Design of Environmental Regulatory Policies for Sustainable Emission Reduction

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DOI 10.1002/aic.10861
Published online May 16, 2006 in Wiley InterScience (www.interscience.wiley.com).

Current environmental emission regulations typically follow a command-and-control approach mandating the installation of state-of-the-art abatement technology to safeguard hard emission thresholds. However, this type of regulation offers no reward for conducting pollution prevention and technological research to reduce emissions below compliance levels through process innovation. Alternatively, market-based regulations stimulate continued improvement of cleaner manufacturing practices by creating economic incentives for sustained waste reduction. The aim of this work is to furnish regulators and manufacturers with a concise tool for quantifying the impact of future regulatory scenarios. The proposed methodology employs realistic mathematical models of pollution abatement operations used in chemical, pharmaceutical, and specialty chemical manufacturing. It assesses the feasibility of treatment options, estimates their cost and expected emissions. Rigorous optimization techniques are introduced for managing regional emission reduction efforts at reasonable cost to manufacturers. The comprehensive mathematical programming formulations will enable plant managers to ascertain expected compliance cost, and regulators to design environmental regulations for reducing regional emissions at tolerable cost to industry. © 2006 American Institute of Chemical Engineers *AIChE J,* 52: 2792–2804, 2006
Keywords: pollution prevention, emission trading, design of environmental regulations, multiperiod optimization, sustainable manufacturing

Introduction

Regulators like the Environmental Protection Agency (EPA) use different regulatory mechanisms to ensure socially acceptable emission levels caused by polluting industries. This work analyzes cost and environmental efficacy of different types of environmental regulations to reduce and control pollution. This article will contrast three different types of regulations for lowering air emissions from industry: Command-and-control policy, environmental tax, and emission trading.

Command-and-Control Policy. U.S. environmental regulations passed in the 1970s and 1980s focused on establishing legal limits on the permissible amount of pollutants discharged to the atmosphere, ambient air quality standards (AAQS). The AAQS applies to every pollution source like a chemical manufacturing site. The EPA also mandates the types of emission control known as best available control technology to abate specific pollution sources such. This *command-and-control* regulatory model "*controls*" emissions by prescribing maximum thresholds and "*commands*" the installation of specific abatement technology to avoid excessive pollutant releases. The regulatory control is enforced by corporate emission reporting and inspections. While manufacturers operating in a command-and-control environment have a legal obligation to ensure compliance, there is no reward for sustained process improvement toward progressively cleaner manufacturing.[1] Therefore, the command-and-control policy does not encourage process innovations beyond the mandated regulatory limits.

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Environmental Taxes. Some countries charge a tax for every unit of emitted pollutant. When the marginal pollution abatement cost are lower than the tax, manufacturers will voluntary reduce their discharges. When they are higher, manufacturers are likely to prefer paying the pollution tax. Air pollution charges have been implemented in Europe and Asia with different objectives. France encourages early adoption of new pollution control technology with subsidies financed by revenues from the pollution tax. In Japan, the tax is used to compensate air pollution victims.[1] Thus, environmental tax does create a stimulus for on-going research and development to reduce pollution by chemical manufacturing. Ideally, the tax level should be set slightly higher than the average marginal abatement cost. However, costs are proprietary corporate parameters that are very difficult to assess externally by regulators. Thus, finding an effective tax level requires an experimental procedure. During the trial-and-error period of establishing a suitable environmental tax level, manufacturers will be faced with varying taxation on their discharges. This regulatory uncertainty is undesirable for producers, as well as policy-makers.

Market-based Regulations. In recent years, economists have proposed novel market-based regulatory models. *Emission trading* engages competitive forces to stimulate pollution prevention to accelerate technological progress.[1-4] In an emission trading market, the regulatory agency collaborates with individual polluters for the common goal of managing acceptable environmental impact levels by *capping* or *reducing* total emissions from manufacturing. The emission cap limits the total discharges from a region or a group of polluters like emission in the State of Illinois or air pollution by power generators. The regulated industries receive titles known as *emission permits* or *credits* bearing the right to release a certain amount of pollutant.[2-8] The number of permits issued also limits the total volume of permissible emissions in that market. Each polluter must render titles equal to the amount of pollution they cause at the end of each period, usually a year. A company can sell surplus credits on a secondary market for profit. If the polluter exceeds its allocated quota, it can purchase additional titles on the market. This type of regulatory policy encourages pollution reduction efforts by offering revenues from the sale of surplus pollution rights. Despite the free exchange of permits, the system guarantees total pollution below the specified *cap*. The fundamentals of cap-and-trade system are further illustrated in the following simplified example.*

Example-Emission Trading. Figure 1 illustrates the basic concept of a cap-and-trade regulatory model considering only three polluters in a region (Plants A, B and C). It is assumed that the initial emissions of the entire region amount to 60 tons/yr of a certain pollutant like SO_2; with plant-A discharging 20 tons/yr, plant-B 18 tons/yr and plant-C 22 tons/yr. Suppose the region needs an emission reduction from 60 tons/yr to 50 tons/yr due to health concerns. Consequently, the regulator issues a smaller permit level reducing the cap by 17%. According to their last manufacturing record, and factoring the 17% emission reduction target, each plant would receive the following permit allocation: plant-A: 17 tons/yr, plant-B: 15 tons/yr and plant-C: 18 tons/yr. The reduced number of credits forces each plant to contribute to the reduction in air pollution. Suppose that plant-A meets the lower emission target by tighter

