseng et al. (2014) aimed to explore by using the analytical network process (ANP) analysis of green supply chain management (GSCM) under uncertainty for differences between close-loop and open network. This study analyzed to evaluate results for a real situation in interdependence among the proposed aspects and used criteria in GSCM. Cole et al. (2018) emphasized the e-waste becoming the fastest-growing waste stream due to technological advancement in the era. They signify that improvements in the efficiency of reverse logistics processes can increase reuse potential and efficient resource recycling. If availability and efficiency challenges can be dealt, it will be possible to protect against value loss in global supply chains. Tan et al. (2020) emphasized that recycling methods for WPCBs manufacture high yields but leads to secondary pollution. They developed waste solutions in the PCB production that are minimize disadvantages with a win–win novel recycling method for WPCBs. Govindan et al. (2015) aimed to review recently published papers in reverse logistic and closed-loop supply chain comprehensive search in scientific journals. They stressed closed-loop supply chain applications that have attracted attention academia and practitioners.

| Authors                    | Methodology                                      | Aim of the study                                                                 |
|---------------------------|--------------------------------------------------|----------------------------------------------------------------------------------|
| Deschamps et al. (2018)   | Life Cycle Impact Method (Software, data analysis) & Monte Carlo Simulation | To gain environmental values in open-loop recycling in a circular economy with glass powder LCA in concrete                                          |
| Huysveld et al. (2019)    | Recyclability Benefit Rate & Recycled Content Benefit Rate | Development of circular economy utility indicators in open-cycle mixed and contaminated plastic waste recycling |
| Kalverkamp (2018)         | Qualitative Research                              | Investigate the influence of independent actors on core supply and supply shortages in automotive remanufacturing |
| Kalverkamp et al. (2019)  | Mixed Method Research Evaluate Three Cases        | Expands the environmental sustainability paradigm of reverse supply chains in automotive remanufacturing |
| Tseng et al. (2020)       | Life Cycle Assessment                             | Examining the effects of a multi-level supply chain system on the circular economy within the closed-loop system |
| Sehnem et al. (2019)      | A Systematic Literature Review                    | Investigating overlaps and differences in circular economy models, within the scope of reverse logistics, closed-loop, industrial symbiosis, and industrial ecology |
| Brydges (2021)            | Interview                                        | Analyzing the circular economy framework which has a more efficient closed-loop economy in the Swedish fashion industry |
suggested future research opportunities for the closed-loop supply chain. Pishvae et al. (2011) suggested a robust optimization model for tackling the doubtfulness of input data in a closed-loop supply chain network design problem. They compared and evaluated the robustness of the solutions get by the novel robust optimization model and the deterministic mixed-integer linear programming model.

**Literature review on open-loop and closed-loop supply chain models with circular economy perspective**

The number of studies, in which "open-loop", "closed-loop", and "circular economy" keywords are used together, is quite limited in the literature. Therefore, since the number of articles found is insufficient for a proper analysis, we first paired the aforementioned three keywords with each other, with the condition of including the "circular economy" keyword, as follows: “Open-Loop & Circular Economy” and “Closed-Loop & Circular Economy”. Then, we searched the studies in the literature with these keyword pairs, and it is seen that the studies found whose details are given in Table 3, have focused on other sectors rather than recycling electronic wastes.

Deschamps et al. (2018) proposed an open-loop-based circular economy approach for the real case problem of regaining mixed waste glasses accumulating in the garbage collection areas of the Quebec Government for the economy. In this context, two different production approaches were discussed, and the selected production processes were compared using the Monte-Carlo simulation method.

Kalverkamp (2018) stated that the circular economy had gained importance in terms of sustainability, and it contributes to the achievement of circularity even though some difficulties are experienced in supply chains as opposed to the case of reproduction. In this scope, the author used a qualitative research approach to investigate the effects of independent actors in the automotive supply chain on basic supply and how these apply supplier relations management for eliminating supply shortcomings in automotive reproduction. As a result of the study, it was revealed that operational costs should be reduced, and information sharing should be increased for open-loop supply chains to be able to compete with closed-loop supply chains.

Stating that supply chain research mainly focuses on closed loops, Kalverkamp and Young (2019) investigated the potential benefits of open loops in the supply chain on the supply chain and their contributions to the weaknesses of the supply chain. With automotive recycling, three examples were selected and examined in the context of circular economy strategies. Afterward, the effects of different alternative cycles on sustainability were analyzed. Finally, the authors emphasized the contribution of “open-loops” that make commercial innovation possible in supply chains and may improve sustainability outcomes in material supply chains.

Emphasizing that increasing the recycling of plastic wastes is an important priority in a circular economy, Huysveld et al. (2019) conducted an implementation showing that recycling mixed and contaminated plastic wastes without combustion is more beneficial for the environment. By analyzing recyclability benefit ratio and recycled content benefit ratio indicators with a product lifecycle perspective, they presented the potential environmental benefits of open-loop recycling.

Under the economic benefits of previous circular economy studies, Tseng et al. (2020) emphasized that resource utilization optimizes resource and environmental sustainability within the closed-loop system, especially by minimizing waste, emissions, energy leakage, and resource input. The authors examined the effects of a multi-level supply chain system on circular economy diffusion effects using the lifecycle assessment tool.

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**Fig. 1 Flowchart of proposed methodology**

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Sehnem et al. (2019) aimed to investigate overlaps, complements, and differences in circular economy models, within the scope of reverse logistics, closed-loop, industrial symbiosis, and industrial ecology. The authors identified areas in which it is often contradictory, requiring further research, unlike other literature surveys.

Brydges (2021) stressed a transition to a more sustainable and less wasteful fashion industry within the review of the circular economy framework which has a more efficient closed-loop economy. He searched and examined how to apply the circular economy principles in the Swedish fashion industry. After a detailed analysis, they identified the gaps between circular economy principles in fashion brand approaches.

As far as the authors know, according to the comprehensive literature review that was conducted did not reveal any study on the open-loop and closed-loop supply chain network model based on circular economy regarding the recycling of electronic card wastes. In particular, it was seen that open-loop and closed-loop recycling products were associated with LCA in many studies. Likewise, it was determined that circular economy studies mostly intensified in the theoretical aspect, and there were fewer studies in the applied research aspect.

