E-WASTE LOGISTICS NETWORK DESIGN

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Abstract: *E-waste represents one of the fastest-growing waste streams due to rapid scientific and technological development which contains both valuable and dangerous substances. So, this waste stream requires an adequate logistics network for collection, transport, and treatment. This paper presents an approach for e-waste logistics network design which is tested on a real-scale example.*

Keywords: *e-waste, logistics network, facility location.*

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1. INTRODUCTION

Electrical and electronic devices such as mobile phones, laptops, air-conditioners, etc. have become an essential part of modern everyday life. At the end of use, end-users discard electrical and electronic devices, in that way, generating an e-waste stream. In 2019, 53.6 million metric tons of e-waste were generated globally (Forti et al., 2020). The problem with e-waste, besides the generated quantities, is in its composition. Namely, e-waste contains toxic or hazardous substances, such as mercury, cadmium, brominated flame retardants (BFR), etc. On the other hand, e-waste contains precious and other metals such as iron, copper, gold, silver, etc. So, e-waste represents a valuable resource for secondary materials, if those materials are properly extracted (Figure 1).

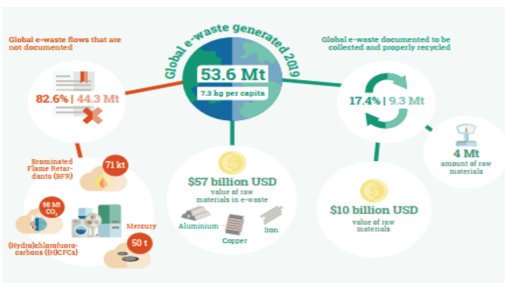

Figure 1. Global e-waste in 2019 (Forti et al., 2020)

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Another characteristic of e-waste is its reusability, that is electronic and electrical devices can be reused and sold on the secondary markets. Legislation like WEEE Directive in European Union (2002/96/EC) forces original equipment manufacturers (OEM) to take over their products, once they are discarded by users, regardless of the reason. On the other hand, the reuse of returned products, components, and reusable materials is very cost-effective for OEMs, especially with products that have a longer lifespan.

An adequate collection, transport, and treatment of e-waste creates additional flow in traditional logistics networks, and that is reverse flow of goods from end-user to OEMs (Figure 2). Logistics networks for the treatment of e-waste have additional facilities compared to traditional logistics networks, new activities, new involved parties, etc.

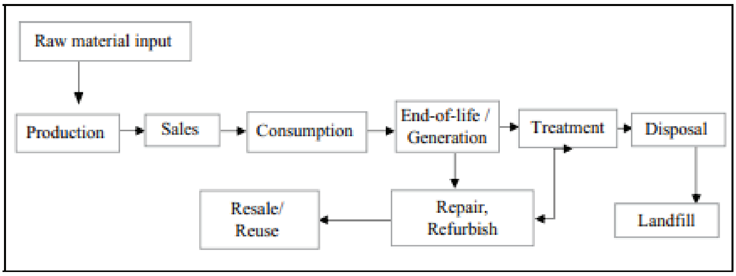

Figure 1. Life cycle of an e-product (Bhagat-Ganguly, 2022)

Many authors addressed the problem of logistics network design for e-waste. Safdar et al. (2020) proposed a multi-objective model to develop the economic, social, and environmental strategies for managing reverse logistic activities of collection, evaluation, reprocessing, and transportation of the returned electrical products. The authors used a neutrosophic optimization approach for the optimization of multi-objective networks. Kilic et al. (2015) proposed a mixed-integer linear programming model for reverse logistics network design for electronic waste in Turkey. The optimum locations of storage and recycling facilities are obtained for each of the defined scenarios. John et al. (2018) proposed an integer linear programming model which determines the optimal number and location of different facilities on the network. Mobile phones and digital cameras are considered for validation of the model. Alshamsi and Diabat (2015) proposed a mixed-integer linear program to address the complex network configuration of a reverse logistics system. The proposed model determines the optimal selection of sites, the capacities of inspection centers, and remanufacturing facilities. In this paper, we used the modified mathematical formulation for integrated logistics network design for e-waste, published in Lee and Dong (2008), and tested on a real-scale numerical example.

