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A Study on Operations Research Models for Environmental Management*

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■ Abstract ■

This paper presents a review on the operations research models for environmental management including water, land, and air pollution in the environmental chain and including waste treatment, reverse logistics, and product recovery in the supply chain for last 30 years. The integrated and globalized environmental issues have given OR professionals a lot of natural opportunities for an effective environmental management with mathematical programming and computer simulation tool.

Keyword : Environmental Management, Reverse Logistics, Waste Management, Pollution control, Operations Research Models

1. Introduction

The protection of the environment has become an issue at all levels of society in the world, and the primary problems in environmental management are how to maintain high quality with as little economic sacrifice as possible. Therefore, within the field of Operations Research, attentions for the environmental issues have been increased rapidly.

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Talcott [64] stated : "… the opportunities for OR and MS are numerous. Environmental problems are substantial ; the costs of dealing with them are imposing." and gave more detailed examples of the contributions of OR to solve environmental decision-making problems. Bloemhof-Ruwaard et al. [6] suggested an integrated chain approach for the interactions between OR and environmental management (EM).

The objectives and goals of the EM have been evolved from end-of-pipe control (reduce waste and emission flows) towards waste prevention at the source by redesign products, processes and recycling. These changes pose many problems which OR can help to solve. Moreover, because the international and integrated characteristics of EM have made the complexities of many environmental problems very high, and because environmental regulations have controlled emissions in quantitative terms, quantitative models of the problems and efficient optimization techniques have been extremely useful for choosing the best among a well-defined set of alternatives. In this article, the mathematical programming models for environmental management including water, land and air quality management are introduced roughly. Air pollution is related to undesirable chemicals (CO_2, SO_2, CO) caused by automobile emissions and industrial emissions. Water pollution is related to the presence of undesirable chemicals which is measured by the concentration of dissolved oxygen, to the groundwater contamination and to the surface water quality control. Land pollution occurs from the pesticides injection and the storage of hazardous waste and solid waste.

The applications of OR on environmental issues can be distinguished between research toward the source of environmental damage and research on the receptors of the undesired effects. Bloemhof-Ruwaard et al. [6] and Daniel et al. [16] propose and apply the supply chain-environmental chain framework. The supply chain contains the extraction of raw materials, manufacturing, distribution and use of goods, and each component of chain generates waste and emissions in the environmental chain. In the environmental chain, emissions and waste are transported, dispersed, transformed and result in water pollution, air pollution, and soil pollution with damaging effects to the environment. OR application to the supply chain is related to modifications in the mix of productive activities to prevent or to control polluting side-effects, and to aim at a green supply chain. The application to the environmental chain is concerned with human interference in the ecosystem to cope with the damages caused by pollution.

2. Operations Research Modeling for Environmental Issues in Supply Chain

As the above-mentioned, OR application to the supply chain is related to modifications in the mix of productive activities to control polluting side-effects in order to aim at a green supply chain. Waste management, location analysis, reverse logistics and recovery management of used products, and life cycle analysis have been discussed in order to prevent the supply chain from environmental problems [6, 16], because they are very important operations and activities to influence environment and to enhance effects in the integration of environmental issues.

2.1 Waste management

The routing and the location problem for hazardous wastes and solid wastes have appeared in the OR literature for a long time.

2.1.1 Routing and risk management problem

Batta and Chiu [5] suggest a single objective formulation for hazardous waste routing, which include the size of the population impacted by an accidental release of hazardous waste. They considered risks on network nodes and links by assigning penalties and accident probabilities.

List et al. [40] suggest the problem of finding a route in a network to transport a hazmat(hazardous material). The model included multiple objectives, such as cost, population exposed and probability of an accident that are uncertain and vary with the time.

List and Turnquist [41] develop a multi-objective goal programming model for hazardous waste routing problem, which focus on finding a set of best routes with the trade-offs between transportation risk and transportation costs.

Jin et al. [33] present two decision-making problems for transporting hazmat (hazard materials). The problems are transformed into a nonlinear and constrained shortest loop-less path problem that can be solved as K- shortest path problem. They suggested an algorithm to search for good dual multipliers and the upper bound, and to close the duality gap.

