$tc_{k,i}^{Cc-Rc}$	Cost of transporting per unit of recoverable product between collection center k and recovery center i
$tc_{k,d}^{Cc-Dis}$	Cost of transporting per unit of unrecoverable product for safe disposal between collection center k and disposal center l
cap_i^{MaxRc}	Max capacity of recovery center i
cap_j^{MazDc}	Max capacity of distribution center j
cap_k^{MaxCc}	Max capacity of collection center k
W_i^M	Capacity of manufacture i
$d_{cu_n,s}^{NewP}$	New product demand of customer cu_n in scenario s
$d_{cu_f,s}^{RecP}$	Refurbished product demand of customer cu_f in scenario s
$r_{cu_r,s}$	Returns of used products from customer cu_r in scenario s
pr_s	Probability of scenario s
α	Average disposal fraction
M	A large number

Decision variables:

$Z_{i,j,s}^{M-Dc}$	Quantity of new products shipped from recovery center i to distribution center j in scenario s
$Z_{j,cu_n,s}^{Dc-cu_n}$	Quantity of new products shipped from distribution center j to customer cu_n in scenario s
$Z_{j,cu_f,s}^{Dc-cu_f}$	Quantity of refurbished products shipped from distribution center j to customer cu_f in scenario s
$Z_{cu_r,cc,s}^{cu_r-Cc}$	Quantity of returned products shipped from customer cu_r to collection center k in scenario s
$Z_{k,i,s}^{Cc-Rc}$	Quantity of recoverable products shipped from collection center k dc recovery center i in scenario s
$Z_{k,d,s}^{Cc-Dis}$	Quantity of unrecoverable products shipped from collection center k to disposal center d in scenario s
$Z_{i,j,s}^{Rc-Dc}$	Quantity of refurbished products shipped from recovery center i to distribution center j in scenario s
$NS_{cu_f,s}$	Quantity of non-satisfied demand of customer cu_f in scenario s
W_i^{Rc}	Capacity of recovery center i
W_j^{Dc}	Capacity of distribution center j
W_k^{Cc}	Capacity of collection center k

$$x_i = \begin{cases} 1 & \text{Binary variable equals to 1 if a recovery center is located at location } i \\ 0 & \text{Binary variable equals to 0 if a recovery center is located at location } i \end{cases}$$

$$y_j = \begin{cases} 1 & \text{Binary variable equals to 1 if a distribution center is located at location } j \\ 0 & \text{Binary variable equals to 0 if a distribution center is located at location } j \end{cases}$$

$$q_k = \begin{cases} 1 & \text{Binary variable equals to 1 if a collection center is located at location } k \\ 0 & \text{Binary variable equals to 0 if a collection center is located at location } k \end{cases}$$

The objective function of the proposed model is shown in relation (1). The model minimizes capital cost of locating/opening the recovery centers, distribution centers, and collection centers. It also minimizes the cost of capacity based on the capacity decisions for each center. It is assumed that the cost of capacity increases linearly by the capacity of the center. Since the transportation quantity changes based on the stochastic demand, the cost of transportation among different levels of proposed model are minimized for each scenario. While the model is designed to satisfy the demand for new products and also have enough capacity to receive all returns of used products, there is a chance that the demand for refurbished products are not completely satisfied. For this purpose, $\sum_s \Pr_s\left(\sum_{cu2} NS_{cu2s} \times M\right)$ minimizes the quantity of non-satisfied demand of refurbished products.

$$Min\ v = \sum_i x_i f_i^{Rc} + \sum_j y_j f_j^{Dc} + \sum_k q_k f_k^{Cc} + \sum_i W_i^{Rc} c_i^{Rc} + \sum_j W_j^{Dc} c_j^{Dc} + \sum_k W_k^{Cc} c_k^{Cc} \quad (1)$$