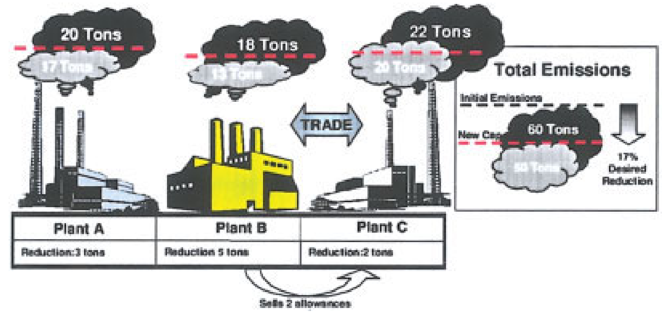

Figure 1. Conceptual representation of cap-and-trade model for reducing industrial air emissions.

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emission control. After investing in new abatement technology, plant-B only discharges 13 tons/yr, thus leaving 2 tons/yr of unused permits, which it will sell for profit. With some minor improvements, plant-C emits 20 tons/yr, 2 tons/yr more than its allocation. Therefore, plant-C has to purchase extra permits from the market, perhaps acquiring plant-B's surplus. Although plant-C releases more than its original permit allocation, the total SO_2 discharge in the entire region meets the desired emission reduction goal (in this case, $17+13+20 = 50$ tons/yr).

In the U.S., the Chicago Climate Exchange[9] adopts market-based principles for limiting green-house gases emissions (GHGs). In Europe, the EU Emissions trading scheme first implemented in Sweden in 2004, also created an emission market for reducing GHGs in accordance with EU commitment to the Kyoto protocol.[10-11]

Research literature, based on microeconomic theory demonstrates that emission trading achieves emission reductions at minimum abatement cost.[12-14] Recently, there is also interest in chemical engineering to study the efficacy of market-based regulations.[15-18] However, the high-level of abstraction used in economic models fails to illustrate the impact on actual operational choices on the plant-floor. In order to relate environmental regulations to plant operations, the model should also consider technological limitations of hazardous waste management and safe disposal. We propose to use computational models capable of generating feasible recycle and treatment options for all effluents in a chemical plant. By considering feasibility, cost and economical effect of all technically known recycle and treatment options for an entire region, this article will quantify the ecological, technological and monetary impact of different regulatory policies. This approach will estimate compliance costs for chemical manufacturing and ecological efficiency of different regulatory policy options in a region.

Outline. The methodology section briefly describes the computer-aided synthesis of different treatment flowsheets for optimally managing plant-wide emissions. The impact of regulations on chemical manufacturing practices section introduces a rigorous mathematical framework for long-term planning of production and investment policies in response to different regulatory scenarios. The impact on manufacturing practices expected by three regulatory models (command-and-control, emission taxation and emission trading) will be analyzed. The discussion section compares the compliance cost and achievable emission control realizable by different regulatory options. The optimal design of market based regulations section introduces the idea of "designing" market-based regulations for achieving desired emission reduction targets at minimum cost. This article closes with conclusions and significance.

Methodology

Systematic selection of waste reduction and pollution prevention technology

There are many different chemical and physical transformations to convert hazardous wastes into environmentally benign effluents. The *Combinatorial Process Synthesis (CPS)* is a computer-aided design approach that automatically produces technically realizable flowsheets of recycle and treatment options for transforming given effluent streams into one or more benign residuals. In step one of the combinatorial process synthesis depicted in Figure 2, the *superstructure generation* synthesizes all possible combinations of treatment flowsheets for all waste streams in a plant. The computer-aided analysis examines physical properties of the chemicals and mixtures for technology selection and estimates treatment cost and unavoidable emission levels and discharges. The methodology also considers each plant's production plan for a period of 10 years, a forecast of future waste scenarios and a database of recovery and treatment options as depicted in Figure 2 (top). A complete description of the *CPS* methodology is available elsewhere.[19-25,16] This article expands the *CPS* methodology *to automatically synthesize all treatment options* for a group of chemical plants in a region. The computer-aided synthesis of separation and chemical reaction networks delineates the technological options for effluent handling available to each manufacturer. Subsequent *superstructure optimization* discovers optimal plant operations and possible technology investments for further waste reduction for a planning horizon of five to 10 years. The multiperiod optimization will account for operating cost, the inventory of chemical processing units for recycle, reuse and chemical treatment steps, and capital cost to acquire new technology for waste reduction. The methodology will synthesize operating and investment strategies for all plants in the region for optimally accommodating different regulatory scenarios and production plans. This procedure also estimates the expected compliance cost to industry and the likely emission reduction imposed by a specific environmental regulation. Before quantifying the effectiveness of different environmental regulations to enforce cleaner manufacturing practices, the modeling assumptions used in this article are briefly discussed next.