Mourao and Almeida [48] present a Capacitated Arc Routing Problem (CARP) model with additional constraints for refuse collection which minimizes the total collecting cost of the household refuse. They made a minimum cost flow problem for lower bound with relaxation, which is solved as a transportation problem, and developed a three-phase heuristic algorithm with a route-first, cluster-second method and the first lower bound.

Jenkins [32] presents an integer programming model to select the sufficiently potential disaster scenarios which may be sudden release of a catastrophic quantity of pollutant into the environment. The objective function is to maximize similarity between the few selected accidents and the total set of potential accidents, subject to choosing just a limited number of the candidate scenarios.

2.1.2 Location problem

In the case of waste disposal location problems, the undesirability of a specific site and the environmental disturbances minimization have higher priorities than costs minimization.

Anandalingam and Westfall [3] suggest multi-attribute utility theory and fuzzy set analysis to select waste disposal alternatives.

Drezner and Wesolowsky [18] present a network algorithm to solve the location problem of an optimal route for pipelines carrying noxious materials.

Erkut and Neuman [21] use a multi-criteria analysis with criteria such as safety, size, distances, investment cost and operating costs.

Swersey and Thakur [63] suggest a mixed integer programming model to get the optimal location of vehicle emissions testing stations.

Erkut and Verter [22] try to develop the risk minimization route problem for hazmat transport. They consider risks of unit road segment, edge and path. The model of nonlinear programming was transformed into shortest path problem. They studied on a bicriterion approach and compared with minimizing total incident probability and total population exposure, but they conclude that incident-minimizing- probability-path produced different optimal solutions from population-exposure-minimizing-path.

ReVelle [56] suggests an air measurement point placement model to reduce unmonitored area and to minimize the maximum area or distance to a measurement point.

Fernandez et al. [23] present a continuous location model for siting an undesirable facility which undesirable effects don't endanger peoples' lives directly. The objective is to minimize the global repulsion of the inhabitants, and an interval analysis algorithm was developed for solving this location model.

2.1.3 Routing and location problem

For the location and routing of waste and hazmat, Greengerg [27] studied on a mixed integer programming for solid waste management model which is a transshipment network with sources, intermediate treatment plants and final disposal sites.

Gopalan et al. [25] and Karkazis et al. [34] identify an optimal transport routes of hazardous materials by using network analysis and integer programming.

ReVelle et al. [54] combine a shortest path algorithm with a zero-one location program and the multi-objective mixed integer programming model to solve the two criteria problem of minimizing transportation costs and minimizing perceived risks of sites in disposal of hazardous wastes.

Bloemhof-Ruwaard et al. [7] present a mixed integer programming model for a distribution network with plant and waste disposal units, and the coordination of product flows and waste flows. They discuss a two-level distribution and waste disposal problem with capacity constraints. The objective is to minimize the sum of fixed costs for plants and waste disposal units and variable costs for flows. Lower bound and upper bound procedures are analyzed in a branch and bound algorithm.

Liebman [39] describes operational researches on the many facets of solid wastes management including household wastes and pointed out multiple chinese postman problem and vehicle routing problems to design the collection routes of trucks, and mixed integer programming problems for location and capacity of various facilities of landfills, incinerators and transferstations. The mixed integer programming minimizes the sum of transport costs, opening costs and processing costs with constraint of road capacities and various limitations.

Chang and Wei [10] present a multi-objective nonlinear mixed integer programming model and genetic algorithms to allocate recycling drop-off stations of appropriate size and to design the collection-vehicle routing and scheduling program related to a geographical information system for the solid waste management systems.

Thiessen et al. [65] studied on the mathematical models of radionuclide distribution and transport, and mention that a quantitative assessment of the uncertainty, such as Monte Carlo sampling and sensitivity analysis, permitted the identification of areas to reduce the uncertainty in environmental transport model for radionuclides.

2.2 Reverse logistics and Product recovery management

Today, consumers and government expect

manufacturers to reduce the waste by handling products after consumer use : reverse distribution, inventory control within return flow, and product recovery management.