$$+\sum_s \Pr_s \left(\begin{aligned} &\sum_i \sum_j Z_{i,j,s}^{M-Dc} \times Tc_{i,j}^{P-Dc} + \sum_i \sum_j Z_{i,j,s}^{Rc-Dc} \times Tc_{i,j}^{P-Dc} + \sum_j \sum_{cu1} Z_{j,cu_n,s}^{Dc-Cu_n} \times Tc_{j,cu_n}^{Dc-Cu_n} \\ &+\sum_j \sum_{cu2} Z_{j,cu_f,s}^{Dc-Cu_f} \times Tc_{j,cu_f}^{Dc-Cu_f} + \sum_{cu3} \sum_k Z_{cu_r,k,s}^{Cu_r-Cc} \times Tc_{cu_r,k}^{Cu_r-Cc} + \sum_k \sum_i Z_{k,i,s}^{Cc-Rc} \times Tc_{k,i}^{Cc-Rc} \\ &+\sum_k \sum_d Z_{k,d,s}^{Cc-Dis} \times Tc_{k,d}^{Cc-Dis} + \sum_{cu2} Ns_{cu_f,s} \times M \end{aligned} \right)$$

Subject to:

$$W_i^{Rc} \le x_i \times cap_i^{Max\,\mathrm{Re}} \qquad \forall i \quad (2)$$

$$W_j^{Dc} \le y_j \times cap_j^{MaxDc} \qquad \forall j \quad (3)$$

$$W_k^{Cc} \le q_k \times cap_k^{MazCc} \qquad \forall k \quad (4)$$

Constraints (2), (3), and (4) ensure that the capacity restrictions for each recovery, distribution, and collection center to be less than the maximum allowable capacity, respectively.

$$\sum_j Z_{i,j,s}^{M-Dc} \le \mathrm{W_i^M} \qquad \forall i, \forall s \quad (5)$$

$$\sum_j Z_{i,j,s}^{Rc-Dc} \le \mathrm{W_i^{Rc}} \qquad \forall i, \forall s \quad (6)$$

$$\sum_i Z_{i,j,s}^{M-Dc} + \sum_i Z_{i,j,s}^{Rc-Dc} \le \mathrm{W_j^{Dc}} \qquad \forall j, \forall s \quad (7)$$

$$\sum_{cu_r} Z_{cu_r,k,s}^{Cu_r-Cc} \le \mathrm{W_k^{Cc}} \qquad \forall k, \forall s \quad (8)$$

Constraints (5-8) are also capacity constraints with regard to the flow of products between the stages of the supply chain. More specifically, Constraint (5) assures that products are not produced more than manufacturers' capacities in each scenario. Constraint (6) shows that in each scenario the quantity of refurbished products shipped from each recovery center to distribution centers cannot exceed its capacity. Constraint (7) ensures that quantity of products (new and refurbished) shipped from manufacture i to distribution center j is lower than the capacity of distribution centers. The capacity of collection centers should be greater than customers' product returns in each scenario, as guaranteed by constraint (8).

$$\sum_{i} Z_{i,j,s}^{M-Dc} = \sum_{cu_n} Z_{j,cu_n,s}^{Dc-Cu_n} \qquad \forall j, \forall s \qquad \textbf{(9)}$$

$$\sum_{i} Z_{i,j,s}^{Rc-Dc} = \sum_{cu_f} Z_{j,cu_f,s}^{Dc-Cu_f} \qquad \forall j, \forall s \qquad \textbf{(10)}$$

$$\sum_{j} Z_{j,cu_f,s}^{\text{Dc-Cu}_f} + \text{Ns}_{cu_f,s} = d_{cu_f,s}^{\text{Rec}P} \qquad \forall cu2, \forall s \qquad \textbf{(11)}$$

$$\sum_{k} Z_{cu_r,k,s}^{Cu_r-Cc} = r_{cu_r,s} \qquad \forall cu3, \forall s \qquad \textbf{(12)}$$

$$\alpha(\sum_{cu_r} Z_{cu_r,k,s}^{Cu_r-Cc}) = \sum_{d} Z_{k,d,s}^{Cc-Dis} \qquad \forall k, \forall s \qquad \textbf{(13)}$$

$$(1-\alpha)(\sum_{cu_r} Z_{cu_r,k,s}^{Cu_r-Cc}) = \sum_{i} Z_{k,i,s}^{Cc-Rc} \qquad \forall k, \forall s \qquad \textbf{(14)}$$

$$\sum_{k} Z_{k,i,s}^{Cc-Rc} = \sum_{j} Z_{i,j,s}^{Rc-Dc} \qquad \forall i, \forall s \qquad \textbf{(15)}$$

$$\sum_{j} Z_{j,cu_n,s}^{Dc-Cu_n} = d_{cu_n,s}^{NewP} \qquad \forall cu1, \forall s \qquad \textbf{(16)}$$