Model input for generation of plant-wide waste management strategies

Only four plants are assumed to operate in a geographical region to demonstrate the methodology, while keeping the results within reasonable page limits. Market and business forecasts for each site lead to expected plant production data for the entire planning period. From these projected production figures, one can infer the expected waste loads and compositions, the so-called *waste forecast*. The expected discharges for each site are depicted in Figure 3 (right). Hence, type, amount and composition of several waste categories are known for each site, and are summarized in the stream tables given in the appendix. The discharges of waste categories associated with high-demand products are expected to increase rapidly, while other effluent mixtures are likely to grow moderately. Each of the hazardous waste categories has to be neutralized in one or more recycle and treatment steps. Each step requires a specific processing unit available in the *plant inventory*. The initial *inventory* of each manufacturing site is depicted in Figure 3 (left). This inventory of processing equipment includes a solvent recovery facility with distillation and scrubbing columns, different onsite incinerators, and wastewater treatment facilities.

The *CPS* algorithm synthesizes a network of all feasible

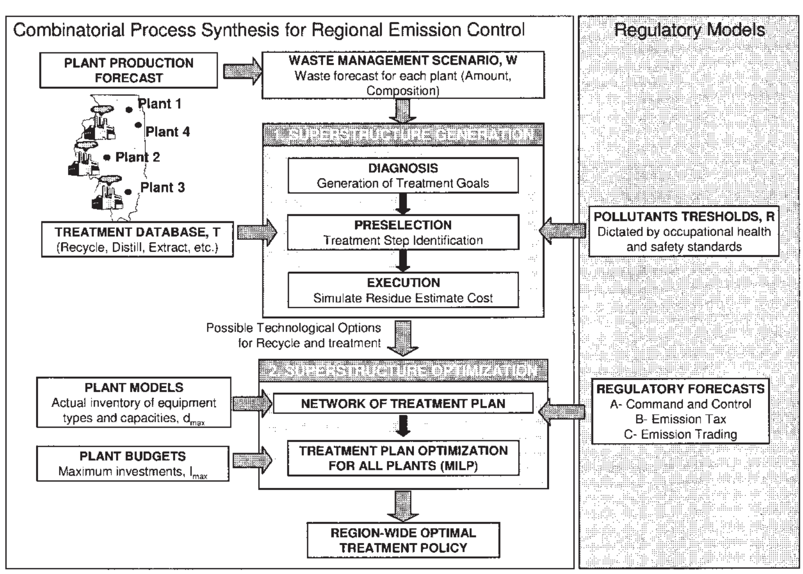

Figure 2. Methodology for assessing regional emissions and compliance cost in response to more stringent environmental regulations.

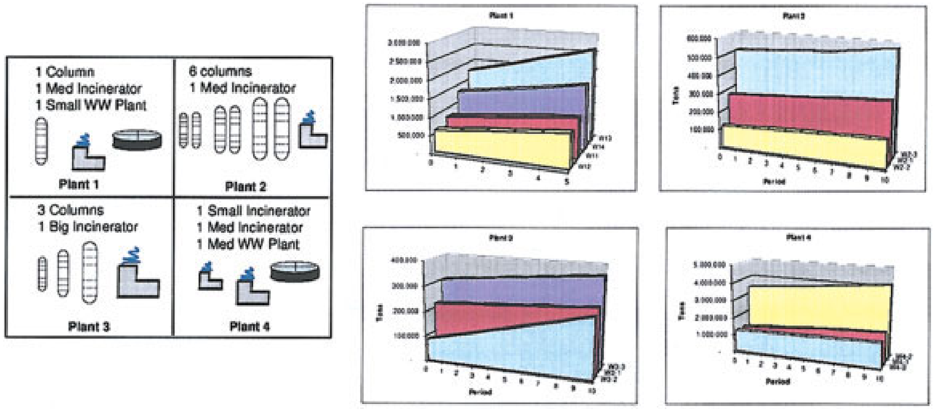

Figure 3. Left: Symbolic representation of initial plant infrastructure for solvent recovery and waste treatment: including distillation towers, incinerators and wastewater treatment plants; right: *Waste forecast* for each plant, indicating the expected waste discharges for the next 10 years.

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recycle and treatment options to convert a given waste category into benign discharges. The exhaustive search of the treatment database is implemented by a linear planning algorithm.[23] The superstructure of recycle and treatment options is complete with respect to the unit operations encoded in the treatment database.

The superstructure for all plants in the region delineates the technological options for waste reduction with state-of-the-art technology. The detailed superstructure for all plants in a region is given in the Appendix. Each superstructure contains multiple treatment policies to manage all plant effluents. Each policy gives rise to different treatment cost and causes specific unavoidable residual emissions. Some of the superstructure operations that are technologically feasible are not realizable at a particular site, when the specific equipment type is not in inventory or its free capacity is insufficient. The subsequent superstructure optimization identifies the most effective waste management strategy embedded in the superstructures including investment options to increase the plant inventory with more effective abatement technologies. The next section will illustrate the degree by which different environmental policies force industry to adopt cleaner manufacturing practices.