The paper is organized as follows. In Section 2, a description of the problem, and a mathematical formulation for logistics network design is described as well as a numerical example. Concluding remarks are given in Section 3.

2. PROBLEM DESCRIPTION

Computer equipment represents part of electric and electronic equipment that primarily does not have to be bought, that is companies can lease computer equipment from distributors or OEMs. By leasing computer equipment, companies have different benefits such as keeping the equipment up to date, and in this way, they are provided with newer equipment. Also, companies that lease computer equipment provide various services relating to repairs, proper permanent removal of data, etc. Companies that provide computer equipment lease services, in addition to the service of delivery of new products, also perform services of collecting products at the end of the lease, which results in complex logistics networks and activities. Namely, there is a need for additional facilities on the network, like collection centers for returned products or warehouses for new products. Forward and reverse flows of products can be observed separately or an integrated logistics network can be established in which forward and reverse flows are considered simultaneously.

In this paper, we used the modified mathematical model for integrated logistics network design published in Lee and Dong (2008) and tested it on a real-scale example. A company that leases computer equipment (in this paper this company will be noted as OEM) delivers it to customers (end-users). Parts or whole products of computer equipment are returned to OEM for treatment or safe disposal. In this integrated logistics network, in which forward and reverse flows of products are considered, a hybrid processing facility (HPF) is located. That is, HPF is a facility in which flows of new and returned products ones take place, and in that way OEM achieves cost savings. The aim of designing an integrated network is to choose locations of OEMs and HPFs, as well as determine the quantities of products to be shipped and return through the network in order to minimize total costs. The following notation was used in order to formulate a mathematical model:

M – a big number

CD – set of potential locations for OEMs

RD – set of potential locations for HPFs

D = CD U RD – set of all potential facility locations

C – set of all customers

E = C U RD – set of customers and potential locations for HPFs

N = D U C – set of all nodes on the network

S_k^F – quantity of the supply of new products at node k, $\forall k \in D$

D_n^F – quantity of the demand for new products at node n, $\forall n \in C$

D_k^R – quantity of the demand of returned products at node k, $\forall k \in D$

S_n^R – quantity of the supply of returned products at node n, $\forall n \in C$

C_{ij}^F – transport costs per unit of new products shipped along arc $a(i, j)$, $\forall i, j \in N$

C_{ji}^R – transport costs per unit of returned products shipped along arc $a(j, i)$, $\forall j, i \in N$

F_l – fixed costs of establishing HPF_l, $\forall l \in RD$

F_t – fixed costs of establishing OEM_t, $\forall t \in CD$

X_{ij} – quantity of new products transported from i to j, $\forall i, j \in N$

Y_{ji} - quantity of new products transported from j to i, $\forall i, j \in N$

Z_k – 1, if the facility is located, 0 otherwise, $\forall k \in D$

U_l – capacity of HPF_l, $\forall l \in RD$

q – number of HFPs to be located

t – number of OEMs to be located

The mathematical formulation of the problem is:

$$\text{Min} \sum_{l\in RD} F_l\, z_l + \sum_{p\in CD} F_p\, z_p + \sum_{i\in N}\sum_{j\in N} C_{ij}^F\, x_{ij} + \sum_{j\in N}\sum_{i\in N} C_{ji}^R\, y_{ji} \quad (1)$$

s.t.