Relation (9) ensures that the total amount of new products shipped from manufacture to distribution center is equal to the total amount of products shipped to customers CU_f from distribution center. Relation (10) presents a flow conservation constraint that assures the outflow of refurbished products from recovery center to each distribution center is equal to the inflow of products from each distribution center to the targeted customers in each scenario.
Relation (12) ensure that all returned products of customer CU_r are received and inspected in collection center K. The returned products are then classified into scrapped and recoverable products, so a portion of returned products are sent from collection center K to disposal centers D (i.e. constraint (13)) and the rest are shipped to the recovery centers I as described in relations (14).
Relation (15) assures that the outflow of recoverable products in a collection center is equal to the inflow of refurbished products in that distribution center at each scenario. Finally, relation (16) ensures that all new products demand of customers are equal to outflow of new products from all distribution centers at each scenario.

5. Conclusions and guidelines for future research

The need for strategic network design for reverse logistics which is constituent of returned products is more apparent than ever. Aside from national and international regulations for collecting and processing used products with the focus on environmental concerns, product stewardship and customers' awareness of global warming and other environment issues have changed the consumption behavior towards more sustainable products. The importance of systematic thinking for reverse logistics supply chain can be shown by economic impacts of various decisions that should be made for returned products. Specifically, returned products can be refurbished and sold to the customers in a lower price, remanufactured so that some parts can be reused in the manufacturing processes of new products, dispatched to raw materials when the raw material acquisition is costly or the natural supply of the raw material is limited and finally disposed safely with least harm to environment.
In this paper, a stochastic Mixed Integer Linear Programming Model (MILP) has been proposed for closed-loop supply chain network design problems under uncertainty. The closed-loop supply chain model considers the flow of both new and remanufactured products. The model is designed to make decisions about the number and location of collection centers to collect used products, recovery centers to remanufacture the used products, and finally distribution centers to receive the recovered products from manufacturers and sell it to the customers. It is assumed that the quantity and quality of returned products are stochastic and may change in each scenario. The model proposes a hybrid manufacturing/remanufacturing site when the location of remanufacturer is beneficial to be the same as manufacturer. Furthermore, the risk pooling concept is considered in distribution centers where new and refurbished products are aggregated.
While the proposed MILP model provides a generic platform for building closed loop supply chains, the limitations, processes, costs, regulations, and value stream of handling used products differ based on the industry. A remarkable

next step is to utilize this model for different industries and tailor the model based on industry features accordingly. Finally, in order to solve the model, Benders' decomposition approach is an appropriate exact method candidate since the model is structured as a two-stage stochastic model. The first stage of the problem decides around strategic decisions (i.e. the number and the locations of reverse logistic centers), while in the second stage, decisions pertaining the transportation costs are minimized. However, since the problem is NP-hard, therefore, achieving optimal solution in real-world problems could be intricate. Heuristics and Metaheuristic methods that provide a near optimal solutions for large scale problems are an appropriate replacement for exact methods in solving the proposed model.

References

Akçalı, E., Çetinkaya, S., & Üster, H. (2009). Network design for reverse and closed-loop supply chains: An annotated bibliography of models and solution approaches. *Networks, 53*(3), 231-248.

Amiri, A. (2006). Designing a distribution network in a supply chain system: Formulation and efficient solution procedure. *European Journal of Operational Research, 171*(2), 567-576.

Ayvaz, B., Bolat, B., & Aydın, N. (2015). Stochastic reverse logistics network design for waste of electrical and electronic equipment. *Resources, conservation and recycling, 104*, 391-404.

Batarfi, R., Jaber, M. Y., & Aljazzar, S. M. (2017). A profit maximization for a reverse logistics dual-channel supply chain with a return policy. *Computers & Industrial Engineering, 106*, 58-82.

Bidhandi, H. M., Yusuff, R. M., Ahmad, M. M. H. M., & Bakar, M. R. A. (2009). Development of a new approach for deterministic supply chain network design. *European Journal of Operational Research, 198*(1), 121-128.