Impact of Regulations on Chemical Manufacturing Practices

This section analyzes the expected compliance cost and projected emission reduction for reducing the regional carbon dioxide output by 15% under three different environmental regulatory types. The first section estimates the compliance cost for this region under a command-and-control type of regulation. The second estimates the impact of a similar regulatory change guided by pollution tax. The third problem assesses cost for air pollution reduction using a market-based approach. It will be interesting to explore whether the cap-and-trade regulatory policy really leads to the desired air emission reduction at minimal cost to manufacturers as suggested by economic theory.

Command-and-control policies

Under a command-and-control environmental policy, all polluters are forced to comply with prescribed emission thresholds. Our models provide an analytical approach to predict the compliance cost for implementing a more stringent command-and-control emission standard. The multiperiod formulation shown in expressions 1 to 9, constitutes a mixed-integer-linear program for modeling the industry's waste management strategies under *command-and-control* regulations. The proposed mathematical programming approach predicts the manufacturers' operational and investment choices under the assumption of utility maximization. The proposed formulation is a multiobjective program with equal weight γ^p for the plants' individual cost minimization goals. Alternatively, a multiplayer game-theoretic model is possible; this approach however is beyond the scope of this article. A planning horizon of 10 years limits the interval for making investment decisions. Plant operating policies and emissions are locked after the end of the planning period ($n = 10$). Nevertheless, an economic horizon of $N = 20$ years is considered in order to asses the long-term impact of technological investments. The optimal solution fixes binary decision variables $x^p(t)$, reflecting different choices of recycle or treatment steps in each plant during each period. It allocates each unit operation to a specific piece of equipment e, and optimally places investment decisions to augment the plant capacity or acquire equipment for new recycle or treatment operations. From a pure cost optimization point-of-view, some pollution control options may not be adopted by manufacturers unless environmental regulations limit discharges or create monetary incentives for pollution avoidance. The objective in Eq. 1 is to minimize the total net present cost of each plant NPC, factoring the net present operating cost and the annualized capital investment. The term, NPC_{Op}, includes the operating costs in each period as given in Eq. 2. Inequality (Eq. 3) limits the waste streams directed to an equipment to its available capacity $C_T^p(t)$. The capacity of the waste treatment unit can be increased by capital investment decisions. The capital cost for investments in Eq. 4 accounts for the purchase price of each equipment type, C_e, and the number of units bought in the period $\Delta n_e^p(t)$. The resulting plant capacity expansion is reflected in Eqs. 6 and 7. Constraint (Eq. 8) performs facility

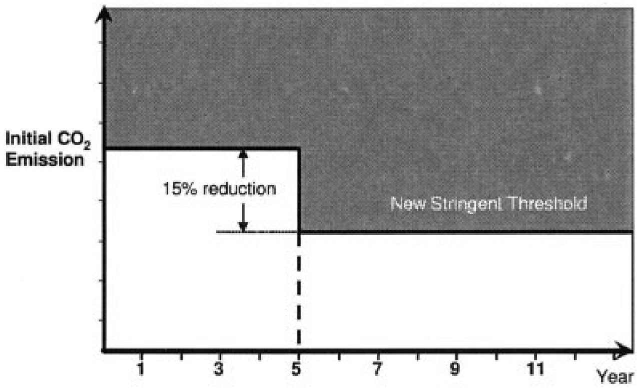

Figure 4. Expected command-and-control regulation to reduce CO_2 emissions by 15% over five years.

allocation of each recycle and treatment task into a corresponding plant equipment e.

$$Z = \min_{x_j^p, \Delta n_e^p} \sum_{\forall p} \gamma^p (NPC_{Op}^p + NPC_{Cap}^p)$$
s.t.

$$\textit{Minimize Each Plant's Cost} \quad (1)$$

$$NPC_{Op}^p = \sum_j \sum_{t=0}^{N} (1+r)^{-t} \cdot \underbrace{c^p(t) \cdot x_j^p(t)}_{\textit{Operating Cost}}$$

$$\textit{Net Present Operating Cost} \quad (2)$$

$$\sum_j x_j^p(t) \cdot Cpt_T^p(t) \leq C_T^p(t) \qquad \textit{Capacity Constraints} \quad (3)$$

$$NPC_{Cap}^p = \sum_{t=0}^{n} (1+r)^{-t} \sum_{\forall e \in I_e} C_e \cdot \Delta n_e^p(t)$$

$$\textit{Expansion Capital Cost} \quad (4)$$

$$n_e^p(t) = n_e^p(t-1) + \Delta n_e^p(t) \qquad \textit{Equipment Purchase} \quad (5)$$

$$C_T^p(t) = C_T^p(t-1) + \Delta C_T^p(t) \qquad \textit{Capacity Expansion} \quad (6)$$

$$\Delta C_T^p(t) = \sum_{\forall e} \Delta n_e^p(t) \cdot S_e \qquad \textit{Capacity increase} \quad (7)$$

$$map(x_j^p(t), e); \ \forall x_j^p \neq 0 \qquad \textit{Facility Allocation} \quad (8)$$

$$\sum_j x_j^p(t) \cdot E_j^p(t) \leq e_{\max}^p(t) \qquad \textit{Emission Standard Limit} \quad (9)$$