**Methodology**

In this section, the proposed methodology will be elaborated; in particular, the optimization model will be thoroughly discussed, followed by presenting the details about the data used. The flowchart of the proposed methodology is demonstrated in Fig. 1.

**Simultaneous optimization of closed-loop and open-loop networks with a circular economy perspective**

As a result of a comprehensive literature review and interviews conducted with implementers, a model involving
integrated closed-loop and open-loop supply chain network design for the lifecycle of PCBs is developed. The network design of the developed model is shown in Fig. 2, where the circular economy perspective represents value-adding processes such as repair, reuse, reproduction and recycling. The circular economy perspective discussed in this network design consists of a closed-loop supply chain involving a forward and a reverse supply chains together. The forward supply chain consists of four centers, namely suppliers, manufacturers, customers, and users, while the reverse supply chain consists of five centers as collection centers, disassembly centers, dismantler centers, recycling centers, and waste. Moreover, the materials dismantled at the dismantler centers are sent to open-loop users to be sold in the internal market. According to the developed model, the flow in the network starts with the purchase of a certain amount of tons of four types of materials (A, B, C, D) to be used in PCB production from suppliers. The materials obtained from the suppliers are assembled at the manufacturing center, and PCBs are produced, which the produced PCBs are then sent
to the customers who are the producers of electrical and electronic equipment (EEE), using these PCBs. The produced EEE is sent to the users who are at the final point of the forward supply chain. These EEE that are used by the users turn into products whose lifespan has ended after a while, and such products are referred to as WEEE, and they are obtained from the users by disassembly centers as a first point of the reverse supply chain. As the PCBs inside WEEE deteriorate over the time due to physical, chemical, and environmental effects, they become WPCBs once they become unfunctional. At the disassembly center, after the WPCBs inside the WEEE are dismantled, they are sent to the collection center when WPCBs reach a certain capacity. The WPCBs collected at the collection center are then sent to the dismantler centers, where the waste PCBs are first sorted into four main parts. \(\mu\) percent is divided as material A, \(\omega\) percent is divided as material B, \(\varphi\) percent is divided as material C, and \(\eta\) percent is divided as material D. These separated parts are sent to the open-loop users to be sold in the internal market. After first dismantling, material A, which constitutes a significant part of the PCBs, is turned into small pieces by grinding and crushing machines (This second-hand material A is referred to disassembled metal core board). Separated materials are then sent to the recycling center where they are subjected to chemical processing to obtain the minerals in the structure of this metal core board which constitutes the tz percent of the WPCBs. After chemical procedure, what remains is waste with a tt percent ratio. The raw materials, such as gold, copper, silver and palladium, from the WPCBs at the recycling center are processed for reclamation, and they that are obtained are sent to the suppliers to be reused.

During the solution of the model, an upper limit was determined regarding the numbers of manufacturing centers, disassembly centers, dismantler centers and recycling centers that needed to be opened for each period. This article aims to make optimum decisions regarding the capacity, the number of facilities, and their distances of the recycling, dismantler disassembly, collection centers for the most feasible solution. In the model shown in Fig. 3, the decision-maker (disassembly center) aims to maximize their net profit by minimizing their total transportation, purchasing and operation costs. Moreover, this article aims to make optimum decisions regarding the capacity, the number of facilities, and their distances of the recycling, dismantler disassembly, collection centers for the most feasible solution. Notations related to the model are presented in the ‘Appendix’ section. Other assumptions regarding the model are given below.

- Customer demands are exactly and completely met for each period.
- The capacities of all facilities in the network are constant and exact.
- Transportation, purchasing, operation and fixed facility costs are constant and separate.
- The recycling rates are known beforehand.
- It is assumed that no waste is created during manufacturing of parts and from the disassembly center.
- It is assumed that the raw materials obtained from the recycling center are not different to the original raw materials directly purchased by the supplier.
- It is assumed that the manufacturing centers are units that transform parts and raw materials into materials.
- The sum of the part percentages of the deliveries made from the dismantler center to different centers is assumed to be 1. That is, \(\mu + \omega + \varphi + \eta = 1\).
- It is assumed that the recycling center and disassembly center are controlled from a single center.
- The recycling rate and waste rate are assumed to be 1. That is, \(tt + tz = 1\).
- It is assumed that the transportation costs do not vary based on the type or dimensions of the parts.
- It is assumed that the second-hand material constituting a large part of the PCB is not different to semi-finished products.
- It is assumed that there is no carrying and sell-out cost.

Explanation of optimization model

The objective function in (5.1) belonging to the given MILP model consists of four parts. The first part (5.1) refers to the revenue obtained from the hybrid loop. The second part (5.1) refers to the operation costs for each facility, while the third part (5.1) refers to the fixed facility establishment cost. The fourth part (5.1) represents the transportation costs. With the objective function, it is aimed to maximize the profit regarding the flow in the network.

Objective Function

\[
Maksz = \left( \sum_{q=1}^{O} \sum_{p=1}^{P} H_{q,p} U_{q,p} + \sum_{p=1}^{P} \sum_{s=1}^{S} \sum_{w=1}^{W} USR_{q,p} d_{d,qp} \right. \\
\left. + \sum_{o=1}^{O} \sum_{fb=1}^{FB} \sum_{s=1}^{S} \sum_{w=1}^{W} SUP_{o,fb} e_{e,fb} \right) \\
+ \sum_{c=1}^{C} \sum_{s=1}^{S} \sum_{p=1}^{P} SUPC_{csp} g_{s,cp} \\
\left. - \sum_{j=1}^{J} \sum_{k=1}^{K} B_{j,kp} V_{j,kp} - \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{p=1}^{P} C_{klp} W_{lp} \right) 
\]

(5.1)
\[ \sum_{i=1}^{J} \sum_{j=1}^{J} \sum_{x=1}^{P} \sum_{y=1}^{P} a_{ijp} A_{ijp} + \sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{y=1}^{P} \sum_{m=1}^{N} \sum_{n=1}^{O} \sum_{p=1}^{P} r_{mp} D_{mp} \]

\[ \sum_{m=1}^{N} \sum_{n=1}^{O} \sum_{p=1}^{P} \beta_{mp} F_{mp} \]

\[ \sum_{o=1}^{O} \sum_{q=1}^{Q} \sum_{p=1}^{P} K_{arp} G_{ap} \]