Chopra, S., & Meindl, P. (2007). Supply chain management. Strategy, planning & operation *Das summa summarum des management* (pp. 265-275): Springer.

Doppelt, B., & Nelson, H. (2001). Extended producer responsibility and product take-back: applications for the Pacific northwest.

Dornfeld, D. A. (2014). Moving towards green and sustainable manufacturing. *International Journal of Precision Engineering and Manufacturing-Green Technology, 1*(1), 63-66.

Du, F., & Evans, G. W. (2008). A bi-objective reverse logistics network analysis for post-sale service. *Computers & Operations Research, 35*(8), 2617-2634.

Duta, L., Zamfirescu, C.-B., & Filip, F. G. (2014). Mathematical decision model for reverse supply chains inventory. *International Journal of Computers Communications & Control, 9*(6), 686-693.

El Ashhab, M., Afia, N., & El-Kharbotly, A. (2010). *A stochastic model for forward–reverse logistics network design under risk* (Vol. 58).

Erbis, S., Kamarthi, S., Namin, A. A., Hakimian, A., & Isaacs, J. A. (2016). Sustainable CNT-enabled lithium-ion battery manufacturing: evaluating the tradeoffs. *Environmental Science: Nano, 3*(6), 1447-1459. doi: 10.1039/C6EN00190D

Fattahi, M., & Govindan, K. (2017). Integrated forward/reverse logistics network design under uncertainty with pricing for collection of used products. *Annals of Operations Research, 253*(1), 193-225.

Fattahi, M., Govindan, K., & Keyvanshokooh, E. (2017). Responsive and resilient supply chain network design under operational and disruption risks with delivery lead-time sensitive customers. *Transportation Research Part E: Logistics and Transportation Review, 101*, 176-200.

Govindan, K., Fattahi, M., & Keyvanshokooh, E. (2017). Supply chain network design under uncertainty: A comprehensive review and future research directions. *European Journal of Operational Research*.

Hatefi, S., & Jolai, F. (2014). Robust and reliable forward–reverse logistics network design under demand uncertainty and facility disruptions. *Applied Mathematical Modelling, 38*(9), 2630-2647.

HP Innovates "Closed Loop" Inkjet Cartridge Recycling Program, Gives Plastic Water Bottles Second Life. (2008, 1/30/2008). Retrieved 05/10/2018, 2018, from http://www.hp.com/hpinfo/newsroom/press/2008/080130xa.html

Ilgin, M. A., & Gupta, S. M. (2010). Environmentally conscious manufacturing and product recovery (ECMPRO): a review of the state of the art. *Journal of environmental management, 91*(3), 563-591.

Jawahir, I., Dillon, O., Rouch, K., Joshi, K. J., Venkatachalam, A., & Jaafar, I. H. (2006). *Total life-cycle considerations in product design for sustainability: A framework for comprehensive evaluation*. Paper presented at the Proceedings of the 10th International Research/Expert Conference, Barcelona, Spain.

Jawahir, I. S., & Bradley, R. (2016). Technological Elements of Circular Economy and the Principles of 6R-Based Closed-loop Material Flow in Sustainable Manufacturing. *Procedia CIRP, 40*, 103-108. doi: https://doi.org/10.1016/j.procir.2016.01.067

Kasarda, J. D. (2017). Logistics Is about Competitiveness and More. *Logistics, 1*(1). doi: 10.3390/logistics101000

Keyvanshokooh, E., Ryan, S. M., & Kabir, E. (2016). Hybrid robust and stochastic optimization for closed-loop supply chain network design using accelerated Benders decomposition. *European Journal of Operational Research, 249*(1), 76-92.

Klibi, W., Martel, A., & Guitouni, A. (2010). The design of robust value-creating supply chain networks: a critical review. *European Journal of Operational Research, 203*(2), 283-293.

Ko, H. J., & Evans, G. W. (2007). A genetic algorithm-based heuristic for the dynamic integrated forward/reverse logistics network for 3PLs. *Computers & Operations Research, 34*(2), 346-366.