$$\sum_{m\epsilon E} x_{km} - \sum_{i\epsilon N} x_{ik} = S_k^F z_k, \forall k\epsilon D \quad (2)$$

$$\sum_{i\epsilon N} x_{in} - \sum_{m\epsilon E} x_{nm} = D_n^F, \forall n\epsilon C \quad (3)$$

$$\sum_{i\epsilon N} y_{ni} - \sum_{m\epsilon E} y_{mn} = S_n^R, \forall n\epsilon C \quad (4)$$

$$\sum_{m\epsilon E} y_{mk} - \sum_{i\epsilon N} y_{ki} = D_k^R z_k, \forall k\epsilon D \quad (5)$$

$$\sum_{m\epsilon E} x_{km} \le M_{zk}, \forall k\epsilon D \quad (6)$$

$$\sum_{m\epsilon E} y_{mk} \le M_{zk}, \forall k\epsilon D \quad (7)$$

$$\sum_{n\epsilon C} y_{nl} \le U_l, \forall l\epsilon RD \quad (8)$$

$$\sum_{p\epsilon CD} Z_p = t \quad (9)$$

$$\sum_{l\epsilon RD} Z_l = q \quad (10)$$

$$Z_k=\{0,1\}, \forall k\epsilon D \quad (11)$$

$$x_{ij} \ge 0, y_{ji} \ge 0, \forall i, j\epsilon N \quad (12)$$

The objective function (1) minimizes the total costs of establishing an integrated logistics network: the costs of establishing HPFs, the costs of establishing OEMs, the transportation costs of shipping new products from OEM locations to customers directly or via HPFs, as well as transportation costs of collecting returned products from customers to OEM directly or via HPFs. Constraints sets (2) - (5) are flow conservation constraints. Constraints (6) and (7) enable the flow of new and returned products being transferred through HPFs only if the locations for HPFs are selected by the model. Constraints (8) are the capacity constraints for HPFs. Constraints (9) and (10) define the numbers of OEMs and HPFs to be established. Constraints (11) and (12) define the nature of the variables.

2.1 Numerical example

The described model was tested on a real-scale example for Vojvodina, the northern part of the Republic of Serbia. Vojvodina consists of 45 municipalities divided into 7 districts. In this example, we assumed that there are 4 potential locations for OEMs, 12 potential locations for HPFs, and the rest 29 municipalities are customers (end-users). Those locations for OEMs, HPFs, and customers are presented in Figure 3.

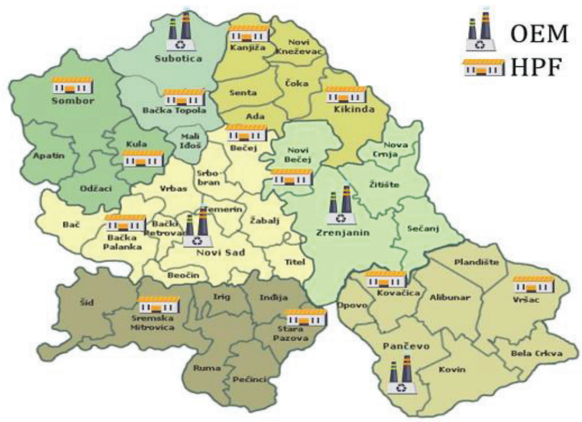

Figure 3. Potential locations for OEMs and HPFs

Input parameters for modeling are presented in tables 1 and 2. Capacities for all potential locations are sufficient. Quantities of supply and demand for new and returned products are expressed in the number of IT equipment units. This number is obtained on the basis of the number of inhabitants of each municipality and data on the number of IT equipment units placed on the market in 2020. Unit transportation costs for delivery of new products on the route OEM-end-user are set to 0.01€, OEM-HPF 0.0025€, and between HPF and end-user is set to 0.005€. Unit transportation costs for collection of returned products on the route OEM-end-user are set to 0.016€, OEM-HPF 0.004€, and between HPF and end-user is set to 0.008€. Fixed costs of opening HPFs are set to 100€, while fixed costs of opening OEMs are set to 500 €. All input parameters are normalized to a daily level.