(5.1b)

\[ \sum_{j=1}^{J} \sum_{i=1}^{I} \sum_{s=1}^{S} \sum_{t=1}^{T} \sum_{p=1}^{P} f_{isp} X_{isp} + \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{p=1}^{P} \mu_{mp} Y_{mp} + \sum_{n=1}^{N} \sum_{o=1}^{O} \sum_{p=1}^{P} \nu_{op} F_{op} \]

\[ \sum_{o=1}^{O} \sum_{q=1}^{Q} \sum_{p=1}^{P} f_{qop} T_{qop} + \sum_{q=1}^{Q} \sum_{p=1}^{P} f_{qop} Z_{qop} \]

(5.1c)

\[ \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{p=1}^{P} C_{klp} \Delta_{kl} + \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} B_{jkp} \Delta_{kp} \]

\[ \sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{p=1}^{P} D_{klp} \Delta_{kl} \]

\[ \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{p=1}^{P} E_{mp} \Delta_{mn} + \sum_{n=1}^{N} \sum_{o=1}^{O} \sum_{p=1}^{P} F_{nop} \Delta_{no} \]

\[ \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{s=1}^{S} \sum_{p=1}^{P} SU_{cosp} \Delta_{ocp} + \sum_{o=1}^{O} \sum_{c=1}^{C} \sum_{s=1}^{S} \sum_{p=1}^{P} SU_{cosp} \Delta_{ocp} \]

\[ \sum_{a=1}^{A} \sum_{b=1}^{B} \sum_{s=1}^{S} \sum_{p=1}^{P} SU_{aps} \Delta_{aps} \]

(5.1d)

The constraints (5.2)–(5.7) explain the capacity constraint regarding the relevant center. These constraints show that the quantity of product/material coming to the center cannot exceed the capacity of the relevant center. The constraint (5.2) shows that the quantity of the material carried from the supplier to the manufacturer cannot exceed the capacity of the relevant supplier.

\[ \sum_{j=1}^{J} A_{ijp} \leq e_{ijp} \]

(5.2)

The constraint (5.3) shows that the quantity of the product carried from the manufacturer to the customers cannot exceed the capacity of the relevant manufacturer.

\[ \sum_{j=1}^{J} B_{j kp} \leq t_{kp} X_{kp} \]

(5.3)

The constraint (5.4) shows that the quantity of the product carried from the users to the disassembly center cannot exceed the capacity of the disassembly center.

\[ \sum_{m=1}^{M} D_{mp} \leq d_{mp} Y_{mp} \]

(5.4)

The constraint (5.5) shows that the quantity of the product carried from the disassembly center to the collection center cannot exceed the capacity of the collection center.

\[ \sum_{n=1}^{N} E_{nop} \leq q_{np} P_{np} \]

(5.5)

The constraint (5.6) shows that the quantity of the product carried from the collection center to the dismantler center cannot exceed the capacity of the dismantler center.

\[ \sum_{n=1}^{N} F_{nop} + \sum_{s=1}^{S} \sum_{f=1}^{F} US_{afsp} \]

(5.6)

\[ + \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{p=1}^{P} US_{afsp} \]

\[ \forall o, p \]

The constraint (5.7) shows that the total quantity of the material carried from the dismantler center to the recycling center and the material sent to the waste center cannot exceed the capacity of the recycling center.

\[ \sum_{a=1}^{A} \sum_{f=1}^{F} \sum_{c=1}^{C} \sum_{s=1}^{S} \sum_{p=1}^{P} SU_{aps} \Delta_{aps} \]

(5.7)

The constraints (5.8)–(5.9) guarantee that the customer and user demands are completely met for each period.

\[ \sum_{j=1}^{J} B_{j kp} \geq z_{kp} \]

(5.8)

\[ \sum_{k=1}^{K} C_{klp} \geq n_{lp} \]

(5.9)

The constraints (5.10) to (5.14) show that the number of facilities belonging to the manufacturing, disassembly, collection and dismantler centers is constrained by an upper limit. In other words, they ensure that the number of facilities is under a desired level.
The constraints (5.15) to (5.25) are the balance constraints. These constraints show that the quantity of the product or material entering the relevant facility is equal to the quantity of the product or material leaving the facility.

\[
\sum_{j=1}^{J} X_{jp} \leq L_p \quad \forall p
\]

(5.10)

\[
\sum_{m=1}^{M} Y_{mp} \leq N_p \quad \forall p
\]

(5.11)

\[
\sum_{n=1}^{N} PP_{np} \leq R_p \quad \forall p
\]

(5.12)

\[
\sum_{o=1}^{O} T_{op} \leq ZZ_p \quad \forall p
\]

(5.13)

\[
\sum_{q=1}^{Q} Z_{qp} \leq S_p \quad \forall p
\]

(5.14)

The constraints (5.15) to (5.25) are the balance constraints. These constraints show that the quantity of the product or material entering the relevant facility is equal to the quantity of the product or material leaving the facility.

\[
\sum_{j=1}^{J} \sum_{s=1}^{S} A_{isp} = ws \sum_{k=1}^{K} B_{kp} = 0 \quad \forall i, p
\]

(5.15)

\[
\sum_{j=1}^{J} B_{kp} - \sum_{l=1}^{L} C_{lkp} = 0 \quad \forall k, p
\]

(5.16)

\[
\sum_{k=1}^{K} C_{lkp} - \sum_{m=1}^{M} D_{lm(p+1)} = 0 \quad \forall l, p
\]

(5.17)

\[
\sum_{n=1}^{N} E_{nm(p+1)} - \sum_{n=1}^{N} F_{no(p+1)} = 0 \quad \forall n, p
\]

(5.18)

\[
\sum_{m=1}^{M} E_{nm(p+1)} - \sum_{n=1}^{M} F_{no(p+1)} = 0 \quad \forall o, p
\]

(5.19)

\[
\sum_{n=1}^{N} F_{no(p+1)} \mu - \sum_{q=1}^{Q} \sum_{r=1}^{R} G_{oqr(p+1)} = 0 \quad \forall o, p
\]

(5.20)

\[
\sum_{n=1}^{N} F_{no(p+1)} \omega - \sum_{f=1}^{F} \sum_{s=1}^{S} USRA_{ofsp(p+1)} = 0 \quad \forall o, p
\]

(5.21)

\[
\sum_{n=1}^{N} F_{no(p+1)} \varphi - \sum_{f=1}^{F} \sum_{s=1}^{S} USRB_{ofsp(p+1)} = 0 \quad \forall o, p
\]