where $p \in$ {Plants}, e = {equipment}, r: interest rate

Results of the Command-and-Control Policy. Command-and-control regulations prescribe hard limits on total emissions for each site. Therefore, the total emissions emanating from a site, $E^p(t)$, must remain below the regulated threshold, $e_{\max}^p(t)$, imposed by inequality (Eq. 9). It is also possible to implement best-available-technology specifications, such as the MACT standards by fixing *a priori* decision variables associated with mandated environmental control technology, for example, the rule "*definitely use a scrubber after every incinerator*". The regulatory forecast of the command-and-control scenario in the case study assumes a hypothetical goal of cutting CO_2 emissions by 15% within a period of five years. The regulation establishes hard bounds on the maximum permissible carbon dioxide discharges as depicted in Figure 4. The corporations have to invest in new treatment technology in order to reduce pollution, while at the same time increase production. This is a challenge for this industry because production is expected to grow at an average rate of 3% per year.

The computational analysis generates novel plant operating schemes for polluters to comply with the hard carbon dioxide (CO_2) reduction goal. Figure 5 shows that plants one, three and four have to purchase new separation equipment. Most investments are necessary immediately after the enactment of the lower CO_2 limit. These technological investments include distillation columns to recover solvents, thus, eliminating CO_2 emissions associated with waste incineration. Plant-2 equipped with the best initial infrastructure can afford to delay investments by initially shifting from waste incineration to more solvent recovery with available in-house equipment. This manufacturing site maintains on-site solvent recycling until year nine. At that point, it has to acquire more distillation columns to accommodate its moderate increment in organic waste loads. Plant-4 also needs to reduce waste incineration in favor of more environmentally friendly solvent reuse for compliance. The adoption of waste recycling requires substantial capital investment in years four and seven.

Figure 6 displays the projected CO_2 discharges by each plant over time. The plot confirms each plant's compliance with the hard emission reduction goal of 15% in year five. The optimal solution of the proposed methodology computes budget and schedule for introducing necessary plant investments for manufacturers in the region. These expenditures are a good estimate of the cost to industry for achieving the desired reduction in air emissions.

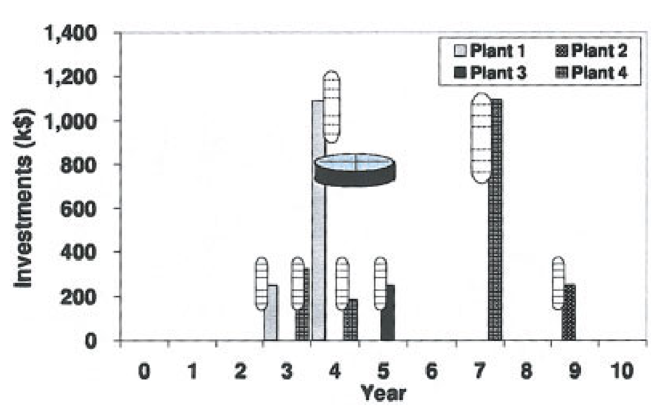

Figure 5. Yearly expenditure under command-and-control regulation with the corresponding investments for new plant equipment types.

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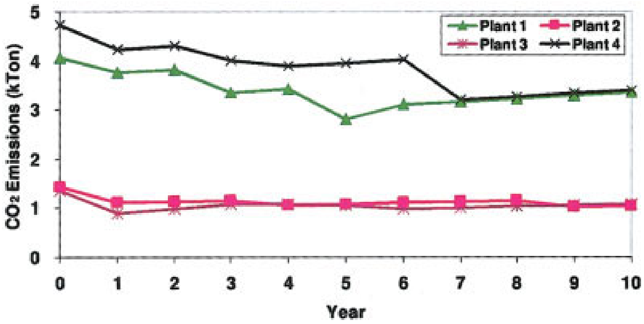

Figure 6. Expected CO_2 discharges under command-and-control regulation. Emission reduction is due to the departure from waste incineration to solvent recovery.

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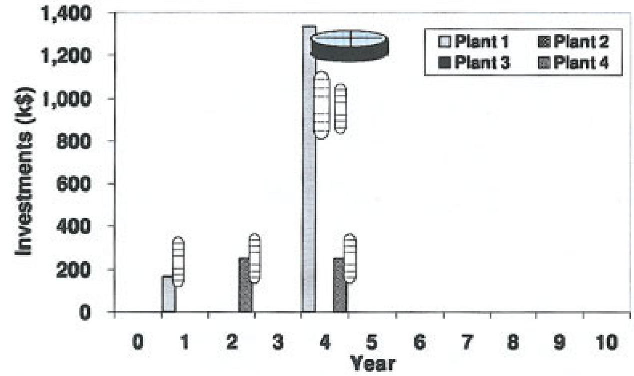

Figure 7. Yearly investments following the induction of an environmental tax with corresponding equipment purchases.