Table 1. Input parameters for OEMs and HPFs locations

Potential locations for OEMs and HPFs	S_k^F	D_k^R
Subotica (OEM1)	451	369
Novi Sad(OEM2)	1206	987
Zrenjanin(OEM3)	382	312
Pančevo(OEM4)	396	324
Bačka Topola(HPF1)	101	83
Sombor (HPF2)	258	211
Kula(HPF3)	129	106
Bačka palanka(HPF4)	171	140
Bečej(HP5)	116	95
Kikinda(HPF6)	178	146
Kanjiža(HPF7)	78	64
Vršac(HPF8)	162	132
Kovačica(HP9)	79	64
Sremska Mitrovica(HPF10)	248	203
Stara Pazova(HPF11)	215	176
Novi Bečej(HPF12)	74	61

Table 2. Input parameters for end-users

End-user	D_n^F	S_n^R	End-user	D_n^F	S_n^R
Mali Iđoš	37	31	Ada	52	43
Apatin	87	71	Čoka	34	28
Odžaci	89	73	Žitište	49	40
Bač	43	36	Nova Crnja	31	25
Bački Petrovac	42	35	Sečanj	39	32
Beočin	50	41	Alibunar	61	50
Vrbas	129	106	Bela Crkva	53	43
Žabalj	83	68	Kovin	103	84
Srbobran	51	42	Opovo	32	26
Temerin	92	76	Plandište	34	28
Titel	50	41	Inđija	151	124
Sremski Karlovci	28	23	Irig	33	27
Novi Kneževac	34	28	Pećinci	64	52
Senta	72	59	Ruma	170	139
			Šid	102	84

The model was developed by Python programming language and solved by open-source software LP Solve IDE. We tested the proposed model for different values of parameters t and q. Parameter t is set to 1, 2 and 3, while parameter q takes values from range [1, 12]. The obtained results are presented in tables 3, 4, and 5.

Table 3. Numerical results for t = 1 and q = [1, 12]

Parameter *t* value	**Parameter *q* value**	**Objective function value**	**Opened OEM**	**Opened HPFs**									
1	1	2572.97	OEM2	HPF5									
	2	2285.05	OEM2	HPF11	HPF5								
	3	2174.7	OEM2	HPF3	HPF11	HPF5							
	4	2106.28	OEM2	HP3	HPF11	HPF5							
	5	2065.89	OEM3	HPF2	HPF5	HPF8	HPF10	HPF11					
	6	2078.01	OEM3	HPF2	HPF8	HPF5	HPF8	HPF14	HPF11				
	7	2098.9	OEM3	HPF2	HPF8	HPF5	HPF8	HPF14	HPF11	HPF9			
	8	2136.31	OEM3	HPF2	HPF3	HPF8	HPF5	HPF8	HPF10	HPF11	HPF9		
	9	2182.38	OEM3	HPF2	HPF3	HPF8	HPF5	HPF8	HPF10	HPF11	HPF9	HPF7	
	10	2283.51	OEM3	HPF2	HPF3	HPF8	HPF5	HPF8	HPF10	HPF11	HPF9	HPF7	HPF12

Table 4. Numerical results for t = 2 and q = [1, 12]

Parameter *t* value	**Parameter *q* value**	**Objective function value**	**Opened OEMs**	**Opened HPFs**								
2	1	2836.2	OEM3 OEM4	HPF3								
	2	2686.29	OEM3 OEM4	HPF5	HPF11							
	3	2579.23	OEM3 OEM4	HPF5	HPF11	HPF2						
	4	2560.03	OEM3 OEM4	HPF5	HPF11	HPF2	HPF1					