(5.22)

\[
\sum_{n=1}^{N} F_{no(p+1)} \mu + \sum_{o=1}^{O} \sum_{r=1}^{R} \sum_{q=1}^{Q} G_{oqr(p+1)} = 0 \quad \forall q, r, p
\]

(5.24)

\[
\sum_{o=1}^{O} \sum_{r=1}^{R} \sum_{q=1}^{Q} H_{qir(p+1)} = 0 \quad \forall q, r, p
\]

(5.25)

The constraint (5.26) refers to the non-negative values of the decision variables.

\[
A_{isp}, B_{kp}, C_{lkp}, D_{lm}, E_{nm}, F_{no}, G_{oqr}, H_{qir}, J_{r}, Q, \text{USRA}_{ofsp}, \text{USRB}_{ofsp}, \text{USRC}_{ofsp} \geq 0
\]

(5.26)

The constraint (5.27) refers to the binary variables that can take a value of 0 or 1.

\[
X_{jp}, Y_{mp}, PP_{np}, T_{op}, Z_{qp} \in \{0, 1\}
\]

(5.27)

**Description of Data**

The model consists of 4 suppliers, 2 manufacturers, 3 customers, 5 users and 3 different open-loop users. Additionally, there are 2 disassembly centers, 2 collection centers, 2 dismantler centers and 2 recycling centers in the model, wherein 4 types of parts and 4 types of raw materials are defined. Table 4 shows the values of the parameters used in the model, and it is worth noting that the parameter values are randomly specified in their determined intervals. The model is designed for 3 period flows. In this model, the unit transportation cost is set to 0.5 Turkish Lira (TL) per ton/km. The unit purchasing, processing and fixed facility costs vary periodically. The manufacturing, disassembly, collection, dismantler and recycling centers are restricted to the maximum of three centers. From the dismantler center, the ratio of the B materials sent to user A is 0.25 (\(\alpha\)); the ratio of the C materials sent to user B is 15 (\(q\)), and the ratio of the D materials sent to user C is 0.05 (\(l\)). Material A, 45% of which consists of the second-hand products, is sold to be reused in the internal market, and this way, profit is obtained in the loop. On the other hand, the remaining 55% (\(\mu\)) material A, is sent to the recycling center to be processed. 70% (\(t_z\)) of it is separated into raw materials such as silver, gold, copper, and palladium through chemical analysis methods (Ohajiwa, 2018).

After the chemical processes, 30% (\(t_t\)) waste is created. The ratios of the components found in WPCBs are 64% copper, 20% silver, 12% gold and 4% palladium (Ning et al. 2017). By sending the raw materials dismantled based on
these ratios to the suppliers to be reused in the network, a contribution is made to the circular economy.

The strengths and weaknesses of the model designed are compared in Table 5.

### Results

#### Computational results

MILP model was solved in 0,109 s with the GAMS program and CPLEX solver on a computer with a 1.4 GHz processor.
and 4 GB of RAM. The objective function is implemented on a hybrid network model design that is aimed to maximize the profit within the framework of the circular economy. The objective function value that maximizes profit in network design is found to be 9,712,360,457 TL. Table 6 illustrates data and percentages of each performance indicator in the objective function.

According to the results, the most important factors affecting the profitability are in-cycle acquisition revenues. Transportation cost is negligible compared to other costs, thereby when making investments, businesses can also ignore transportation costs compared to other costs.

### Table 6: Performance indicator values of the objective function

| Performance Indicators of Objective Function | Value (TL) |
|---------------------------------------------|------------|
| OF The objective function value (Net Profit) | 9,712,360,457 |
| PI1 Total revenue                           | 15,256,821,148 |
| PI2 The total cost of operation             | 5,533,357,058 |
| PI3 The total cost of fixed facility        | 1,574,920   |
| PI4 The total cost of transportation        | 9,528,712   |

Fig. 4 The best distribution network related to the third and next periods
In addition, the results also confirm that the recycle and remanufacturer applications provide a high profitability for businesses in circular economy-based approaches. Figures 3 and 4 illustrate overall material flow, quantities, and types of the developed model related to periods.

According to Fig. 3, the first period the flow starts with 1151,220; 1973,520; 767,480; 1589,780-tons material purchase form Supplier1 and 520,814; 892,825; 347,210; 719,220-tons material purchase from Supplier3. PCBs that are produced with these materials by manufacturers are transmitted to customers and users, respectively. The first period flow is completed in users.

In the second period, the flow starts with the supply of material from outside. Furthermore, this flow is continued to the manufacturer, customer and users, respectively. However, in this period, users from the first period 1000; 1700; 2062,06; 852; 548; 1800-tons of the PCBs are transferred to the disassembly center. 5352; 480; 2130,06 tons of waste PCBs removed from disassembled products are sent to the collection center. 3877,931; 1954,069; 2130,06-tons of waste PCBs are sent from the collection center to the dismantler center. Materials removed from the waste PCBs from the dismantler center are sold to open-loop users. Of the sold materials, 1990,517 tons of iron shipped to user A, 1194,311 tons of plastic shipped to user B, and 398,104 tons of iron shipped to user C. Furthermore, 2132,862; 2246,276-tons of waste metal core boards are sent to the recycling center. After chemical processes in the recycling center, the metal core board decomposes to its raw materials at certain rates. After the separation process 131,374; 262,748; 394,122; 525,497 tons of the waste occurred from raw material. During this period, 122,616 tons of palladium, 1961,854 tons of copper, 367,848 tons of gold and 613,079 tons of silver are obtained with chemical operations. Finally, these raw materials are sent to the material suppliers for the production/consumption in the loop. Therefore, the cycle is to get some of its raw material needs from recycling.

In the third period, the flow begins with the supply of material from outside. Furthermore, this flow is continued to the manufacturer, customer and users, respectively. Figure 4 shows that the next period will be transferred to the disassembly center and the cycle will continue in this way. In the third period, products from users in the second period are transferred to the disassembly center and are began their journey through the supply chain, respectively. In this period, the type of materials sent from the dismantler center to open-loop users differs from the second period. Materials removed from the scrap PCBs from the separation center are sold to open-loop users. Of the sold materials, 1973,448 tons of iron sent to user A, 1194,311 tons of aluminum sent to user B, and 394,689 tons of iron sent to user C. The rest is broken down into raw materials and sent to suppliers. Waste metal core boards are sent to the recycling center to chemical analysis and are separated into the raw materials (Yamane et al. 2011). Finally, these raw materials are sent to material suppliers for the production/consumption in the loop. Therefore, recycling in the network is completed simultaneously the open-loop and closed-loop design and within the circular economy perspective.