2.2.1 Reverse distribution

Caruso et al. [9] describe a solid waste management system, including collection, transportation, incineration, composting, recycling and disposal. They suggest a multiple objective location-allocation model and some heuristics to solve the number, the location of waste disposal plants and the amount of waste processed.

Del Castillo and Cochran [17] present a production and distribution planning model with resource constraint for products delivered in reusable containers and for transportation of empty containers back to the plants. The model is applied to a case study of a soft drink company using returnable bottles.

Spengler et al. [61] develop a mixed integer linear programming model for recycling process of industrial byproducts from an economic point of view, which is applied to the steel industry. The model is based on the multi-level capacitated warehouse location problem to decide on the capacities of recycling plants and their location-allocation.

Fleischmann et al. [24] address the reverse logistics of industrial reuse of products and materials from OR perspective. They discuss the implications of the emerging reuse efforts and review the mathematical programming models proposed in the literature, and comment that the influence of return flows on supply chain management is a future topic.

Barros et al. [4] present a multi-level capacitated warehouse location model and scenario analysis to decide the location of the demand points and the return flows in the network for the recycling of sand from construction waste. In this recycling network, there are regional depots to receive construction waste and to test its pollution level, and treatment facilities to clean the polluted sand and to provide sand for construction projects.

2.2.2 Product recovery systems

Product recovery management is defined as the management of all used and discard products, component, and materials for environmental responsibilities or economical benefits, and offers activities to handle products after consumer use : repair/reuse, refurbishing, remanufacturing, cannibalization, recycling and inventory control through return flow.

Simpson [59] introduces a product recovery model considering inventories for serviceables (remanufactured products for new demand) and recoverables (used products to be returned). He proposes a stochastic periodic review inventories model to trade-off between the material saving due to reuse of old products versus additional inventory carrying costs, and proves optimality of a three parameter policy to control the order, the recovery, and the disposal.

Muckstadt and Issac [49] develop an approximation method based on stochastic continuous review inventories model to solve order points and order quantities of returned products which will be remanufactured.

Kelle and Silver [35] present a chance constrained integer programming model for container purchasing with considering the returns of repaired container, and suggest an approximation procedure which can be transformed into the Wagner-Whitin model, and solve with a dynamic programming algorithm.

Mabini et al. [43] suggest a multi-item inventories model in the reverse logistics, which considers stockout service level constraints and a multi-item system where items share the same repair facility.

Salomon et al. [58] consider a periodic review inventory model with return flows of used products which can be either disposed or remanufactured.

Richter [57] proposes a modified EOQ model including a predetermined control policy with optimizing the control parameter of lotsizes for order and recovery and with linear holding costs for serviceables and recoverables. This model considers their dependence on the return rate.

Van der Laan et al. [67] present a numerical comparison of several disposal strategies, and suggest a disposal decisions on both the inventory level of remanufacturables and the total inventory position.

Inderfurth [31] considers the effects of nonzero leadtimes for orders and recovery in a stochastic periodic review model for the product recovery systems and for different leadtimes. The complexity of this model prohibits simple optimal control rules. He considers the case of a PUSH strategy for recovery, avoiding storage of recoverables.

2.3 Life cycle analysis

Life cycle analysis (LCA) is a process to evaluate the environmental burdens and impacts associated with a product, process 'from cradle to grave', and activity by quantifying energy and materials used and wastes released to the environment.

Pirila [52] suggests the emission-oriented production planning model which is a large multiple-period linear program and which leads to alternative strategies including process choices and recovery of waste products.

Weaver and Bloemhof-Ruwaard [69] present two types of linear programming product mix models using an environmental index converted from the environmental impacts of mix of several fats. One has a cost minimization objective and a constraint on environmental impact, and another has an environmental impact minimization objective and a constraint on costs.

Penkuhn et al. [50] present a nonlinear programming for the environmental integrated ammonia production. The objective is to maximize the costs of pure profit after subtracting recycling and disposal cost, and constraints are balances of the process-unit operations, market restrictions, emission control and landfill capacities. They solve this project with a sequential quadratic programming algorithm.