Lee, D.-H., & Dong, M. (2008). A heuristic approach to logistics network design for end-of-lease computer products recovery. *Transportation Research Part E: Logistics and Transportation Review, 44*(3), 455-474.

Lieckens, K., & Vandaele, N. (2007). Reverse logistics network design with stochastic lead times. *Computers & Operations Research, 34*(2), 395-416.

Lu, Z., & Bostel, N. (2007). A facility location model for logistics systems including reverse flows: The case of remanufacturing activities. *Computers & Operations Research, 34*(2), 299-323.

Melo, M. T., Nickel, S., & Saldanha-Da-Gama, F. (2009). Facility location and supply chain management–A review. *European Journal of Operational Research, 196*(2), 401-412.

Nickel, S., Saldanha-da-Gama, F., & Ziegler, H.-P. (2012). A multi-stage stochastic supply network design problem with financial decisions and risk management. *Omega, 40*(5), 511-524.

Pishvaee, M. S., & Rabbani, M. (2011). A graph theoretic-based heuristic algorithm for responsive supply chain network design with direct and indirect shipment. *Advances in Engineering Software, 42*(3), 57-63.

Pishvaee, M. S., Rabbani, M., & Torabi, S. A. (2011). A robust optimization approach to closed-loop supply chain network design under uncertainty. *Applied Mathematical Modelling, 35*(2), 637-649. doi: https://doi.org/10.1016/j.apm.2010.07.013

Pishvaee, M. S., & Torabi, S. A. (2010). A possibilistic programming approach for closed-loop supply chain network design under uncertainty. *Fuzzy sets and systems, 161*(20), 2668-2683.

Ramezani, M., Bashiri, M., & Tavakkoli-Moghaddam, R. (2013). A new multi-objective stochastic model for a forward/reverse logistic network design with responsiveness and quality level. *Applied Mathematical Modelling, 37*(1), 328-344.

Sahyouni, K., Savaskan, R. C., & Daskin, M. S. (2007). A facility location model for bidirectional flows. *Transportation Science, 41*(4), 484-499.

Santoso, T., Ahmed, S., Goetschalckx, M., & Shapiro, A. (2005). A stochastic programming approach for supply chain network design under uncertainty. *European Journal of Operational Research, 167*(1), 96-115.

Simchi-Levi, D., Simchi-Levi, E., & Kaminsky, P. (1999). *Designing and managing the supply chain: Concepts, strategies, and cases*: McGraw-Hill New York.

Snyder, L. V., Atan, Z., Peng, P., Rong, Y., Schmitt, A. J., & Sinsoysal, B. (2016). OR/MS models for supply chain disruptions: A review. *Iie Transactions, 48*(2), 89-109.

Soleimani, H., & Govindan, K. (2014). Reverse logistics network design and planning utilizing conditional value at risk. *European Journal of Operational Research, 237*(2), 487-497.

Tozanli, O., Duman, G. M., Kongar, E., & Gupta, S. M. (2017). Environmentally Concerned Logistics Operations in Fuzzy Environment: A Literature Survey. *Logistics, 1*(1), 4.

Üster, H., Easwaran, G., Akçali, E., & Çetinkaya, S. (2007). Benders decomposition with alternative multiple cuts for a multi-product closed-loop supply chain network design model. *Naval Research Logistics (NRL), 54*(8), 890-907.

Vahdat, V. (2017, 3-6 Dec. 2017). *Using simulation optimization for interdependent operations in health centers.* Paper presented at the 2017 Winter Simulation Conference (WSC).

Vahdat, V., & Vahdatzad, M. A. (2017). Accelerated Benders' Decomposition for Integrated Forward/Reverse Logistics Network Design under Uncertainty. *Logistics, 1*(2), 11.

Wang, F., Lai, X., & Shi, N. (2011). A multi-objective optimization for green supply chain network design. *Decision Support Systems, 51*(2), 262-269.

Wieland, A., Handfield, R. B., & Durach, C. F. (2016). Mapping the landscape of future research themes in supply chain management. *Journal of Business Logistics, 37*(3), 205-212.

Yu, H., & Solvang, W. D. (2017, 10-13 Dec. 2017). *A new two-stage stochastic model for reverse logistics network design under government subsidy and low-carbon emission requirement.* Paper presented at the 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM).

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