From this viewpoint, the computational case study demonstrated the network design contribution profit that consists of mainly economic dimensions in addition to environmental and social impact.

Scenario analyses

In this subsection, we provide a scenario analysis in order to showcase the limits and potentials of the developed model. Each scenario is based on the initial optimal model. The boundary of the model and the situations, in which the performance indicators that constitute the objective function, are comprehensively analyzed here. These are examined in terms of their sensitivities on the objective function as in the optimization study of a supply chain network design by Özceylan et al. (2014). PI1, PI2, PI3 and PI4 represent, respectively, the total revenue, total operation cost, total fixed facility cost, and total transportation cost. In this article, numerical examples are presented showing the cost savings that can be achieved by solving the developed mathematical model with scenario analysis.

Sensitivity to changes in capacities of facilities (Scenario 1)

Based on the assumption that the capacities of these facilities are within the normal limits, the manufacturer capacities are initially reduced by 5%. Then, the capacity values are systematically reduced until an infeasible solution is found. Along with the reduction of manufacturer capacity, a decrease in net profit is observed. Because of the requirement for new facilities to meet the product flow, fixed facility cost and transportation costs have also increased. A noticeable decrease in profit is observed as costs increase. The results are shown graphically in Figs. 5 and 6.
According to Scenario 1b, the capacity of the collection center is augmented from 10 to 90%. The results are shown graphically in Figs. 7 and 8. As collection center capacity is augmented, fixed facility costs and transportation costs are reduced simultaneously. There has been an increase in operating costs as the flow of product/material purchased per center is increased. Because of this flow, the revenue of sales has risen in net profit. In particular, there have been serious rises in profits after a more than 70 percent increase in capacity.

As a consequence of the different changes of capacity,

- Operation and transportation costs are increased due to the reducing capacity of the centers that lead to the requirement of a new plant.
- It is observed that net profit decreases as revenue-generating purchasing costs decrease for the cycle.

Sensitivity to changes in customers’ demands (Scenario 2)

The change in the demand has affected the transportation costs and in-cycle purchasing costs, which depend on the product flow. Since capacities have conformed to the ascend-ant demand, any extra fixed facility costs have not occurred. User demands have balanced customer demands, and therefore, the increased product demand by the customers has been met to a certain level. The results are presented in Table 7 and graphically plotted in Fig. 9.

Sensitivity to changes in manufacturer capacity and transportation cost (Scenario 3)

In this scenario, a rise in the manufacturer’s capacity starting from 15% and an exponential increase in the transportation costs are assumed. For this purpose, the change in the performance indicators in the objective function values is examined, and the results reveal that as the capacity increases, this facility meets the requirements more flexibly. Even if the transportation costs increase, the reduction in the fixed facility and operating costs yields an increase in the net profit. At
Table 7 Results according to Scenario 2

| Change in demand | Net profit   | PI1       | PI2       | PI3       | PI4       |
|------------------|--------------|-----------|-----------|-----------|-----------|
| (+)10%           | 2.063E +10   | 5.533E +09| 1.575E +06| 9.707E +06| 2.063E +10|
| (+)20%           | 2.062E +10   | 5.533E +09| 1.575E +06| 9.694E +06| 2.062E +10|
| (+)30%           | 2.061E +10   | 5.533E +09| 1.575E +06| 9.683E +06| 2.061E +10|
| (+)40%           | 2.061E +10   | 5.533E +09| 1.575E +06| 9.679E +06| 2.061E +10|
| (+)50%           | 2.060E +10   | 5.533E +09| 1.575E +06| 9.671E +06| 2.060E +10|
| (+)60%           | 2.059E +10   | 5.533E +09| 1.575E +06| 9.664E +06| 2.059E +10|

Fig. 9 Results for Scenario 2

Table 8 Results according to Scenario 3

| NC  | Change in capacity | Change in unit transportation cost | Net profit   | PI1       | PI2       | PI3       | PI4       |
|-----|--------------------|------------------------------------|--------------|-----------|-----------|-----------|-----------|
| C1  | 15%                | 3%                                 | 9.721E +09   | 1.526E +10| 5.524E +09| 1.40E +06 | 9.897E +06|
| C2  | 30%                | 7%                                 | 9.727E +09   | 1.526E +10| 5.518E +09| 1.40E +06 | 1.027E +07|
| C3  | 45%                | 12%                                | 9.733E +09   | 1.526E +10| 5.511E +09| 1.40E +06 | 1.064E +07|
| C4  | 60%                | 16%                                | 9.736E +09   | 1.526E +10| 5.509E +09| 1.04E +06 | 1.102E +07|
| C5  | 75%                | 23%                                | 9.735E +09   | 1.526E +10| 5.509E +09| 1.04E +06 | 1.178E +07|
| C6  | 90%                | 30%                                | 9.734E +09   | 1.526E +10| 5.509E +09| 1.04E +06 | 1.235E +07|

Fig. 10 Results for Scenario 3
the last change, high transport costs caused an unbalanced slope by fall in profits. The results are presented in Table 8 and graphically plotted in Fig. 10.

**Sensitivity to changes in the recycling ratio (Scenario 4)**

In this scenario, the effect of the change in the recycling ratio on the objective function is examined, and it is found that as the amount of waste sent to the recycling center decreases, a dramatic increase is observed in the net profit. To this end, from these results, we can come to the conclusion that recycling centers should have advanced technological machinery and equipment. With ionic methods that have high separation potentials, they can get more recycled raw materials in a framework that has higher profit and environmental returns. The results are shown in Table 9 and graphically plotted in Fig. 11.

**Discussion**

This section includes managerial inferences with regard to the obtained results and discusses how circular economy strategies could be effectively used in a WPCB supply chain. All inferences are considered specifically for waste PCBs and discussed in relation to the results of the developed network design.

**Managerial inferences**

The proposed study has significant operational and strategic contributions for decision-makers and policymakers who are associated with the recycling process of electronic cards. This section focuses on the managerial contributions in the framework of the model proposed toward recycling of electronic card wastes.