Parameter *t* value	**Parameter *q* value**	**Objective function value**	**Opened OEMs**	**Opened HPFs**								
	5	2514.5	OEM3 OEM4	HPF5	HPF11	HPF2	HPF5	HPF10				
	6	2558.45	OEM3 OEM4	HPF5	HPF11	HPF2	HPF4	HPF10	HPF9			
	7	2637.05	OEM3 OEM4	HPF5	HPF2	HPF5	HPF7	HPF9	HPF10	HPF11		
	8	2735.88	OEM3 OEM4	HPF5	HPF7	HPF9	HPF10	HPF11	HPF3	HPF4	HPF12	
	9	3166.72	OEM3 OEM4	HPF5	HPF7	HPF9	HPF3	HPF4	HPF12	HPF1	HPF6	HPF8

Table 5. Numerical results for t = 3 and q = [1, 12]

Parameter *t* value	**Parameter *q* value**	**Objective function value**	**Opened OEMs**	**Opened HPFs**					
3	1	3551.84	OEM1 OEM3 OEM4	HPF3					
	2	31522.9	OEM1 OEM3 OEM4	HPF1	HPF11				
	3	3103.15	OEM1 OEM3 OEM4	HPF1	HPF11	HPF10			
	4	3076.167	OEM1 OEM3 OEM4	HPF3	HPF11	HPF7	HPF8		
	5	3132.35	OEM1 OEM3 OEM4	HPF3	HPF11	HPF7	HPF8	HPF12	
	6	3318.52	OEM1 OEM3 OEM4	HPF1	HPF5	HPF9	HPF7	HPF11	HPF12

In case when only one OEM is located, a maximum of 10 HPFs can be opened. The model hasn't feasible solutions for locating 11 and 12 HPFs, due to input data. Minimal costs of 2065.59€ are achieved for locating 5 HPFs (HPF2, HPF8, HPF11, HPF10, HPF5) (Table 3). In case when 2 OEMs are located, a maximum of 9 HPFs can be opened. The model hasn't feasible solutions for locating 10, 11, and 12 HPFs, due to input data. Minimal costs of 2514.5€ are achieved for locating 5 HPFs (HPF2, HPF8, HPF11, HPF10, HPF5) (Table 4). In case when 3 OEMs are located, a maximum of 6 HPFs can be opened. The model hasn't feasible solutions when number of HPFs is larger than 7, due to input data. Minimal costs of 3076.17€ are achieved for locating 4 HPFs (HPF7, HPF11, HPF12, HPF15) (Table 5).

Allocation of direct and reverse flows of products are presented in tables 6, 7 and 8, for different values of parameters t and q and minimal values of objective functions. In case when one location for OEM is determined (Table 6), allocation of direct and reverse flows of products is done through five HPFs.

Table 6. Allocation of product flows for t = 1 and q = [1, 12]

Direct flows/Reverse flows	Zrenjanin (OEM3)	Sombor (HPF2)	Vršac (HPF8)	Stara Pazova (HPF11)	Bečej (HPF5)	Sremska Mitrovica (HPF10)
Mali Iđoš					37/31	
Apatin		87/71				
Odžaci		89/73				
Bač		43/36				
Bački Petrovac		39/31			3/2	
Beočin					50/41	
Vrbas					129/106	
Žabalj	83/68					

Direct flows/Reverse flows	Zrenjanin (OEM3)	Sombor (HPF2)	Vršac (HPF8)	Stara Pazova (HPF11)	Bečej (HPF5)	Sremska Mitrovica (HPF10)
Srbobran					51/42	
Temerin					92/76	
Titel	50/41					
Sremski Karlovci				23/23		
Novi Kneževac					34/28	
Senta					72/59	
Ada					52/43	
Čoka					34/28	
Žitište	49/40					
Nova Crnja					31/25	
Sečanj	39/32					
Alibunar			61/50			
Bela Crkva			53/43			
Kovin			103/84			
Opovo	32/26					
Plandište			34/28			
Inđija				151/124		
Irig				33/27		
Pećinci				64/52		
Ruma				24/20		146/119
Šid						102/84

Table 7. Allocation of product flows for t = 2 and q = [1, 12]