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Air emission reduction by environmental taxes

The environmental tax model tries to entice pollution prevention behavior by charging a tax for emissions. The specific regulatory design question is as follows: Which pollution tax rate brings about a 15% emission reduction in the region over the next five years? We propose to solve this problem in two steps. The first establishes the initial tax level at the current average marginal abatement cost. The marginal abatement costs were estimated by repeated treatment cost simulations with small increments in the waste loads; the base tax was set accordingly. The minimum necessary tax increase for reducing the emissions in the region by 15% can then be obtained by solving problem 10-11. Equation 10 minimizes the region's net present manufacturing cost including expenses for the pollution tax. The annualized pollution tax expenditure, NPCTax, is calculated as a function of the tax rate, $\Phi(t)$, and the plants' emissions, expressed in Eq. 11.

$$\min_{x_j^p, \Delta n_e^p, \Phi(t)} \sum_{\forall p} \gamma^p (NPC_{Op}^p + NPC_{Cap}^p + NPC_{Tax}^p) \tag{10}$$

s.t.

Equations (2)–(8)

$$NPC_{Tax}^p = \sum_t (1+r)^{-t} \sum_j x_j^p(t) \cdot E_j^p(t) \cdot \Phi(t) \tag{11}$$

$$p \in \{Plants\}, \Phi(t): Tax\ Value$$

Although the necessary tax rate, $\Phi(t)$, can be solved for directly, the product of tax and emission variables makes this a mixed integer nonlinear problem (MINLP), which is hard to converge for problems of this size. The mathematical program for a region of four chemical producers involves approximately 7,000 integer decision variables and 800 continuous variables. Alternatively, we propose to solve the problem with different tax rates repeatedly, thus solving successive linear problems (MILP). With the proposed approach, we found an initial tax level of 0.03 \$/ton and a necessary tax increase to 0.10 \$/ton for cutting carbon-dioxide emissions by 15%.

Results of the Environmental Taxes Regulation. The increased tax burden forces plant-1 and plant-4 to invest in cleaner recycle options. The other two plants prefer to pay the higher tax, while using existing equipment capacity to minimize their CO_2 discharges as shown in Figure 7 The CO_2 emission trends in Figure 8 show that plants two, three and four discharge more than they did initially, while plant-1 drastically reduces CO_2 release. This result demonstrates that the pollution tax succeeds in enforcing the desired emission reduction. The ideal tax rate requires a good estimate of the manufacturers' *hidden* marginal abatement costs. This may be difficult for a regulator to assess without methods described in this article. Furthermore, in reality there is no guarantee for the emissions to meet the reduction goal as it is the case in cap and trade. Some manufacturers may discharge more and pay a penalty despite more cost-effective alternatives.

Cap and trade regulatory framework

Finally, we wish to examine a *cap-and-trade* regulatory model. It introduces two new adjustable parameters: the calling price for permit titles and the total permit cap. In this work, we will demonstrate how the regulator can adjust these parameters

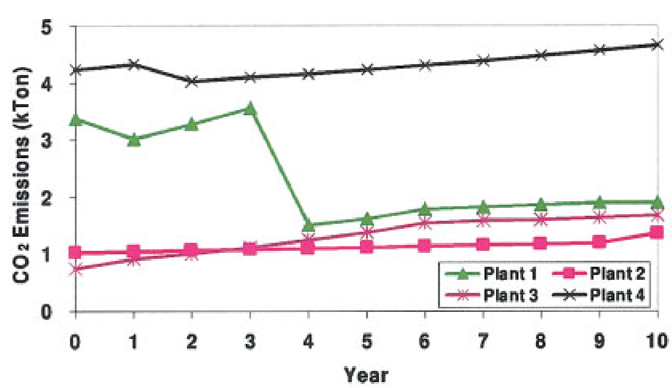

Figure 8. CO_2 emissions discharges under environmental tax policy. Some polluters prefer to pay tax instead of reducing emissions.

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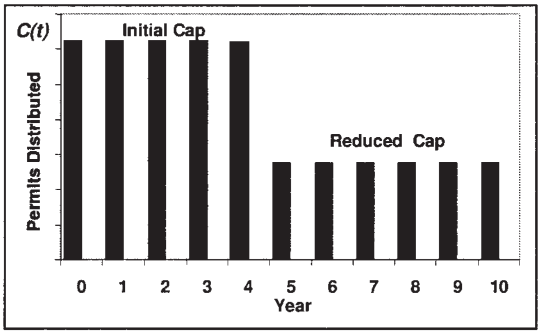

Figure 9. Yearly permit distribution in a cap-and-trade environmental policy for reducing CO_2 discharges by 15%.

to achieve desired levels of acceptable emissions. The limited distribution of emission credits reflects the aim of 15% pollution reduction as displayed in Figure 9. The industry's response to the new emission trading policy is modeled by the problem described in in Eqs. 12–19. The objective (Eq. 12) minimizes the industry's total net present cost. Eq. 13 accounts for the net present cost of *emission trading* as a function of the permits sold or acquired, as well as the permit price, $P_{price}(t)$. Equations 14 and 15 ensure that manufacturers hold at least as many titles as the emissions they cause. Equations 17 and 18 match the supply and demand of permits traded on the market. This simple model corresponds to a balanced closed market. Model variations with open markets did not significantly alter the trends; a discussion is beyond the scope of this article. The total titles a polluter holds is equal to his permit allocation, $P^p_{allocated}(t)$, plus or minus the number of permits bought or sold, $P^p_{buy}(t)$, and $P^p_{sell}(t)$. Equation 16 accounts for the permits allocation to each plant, as a fraction, w_p, of the total permit volume, $C(t)$, issued by the regulator at time t.

$$Z = \min_{x^p_j, \Delta n^p_e, P^p_{buy}, P^p_{sell}} \sum_{\forall p} \gamma^p (NPC^p_{Op} + NPC^p_{Cap} + NPC^p_{Trading}) \tag{12}$$

s.t.