Taking these objectives presented in association with the study, actions that could be performed in the managerial sense and for the purpose of policy development are presented below.

- In the supply chain model proposed in line with the Refuse and Rethink objectives, wasting is prevented. Resources that are put into use again continue to stay in the supply chain ecosystem. It may be seen in the proposed network design that these resources are reused as an input for the suppliers. High-level managers need to enlighten all stakeholders regarding this implementation between the manufacturer and the consumer. Such strategies are compatible with circular economy objectives in terms of both minimizing costs and minimizing the damage induced on the environment.
- The Reduce objective exactly overlaps with the outputs of the proposed study. The products that are offered for reused in the supply chain processes reduce the amount of waste. Reduced amount of waste plays a supportive

**Table 9** Results according to Scenario 4

| Number of change | $T_r$ | $t_z$ | $P_{I1}$ | $P_{I2}$ | $P_{I3}$ | $P_{I4}$ |
|------------------|------|------|---------|---------|---------|---------|
| C1               | 25%  | 75%  | 1.526E+10 | 5.509E+09 | 1.041E+06 | 1.235E+07 |
| C2               | 20%  | 80%  | 1.741E+10 | 5.533E+09 | 1.575E+06 | 9.607E+06 |
| C3               | 15%  | 85%  | 1.849E+10 | 5.533E+09 | 1.575E+06 | 9.646E+06 |
| C4               | 10%  | 90%  | 1.956E+10 | 5.533E+09 | 1.575E+06 | 9.686E+06 |
| C5               | 5%   | 95%  | 2.064E+10 | 5.533E+09 | 1.575E+06 | 9.725E+06 |
role for environmental sustainability by reducing the damage on the environment. It is seen that in a structure where environmental policies are constructed on a strategic level, the hybrid supply chain models have a potential to provide direct contributions. In this sense, policy developers need to develop strategies toward making the supply chain approach as applicable as possible for all sectors for more constructive approaches.

- The Reuse, Refurbish and Remanufacture objectives are for diversifying the reuse and usage areas of products that have completed their usage lifespan. In the proposed model, by introducing electronic cards back into the usage process, an input advantage is provided for different sectors. It is vital for decision-makers to adopt a more systematic approach with the clustering method in the recycling ecosystem. With which sector the sector-based product outputs (waste) could be associated needs to be established accurately. This way, capacity and unavailability costs may be prevented. In addition to this, clustering may provide high profitability by minimizing fixed costs.

- In line with the Repurpose objective, recycled products used for different purposes also contribute to the competitive advantage. In the proposed open-loop supply chain model, secondary users achieve the advantage of accessing products at lower prices and with similar quality. This way, smaller manufacturers in the market may have a competitive advantage in the market. Priority may be given to SMEs with necessary regulations at the point of access to secondary raw materials.

- In the current circular economy environment, the recycling costs are still not on a desired level. There is a need for a more effective management system for recyclable products to be dismantled with lower costs and regained for the economy. In this sense, increasing the number of stakeholders involved in recycling processes may have a cost-reducing effect.

- Based on recycling of electronic cards, the contributions of the hybrid open-loop and closed-loop supply chain model in all sectors in terms of all aspects of sustainability (environmental, economic, social) should be demonstrated. In general, high-level managers focus on the economic aspect. Rather than this, there is a need for a holistic perspective. While the proposed model also focuses more on the economic aspect, the hybrid open-loop and closed-loop supply chain models provide many contributions especially in the environmental sense. In this century where climate change is at the top of the main problems, the environmental aspect has great significance. Moreover, social sustainability should also be considered for a framework where income equality is on a high level, and competitive advantage may be achieved. Circular economy creates new fields of work in many respects and allows obtaining recyclable and more inexpensive inputs. This way, a departure point for firms that are trying to find a place in the market may be provided.

**Assessment of circular economy objectives in the contest of a waste PCB network design**

This section firstly explains the circular economy goals which are complementary to each other and then, inferences proposed in line with these objectives are presented from a supply chain perspective.

Although the *Refuse (R0)* strategy is usually used by customers and users, it is also used by manufacturers. The Refuse strategy provides awareness between the manufacturer and the consumer that makes sense of the concept of circular economy. By directly reducing the need for materials for the relevant product by encouraging the development of other products that will provide the same function as the products included in the supply chain, it allows electronic cards to have a longer usage lifespan.

*Rethink (R1)* is a strategy providing an innovative point of view with a consideration producing value from waste rather than the take-do-dispose understanding of most industrial activities. In this study, rather than repurchasing electronic cards and using them in main products, sharing of recycled products is promoted. The benefits emerging with the adoption of the profitability and circular economy philosophy are also seen in the optimal solution outputs.

With the *Reduce (R2)* strategy, in addition to promotion of the use of technologies that will increase productivity in the manufacturing process of electronic cards, promotion of fewer resources by supporting modular design approaches is also proposed.

The *Reuse (R3)* strategy allows the use of PCB parts, which could serve their functions by being made active via the open-loop supply chain but are idle, by other consumers. This way, additional revenue is obtained, whereas the members of the open-loop supply chain are able to get the products they need with a lower cost and without causing additional use of resources.

The *Repair (R4)* and *Refurbish (R5)* strategies show similar effects in the case of PCBs. The facts that electronic cards constitute the semi-finished product of WEEE and that electronic card design and manufacturing technology does not allow refurbishing to a significant extent limit the effective use of these two strategies. For these technologies to be used effectively in the future, conducting the manufacturing and design processes of electronic cards compatibly with refurbish and repair will increase productivity.

With the *Remanufacture (R6)* strategy, parts that have the quality to be used in a new product after dismantling are sent directly to manufacturing by the relevant center. This way, the raw material need in manufacturing is met from the
inside of the supply chain with the help of the circular economy approach. Additionally, the materials that are harmful to the environment found in the structures of electronic cards are also eliminated.

Regarding the **Repurpose (R7)** strategy, the metal core board coming from the recycling center is dismantled into raw materials such as gold, silver, copper and palladium. The materials extracted from the electronic scrap cards sent to the disassembly center are obtained by open-loop supply chain users. In compliance with the needs of users, these materials are used to produce different products to serve their functions again.