Direct flows/ Reverse flows	Zrenjanin (OEM3)	Pančevo (OEM4)	Sombor (HPF2)	Bečej (HPF5)	Stara Pazova (HPF11)	Vršac (HPF8)	Sremska Mitrovica (HPF10)
Mali Iđoš			37/31				
Apatin			87/71				
Odžaci			89/73				
Bač			43/36				
Bački Petrovac							42/35
Beočin					50/41		
Vrbas				127/106			
Žabalj	83/68						
Srbobran				51/42			
Temerin				92/76			
Titel					50/41		
Sremski Karlovci					28/23		
Novi Kneževac				34/28			
Senta				72/59			
Ada				52/43			
Čoka				34/28			
Žitište	49/40						
Nova Crnja				31/25			
Sečanj						39/32	
Alibunar						53/50	
Bela Crkva						61/43	
Kovin		103/84					
Opovo		32/26					
Plandište						34/28	
Inđija					151/124		
Irig					33/27		
Pećinci					64/52		
Ruma					66/55		104/84
Šid							102/84

In case when two locations for OEMs are opened, allocation of direct and reverse flows of products is done through five HPFs, where flow allocation for HPF8, HPF11 HPF10 is done through OEM4, while flow allocation for HPF2 and HPF5 is done through OEM3 (Table 7). The number of HPFs is the same as in the scenario for opening only one location for OEM, but since more objects are opened in this scenario total costs are higher.

Table 8. Allocation of product flows for t = 3 and q = [1, 12]

Direct flows/ Reverse flows	Zrenjanin (OEM3)	Pančevo (OEM4)	Kula (HPF3)	Vršac (HPF8)	Stara Pazova (HPF11)	Kanjiža (HPF7)
Mali Iđoš			37/31			
Apatin			87/71			
Odžaci			89/73			
Bač			43/36			
Bački Petrovac			42/35			
Beočin					50/41	
Vrbas			129/106			
Žabalj	83/68					
Srbobran			51/42			
Temerin	92/76					
Titel	50/41					
Sremski Karlovci					28/23	
Novi Kneževac						34/28
Senta						72/59
Ada						52/43
Čoka						34/28
Žitište	49/40					
Nova Crnja	31/25					
Sečanj	25/21			14/11		
Alibunar				61/50		
Bela Crkva				53/43		
Kovin		103/84				
Opovo		32/26				
Plandište				34/28		
Inđija					151/124	
Irig					33/27	
Pećinci					64/52	
Ruma					170/139	
Šid					102/84	

In case when three locations for OEMs are determined, allocation of direct and reverse flows of products is done through four HPFs, where flow allocation for HPF8 is done through OEM3, while flow allocation for HPF15 is done through OEM4 (Table 8). Also, since OEM1 supplies only HPF7 (349/288) and HPF3 (114/98) flows from and to OEM1 aren't presented in table 8. The total number of objects that are opened in this scenario is the same as in scenario 2, but since the opening of OEMs is more costly than HPFs, total costs are higher. It should be noted that one of the main characteristics of return flows is uncertainty in quantities of return products, while in this model those quantities are considered deterministic. In terms of total system costs, as expected, opening a larger number of objects on the network contributes to higher costs. However, the increase in costs is not so significant, compared to the number of opened objects in all scenarios of model testing.

3. CONCLUSION

This paper presents an approach for logistics network design in which forward and reverse flows of electronic products are considered. The proposed mathematical model can be applied to design an integrated logistics network with delivery and return flows of products, in which the same facility serves as a distribution center and collection center. The proposed model is tested on a real-scale example and the decision-maker is presented with different network configurations. Results of model testing showed that the model is dependent on input parameters, especially quantities of returned products and fixed costs of opening facilities. Hence, future research will focus on model upgrading to include consideration of uncertainty in determining model parameters (quantities of return products), different fixed costs per potential location, different capacities of located objects, involving different approaches for problem solving, etc.

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