Equations (2)–(8)

$$NPC^p_{Trading} = \sum_{t=0}^{N} (1+r)^{-t} (P^p_{buy}(t) - P^p_{sell}(t)) \cdot P_{price}(t) \tag{13}$$

$$P^p_{tot}(t) = P^p_{buy}(t) - P^p_{sell}(t) + P^p_{allocated}(t) \tag{14}$$

$$\sum_j E^p_j(t) \cdot x^p_j(t) \le P^p_{tot}(t) \tag{15}$$

$$P^p_{allocated}(t) \le w^p \cdot C(t) \tag{16}$$

$$\sum_p P^p_{buy}(t) = \sum_p P^p_{sell}(t) \tag{17}$$

$$P^p_{buy}(t) \le \sum_{k \ne p} P^k_{sell}(t) \tag{18}$$

$$\sum_p \sum_t \sum_j x^p_j(t) \cdot E^p_j(t) \le E_{\max} \tag{19}$$

Results for Cap and Trade Regulations. Under the assumption that utility maximization principle governs the decision for each manufacturer, the solution of problem 12–19 predicts the expected compliance cost and projected emissions for the entire region. Initially, it is beneficial for plant-1 to buy emission permits to defer investments. Therefore, it purchases pollution credits on the emission market. Permits are available because the expansion of existing solvent recovery capacity in plants two and three reduces CO_2 output, thus, creating free titles for trading. In year four, plant-1 is finally forced to invest in additional recovery technology. Its subsequent low-CO_2 discharge creates a return-on-investment from the sale of surplus credits. These free permits provide plants three and four with the flexibility to optimally time necessary upgrades on their site. Eventually plants three and four make their major investment decisions in year eight and nine, respectively as depicted in Figure 10. The trading activity among the polluters is shown in Figure 11 according to which plants three and four are net

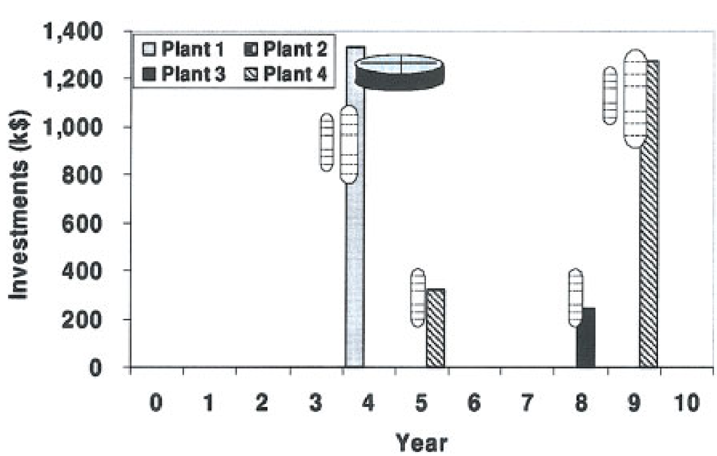

Figure 10. Yearly investments under cap-and-trade environmental policy. Plants delay their investments to optimally schedule capital expenditure.

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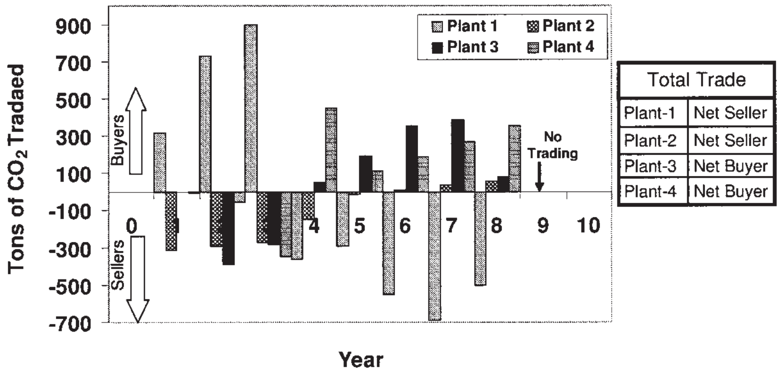


Figure 11. Emission trading activity under cap-and-trade environmental policy.

buyers and plants one and two are net sellers. In this model, the permit price was considered independent of the supply and demand situation of these four polluters. This assumption is accurate when the market is much larger than the trading volume of the four manufacturers.

Figure 12 depicts the projection of the expected annual CO_2 discharges for the next 10 years. Initially, plant-1 is the biggest polluter, after implementing several upgrades in recovery technology; its emissions are reduced drastically. Plant-3 with the better initial infrastructure recycles solvents by exploiting its free solvent recovery capacity in early periods. In year eight, plant-3 has to expand its solvent recovery facilities to lower its emissions due to its growing production. Although the plants can trade emission permits, the total cap can never be legally violated and the regional emission levels are guaranteed to be reduced according to the regulators' guidelines.