**Recycle (R8)** is the most important strategy that allows integration of PCBs into a mode with the environmental, social and economic aspects. Examining the results of the model in detail, the highest profitability is obtained after the recycling processes. Furthermore, the recycling ratios, the method used for recycling and reducing the amount of waste are the most important factors that affect the productivity of the network loop. For this reason, by examining the effectiveness of the recycle strategy also with the conducted scenario analyses, its necessity for the case of waste PCB is presented.

While the **Recover (R9)** strategy may be presented as an effective solution for many recycling processes, it is not used with the same effectiveness in the waste PCB recycling process. A significant part of waste PCBs are used at different stages of the supply chain by recycling. The remaining small amount of waste is disposed of with different methods.

### Conclusion

In the scope of this study, by designing a network that deals with the circular economy perspective and the hybrid open-loop and closed-loop supply chain for recycling of waste PCBs, an optimal solution was searched with a mixed-integer linear programming model, which model was solved in 0.109 s with the GAMS program and CPLEX solver on a computer with a 1.4 GHz processor and 4 GB of RAM. With the developed network design, the lifecycle of PCBs depending on the ratio of the outputs obtained from recycling of waste and high profitability was examined. The objective function value that maximizes profit in network design is found to be 9,712,360,457 TL. In the function consists of the total revenue the total costs of operation, fixed facility, and transportation are 15,256,821,148 TL, 5,533,357,058 TL, 1,574,920 TL, and 9,528,712 TL, respectively. With this study, for the purpose of contributing to the literature, (i) an integrated open-loop and closed-loop supply chain network with a circular economy perspective was modeled by MILP, (ii) a case study on WPCBs was performed WPCBs, (iii) the model outputs were associated with the sustainability and circular economy objectives. Moreover, in the last part of the study, the sensitivities of the results regarding the changes in the parameters of the centers, such as capacity, demand, recycling ratio, and unit transportation costs, were measured with the scenario analyses, where the sensitivity of the relevant parameter was computed within the limits set in the range of 5%—95%, and managerial inferences were made.

According to the obtained results, product/material flows that affected revenues were among the most important factors affecting profitability. Considering the circular economy objectives, the reuse and repair objective mainly provide revenues for the activities included in the hybrid open-loop and closed-loop supply chain. In this context, it is seen that the CE objectives are applicable for not only closed-loop supply chain models but also open-loop supply chains. The obtained results also supported the idea that the rethink, repurpose, recover and refuse strategies discussed in the scope of the study are significant building blocks that make circular economy meaningful. As a result of the scenario analyses, the positive effects of the circular economy strategies on firm profitability were clearly demonstrated. The scope of recycling target demonstrates that in the second period, 122,616 tons of palladium, 1961,854 tons of copper, 367,848 tons of gold, and 613,079 tons of silver are obtained with chemical operations in the model. Furthermore, the higher recycling ratios, the method used for recycling, and reducing the amount of waste affected the productivity of the network loop and increased these recycling amounts.

This study also contributes to the literature by considering the gap with an open-loop and closed-loop supply chain network model based on a circular economy perspective regarding the recycling of electronic card waste. Furthermore, this study also contributes to sustainability studies by proposing a model that will protect natural resources and manage recycling flows. It is believed that this study, which presents a thorough model design regarding recycling of waste PCBs and also simultaneously discusses the hybrid model together within the circular economy perspective, will provide a significant contribution for academics, the scientific world and researchers.

Some issues which may be considered in future studies may be listed as: (i) facility selection and assignment problems regarding collection of electronic card wastes, (ii) looking for solutions by deep learning and artificial intelligence applications for waste collection methods, (iii) development of meta-heuristic techniques or technique providing exact results for large-scale problems, (iv) analysis of the closed-loop and open-loop supply chain practices in more specific sectors (automotive, computer, telephone, etc.), (v) analyzing the effects of technologies such as IoT and blockchain emerging with digitalization on supply chain management and a more in-depth analysis of technologies that affect sustainability in the ear of industry 4.0 in this context.
(vi) examination of the economic, environmental and social aspects of industry 4.0 technologies on sustainability dimensions and circular economy with actual case analyses.

Appendix

Nomenclature

Notations

The formulation for the mixed-integer model developed in light of the above information is given below.

Indices

\[
\begin{align*}
    i & : \text{set of material suppliers } i \in \{1, 2, \ldots, I\}. \\
    j & : \text{set of manufacturer } j \in \{1, 2, \ldots, J\}. \\
    k & : \text{set of customer } k \in \{1, 2, \ldots, K\}. \\
    l & : \text{set of users } l \in \{1, 2, \ldots, L\}. \\
    m & : \text{set of disassembly center } m \in \{1, 2, \ldots, M\}. \\
    n & : \text{set of collection centers } n \in \{1, 2, \ldots, N\}. \\
    o & : \text{set of dismantler centers } o \in \{1, 2, \ldots, O\}. \\
    q & : \text{set of recycling centers } q \in \{1, 2, \ldots, Q\}. \\
    v & : \text{set of dispose center } v \in \{1, 2, \ldots, V\}. \\
    fa & : \text{set of user } A fa \in \{1, 2, \ldots, FA\}. \\
    fb & : \text{set of user } B fb \in \{1, 2, \ldots, FB\}. \\
    fc & : \text{set of user } C fc \in \{1, 2, \ldots, FC\}. \\
    s & : \text{set of material types } s \in \{1, 2, \ldots, S\}. \\
    r & : \text{set of raw material types } r \in \{1, 2, \ldots, R\}. \\
    p & : \text{set of period } p \in \{1, 2, \ldots, P\}.
\end{align*}
\]

Positive Variables

\[
\begin{align*}
    A_{isp} & : \text{amount of material } (s) \text{ transported from raw material center } i \text{ to manufacturer } j \text{ in period } p \text{ (ton).} \\
    B_{jsp} & : \text{amount of product transported from manufacturer } j \text{ to customer } k \text{ in period } p \text{ (ton).} \\
    C_{ksp} & : \text{amount of product transported from customer } k \text{ to user } l \text{ in period } p \text{ (ton).} \\
    D_{lsp} & : \text{amount of product transported from user } l \text{ to disassembly center } m \text{ in period } p \text{ (ton).} \\
    E_{mp} & : \text{amount of product transported from disassembly center } m \text{ to collection center } n \text{ in period } p \text{ (ton).}
\end{align*}
\]