Mayer et al. [45] report that genetic algorithms and simulated annealing search usually produced better results than general mathematical programming (including LP, IP, NLP, Quadratic Programming) for an optimization problem of a large and herd dynamic model, as the number of dimensions and complexities are increased.

Chao and Peck [11] formulate a decision tree model with the Bayesian approach to investigate the optimal funding level for an environmental R&D activity.

3. Integrated Operations Research Modeling in Environmental Chain

The O.R application to the environmental chain is concerned with human interference in the ecosystem to cope with the damages caused by pollution. The scale of environmental problems has shifted over from the local and regional level to a continental and global level in the last few decades. The use of OR techniques has become spread in integrated environmental problem solving including water pollution, air pollution, and land pollution, and chemical/nuclear waste policy.

3.1 Air quality improvement

Kohn [37] uses principles of welfare economics to develop a LP model and give its application to policy analysis of electricity generation in particular airsheds. The LP models have the minimizing cost objective function and quality constraints that are formulated with the rates of pollutant emissions by activities and maximum allowable emission level of pollutant.

Modak and Lohani [47] present a spatial correlation analysis approach for the problem of optimal location and configuration of ambient air quality monitors.

Hordijk [30] and Alcamo et al. [1] develop an integrated assessment model(RAINS : Regional Acidification INformation and Simulation) based on linear and nonlinear programming with multiple objectives, which describes pollution generation and control, atmospheric transport and deposition, and environmental impacts for a Europe-wide reduction of the SO_2 emission and acid rain.

Ellis [20] proposes a LP model to minimize the cost of reducing SO_2 emissions, and shows how stochastic programming can be effective for the policy debate on acid rain, and introduces a method to incorporate estimates from different long-range transport models into one multi-objective stochastic program.

Alcamo [2] builds a dynamic simulation model based on non-stationary Markov chains for the greenhouse project to reduce the global warming effect and especially CO_2, and for the acid rain problem.

Cooper et al. [14] review the optimization models of air quality management for acid rain control, and describe the fundamental deterministic model for control of a single air pollutant as a linear programming to reduce the total unknown emission costs, and introduce a sensitivity analysis and multi-objective trade-offs involving total cost and measures of equity.

Loulou and Kanudia [42] propose a Minimax Regret formulation suitable for large-scale linear programming models for greenhouse gas abatement and for long-term analysis of energy-environment systems. Seven strategies are examined and compared : the Minimax Regret (MMR), the Minimum Expected Cost, and five short-sighted strategies, and they suggest that MMR strategy succeeded in reducing the worst regret incurred under any outcome of the uncertain target in the industrial gas consumption, alcohol consumption and commercial sector electricity consumption.

3.2 Land quality control

Colarullo et al. [13] present a quadratic programming model to determine discharge rates that minimize total cost, which has been a basis for more general model of land and ground quality control.

Heady and Vocke [29] collect and analyzed various LP models for soil erosion and land use including storage of crops and livestock growth, where the environmental impacts are soil erosions and chemical contaminations. Typically, the objectives are to minimize total production /transportation cost and violation, subject to constraints on the soil loss and damage limit, available land uses in producer regions, and contamination level under the activities of production and distribution.

Corbett et al. [15] present a mixed integer programming model in allocating a central budget on soil pollution problems to obtain the best overall environmental effect, subject to budget constraints, generated waste storage limits, and labor supply conditions in each region. As the integer programming model was too large to solve, they propose two-step heuristic procedure using a dynamic programming recursion and optimal path backtracking to find a maximum environmental effect for budget.

Reinhard et al. [53] compare a Stochastic Frontier Analysis(SFA) with a Data Envelopment Analysis(DEA) in order to estimate environmental efficiency measures based on the emissions and energy use for Dutch dairy farms. In DEA, environmental efficiency is computed with a linear programming which measures performance in terms of the ability of a producer to contract its environmentally detrimental inputs, given its output and its conventional inputs.

3.3 Water quality management

The LP model in the water quality control tends to minimize total cost subject to the flow equations and dissolved oxygen reductions at each segment of a stream (reach), and subject to balance equations of amount of pollutants as inventories of reach.