Parameters

\[
\begin{align*}
    F_{nop} & : \text{amount of product transported from collection center } n \text{ to dismantler center } o \text{ in period } p \text{ (ton).} \\
    G_{osp} & : \text{amount of second-hand products from dismantler center } o \text{ to recycling center } q \text{ in period } p \text{ (ton).} \\
    H_{qrp} & : \text{amount of raw material } (r) \text{ from recycling center } q \text{ to raw material center } i \text{ in period } p \text{ (ton).} \\
    J_{qvp} & : \text{amount of material } (r) \text{ from recycling center } q \text{ to dispose center } v \text{ in period } p \text{ (ton).} \\
    USRA_{ofsp} & : \text{amount of material } (s) \text{ from dismantler center } o \text{ to user } A fa \text{ in period } p \text{ (ton).} \\
    USRB_{ofsp} & : \text{amount of material } (s) \text{ from dismantler center } o \text{ to user } B fb \text{ in period } p \text{ (ton).} \\
    USRC_{ofsp} & : \text{amount of materials } (s) \text{ from dismantler center } o \text{ to user } C fc \text{ in period } p \text{ (ton).} \\
    X_{jp} & : \text{If the manufacturer } j \text{ opens in period } p \text{ 1; otherwise 0.} \\
    Y_{mp} & : \text{If the disassembly center } m \text{ opens in period } p \text{ 1; otherwise 0.} \\
    PP_{mp} & : \text{If the collection center } n \text{ opens in period } p \text{ 1; otherwise 0.} \\
    T_{vp} & : \text{If the dismantler center } o \text{ opens in period } p \text{ 1; otherwise 0.} \\
    Z_{vp} & : \text{If the recycling center } q \text{ opens in period } p \text{ 1; otherwise.}
\end{align*}
\]

\[
\begin{align*}
    e_{isp} & : \text{material capacity } (s) \text{ of material supplier } i \text{ in period } p. \\
    t_{jp} & : \text{manufacturer } j \text{ of capacity in period } p. \\
    z_{kp} & : \text{the demand of customer } k \text{ in period } p. \\
    n_{lp} & : \text{the demand of user } l \text{ in period } p. \\
    a_{mp} & : \text{disassembly center } m \text{ of capacity in period } p. \\
    q_{np} & : \text{collection center } n \text{ of capacity in period } p. \\
    b_{op} & : \text{dismantler center } o \text{ of capacity in period } p. \\
    c_{qrp} & : \text{recycling center } q \text{ of material capacities } (r) \text{ in period } p. \\
    aa_{jasp} & : \text{user } A fa \text{ of material capacities } (s) \text{ in period } p. \\
    bb_{josp} & : \text{user } B fb \text{ of material capacities } (s) \text{ in period } p. \\
    cc_{josp} & : \text{user } C fc \text{ of material capacities } (s) \text{ in period } p. \\
    \Delta_{ij} & : \text{distance between supplier } i \text{ and manufacturer } j \text{ (km).} \\
    \Delta_{jk} & : \text{distance between manufacturer } j \text{ and customer } k \text{ (km).}
\end{align*}
\]
A novel hybrid network optimization model for printed circuit boards recycling: a circular...

$\Delta_{kl}$ distance between customer $k$ and user $l$ (km).

$\Delta_{lm}$ distance between user $l$ and disassembly center $m$ (km).

$\Delta_{mn}$ distance between disassembly center $m$ and collection center $n$ (km).

$\Delta_{no}$ distance between collection center $n$ and dismantler center $o$ (km).

$\Delta_{qi}$ distance between recycling center $q$ and material supplier center $i$ (km).

$\Delta_{ofa}$ distance between dismantler center $o$ and user $fa$ (km).

$\Delta_{ofb}$ distance between dismantler center $o$ and user $fb$ (km).

$\Delta_{ofc}$ distance between dismantler center $o$ and user $fc$ (km).

$U_{isp}$ purchasing cost from material $i$ of material $s$ in period $p$ (TL/ton).

$u_{jp}$ manufacturing cost of manufacturer $j$ in period $p$ (TL/ton).

$V_{kp}$ purchasing cost of customer in period $p$ (TL/ton).

$W_{lp}$ purchasing cost of user in period $p$ (TL/ton).

$\gamma_{mp}$ operation cost of disassembly center $m$ in period $p$ (TL/ton).

$\theta_{np}$ operation cost of collection center $n$ in period $p$ (TL/ton).

$\beta_{op}$ operation cost of dismantler center $o$ in period $p$ (TL/ton).

$K_{qrp}$ operation cost of raw material $r$ in recycling center $q$ in period $p$ (TL/ton).

$cc$ transportation cost (TL/km*ton).

$ws$ the ratio of the weight of one-pieces to the total weight of the product (ton).

$wr$ the ratio of the weight of the semi-finished product (ton).

$dd_{osp}$ purchasing cost from dismantler center $o$ of material $s$ in period $p$ for user A (TL/ton).

$ee_{osp}$ purchasing cost from dismantler center $o$ of material $s$ in period $p$ for user B (TL/ton).

$gg_{osp}$ purchasing cost from dismantler center $o$ of material $s$ in period $p$ for user C (TL/ton).

$f_{jp}$ fixed facility cost of manufacturer $j$ in period $p$ (TL/ton).

$f_{mp}$ fixed facility cost of disassembly center $m$ in period $p$ (TL/ton).

$f_{np}$ fixed facility cost of collection center $n$ in period $p$ (TL/ton).

$f_{op}$ fixed facility cost of dismantler center $o$ in period $p$ (TL/ton).

$f_{qp}$ fixed facility cost of recycling center $q$ in period $p$ (TL/ton).

$L_p$ the largest number of the manufacturer in period $p$.

$N_p$ the largest number of disassembly center in period $p$.

$R_p$ the largest number of collection center in period $p$.

$ZZ_p$ the largest number of dismantler center in period $p$.

$S_p$ the largest number of a recycling center in period $p$.

$\mu$ percentage of material sent from dismantler centers to recycling centers.

$\omega$ percentage of material sent from dismantler center to user A.

$\varphi$ percentage of material sent from dismantler center to user B.

$ll$ percentage of material sent from dismantler center to user C.

$tt$ percentage of material sent from dismantler center to dispose center.

$tz$ percentage of raw material separated from the recycling center.

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Declarations

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