Yeh [70] shows the utilization of the techniques of linear programming, dynamic programming, and simulation for the design and the operation of reservoirs systems and to optimize the water resources management.

Somlyody and Wets [60] develop a simulation models combined with aggregated optimization model for controlling water quality of eutrophic lakes. The model contains a decomposition step with a hierarchy of simulation and an aggregation step incorporated in an optimization model to cope with complexity.

Meyer and Brill [46] suggest a simulation model of contaminant transport coupled with a facility location model to generate optimal locations for monitoring wells.

Bouzaher et al. [8] present a 0-1 knapsack problem with additional upper boundary constraints to assist control agencies for non-point source pollutions as a sediment deposition of reservoirs and lakes. The model is solved using dynamic programming and identified how and where selective actions can be taken for the most cost- effective manner.

RaVelle [55, 56] describes linear and dynamic programming to be applied to the water quality management models that are the allocation problems of pollution removal system to enhance the efficiency of the treatment plants of the cities and industries that discharge liquid wastes into a stream or a river system.

3.4 Integrated/global environmental policy

Continental and global problems are related with acidification and climate change. This macroscopic analysis has been important because emission in one country has effected environmental quality in other countries. Many researches on the integrated environments and the environmental economics have used various mathematical programming and especially Lagrangian duality.

Manne and Richels [44] develop Global 2100 model which is an integrated model of the macroeconomic relations, electricity generation, energy supplies, international oil trade and carbon emissions. The model is a partial equilibrium and nonlinear programming whose objective function is a logarithmic utility function of consumption. Most constraints are linear, and carbon emissions are determined by processes.

Stam et al. [62] develop a multi-objective linear programming model in order to determine trade-offs between environmental and economic criteria and to assist energy planners at the national level to build-up policies for fuel substitution.

Van Ierland [68] describes the development of environmental economics and the use of taxation and regulation in nonlinear programming models to search a Pareto optima for minimizing abatement and damage costs.

Cohan et al. [12] suggest deterministic global models of physical, biological and economic systems that are integrated into a decision tree system to accommodate uncertainties.

Pinter et al. [51] develop the Environmental Sensitive Investment System (ESIS) to assist both industry and government in policy analysis. The core of ESIS was a generic nonlinear programming, and it had potentials to show the economic impacts of environmental controls. It has been applied to the pulp and paper industry.

Kickert et al. [36] present the status of computer simulation model for evaluating the ecological, environmental, and societal consequences of global change in climate, land use, natural resources, human population dynamics, economics and energy. A lot of simulation model have applied various mathematical programming and OR methodologies to the subproblem-solving of the integrated environmental problems.

4. Conclusion

The integration-oriented and globalized environment issues have caused a natural opportunity for the interaction between OR and EM.

Greenberg [26] reported that LP and NLP have been used to address problems and to improve a model's validity, and most of the integrated modeling and environmental economics have used NLP analysis techniques and Lagrangian duality, and multiple objectives mathematical programming is regarded as an important frontier.

However, issues like hard measurability, highly integrated characteristics, and excessive complexity of environmental problems may impose serious barriers to this interaction. Kickert et al. [36] commented about using a meta-analysis technology for predictive modeling of effects under global change, because ecological risk assessment for policy analysis will be hampered by considerable uncertainties with the output of existing models.

Therefore, it will have been more important to design the models to handle easily uncertainty and sensitivity analysis, because EM models will have been more integrated, dynamic, stochastical and globalizing with physical, biological and economic systems. Integrated modeling with environment and economics have revealed opportunities for OR professionals in effective environmental management through the use of mathematical programming. OR professionals have to integrate with related sciences to be able to use tools like an advanced computer simulation model, environmental economics model, meta-analysis and life cycle assessment. Some adaptation to global environmental change caused by OR professionals will be necessary over this new century, because environmental issues and global climate change will have been more significantly harmful to human life, but on the other hand, it is extremely difficult to develop global win-win policy that will successfully prevent a dangerous anthropogenic interference with this global environment system.

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