Discussion

Infrastructure Augmentation. Table 1 reports the final infrastructure and the necessary investments of each plant under the different types of environmental policies. The *command-and-control* scenario imposes the largest number of investments, because it forces emission reductions without allowing flexibility in distributing the investments or scheduling its timing optimally. In this case study, emission tax and trading required fewer investments.

The effluents of the industry sector in the examples are composed of solvent-rich organic compounds stemming from extraction and washing steps. Although the superstructure synthesis detects many different treatment options to treat these waste mixtures (see appendix). However, the stringent air emissions force avoidance of CO_2 producing treatment options such as biological or wet-air oxidation. Distillation, which does not destroy organic compounds, was identified as the most effective way to reduce the CO_2 emission in these cases. Other decisions may be prompted simply by the increase in production. As an example, the waste-waster treatment facility of plant-1 needs an expansion due to more wastewater discharges unconditionally.

Economical Impact. Figure 13 depicts the cumulative cost for each plant under the three regulatory scenarios. The tax policy due to its additional emission charges punishes plants with strong growth in production rates leading to higher total costs for industry. Figure 14 shows that the *cap-and-trade* strategy achieves similar pollution levels than a *command-and-control* policy for almost 10% less expenditures ($360,000 less). Emission taxation model is twice as expensive for the industry. With taxation, an arbitrarily high charge is added to the production cost. Taxation may lead to prohibitive production cost hikes for the whole region thus distorting the competitiveness of the manufacturers. This problem is usually alleviated by tax return policies. Because this a voluntary political measure that partially undoes the purpose of the initial taxation, it was not considered in this work. A detailed analysis of the individual plants' annualized expenditures for emission

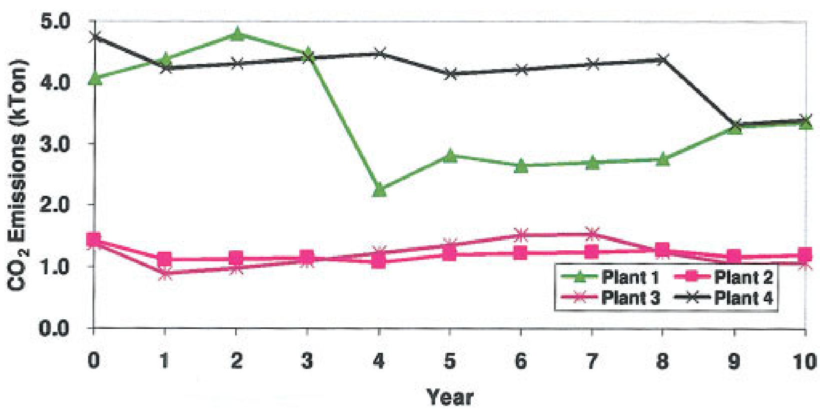


Figure 12. CO_2 emissions under cap-and-trade regulatory framework.

Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.

Table 1. Initial and Final Infrastructure of the Four Manufacturers in Each of the Regulatory Policies

	Initial Infrastructure				Command and Control				Emission Tax				Cap and Trade			
Equipments	Plant-1	Plant-2	Plant-3	Plant-4	Plant-1	Plant-2	Plant-3	Plant-4	Plant-1	Plant-2	Plant-3	Plant-4	Plant-1	Plant-2	Plant-3	Plant-4
C_1 (22′ × 12″)	0	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0
C_2 (35′ × 12″)	**1**	**2**	**1**	0	**1**	**2**	**1**	0	**1**	**2**	**1**	0	**1**	**2**	**1**	0
C_3 (82′ × 12″)	0	0	0	0	0	0	0	**1**	0	0	0	**2**	0	0	0	**1**
C_4 (25′ × 12″)	0	0	0	0	**1**	0	**1**	0	**2**	0	0	0	**1**	0	0	0
C_5 (35′ × 18″)	0	**2**	0	0	0	**2**	0	**1**	0	**2**	0	0	0	**2**	0	**1**
C_6 (82′ × 18″)	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0
C_7 (82′ × 24″)	0	0	0	0	**1**	0	0	0	0	0	0	0	0	0	0	0
C_8 (200′ × 24″)	0	**2**	0	0	0	**2**	0	**1**	0	**2**	0	0	0	**2**	0	**1**
C_9 (200′ × 36″)	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0
TO_1 (23.4 Mw)	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0
TO_2 (14.65 Mw)	**1**	**1**	0	**1**	**1**	**1**	0	**1**	**1**	**1**	0	**1**	**1**	**1**	0	**1**
TO_3 (8.8 Mw)	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**
WW_1 (5 Mgd)	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**
WW_2 (15 Mgd)	0	0	0	0	**1**	0	0	0	**1**	0	0	0	**1**	0	0	0
Total	**2**	**7**	**4**	**3**	**5**	**8**	**5**	**6**	**5**	**7**	**4**	**5**	**4**	**7**	**5**	**6**
Units Purchased	—	—	—	—	+3	+1	+1	+3	+3	0	0	+2	+2	0	+1	+1

C_i: Distillation or Stripping Columns; TO_i: Thermal Oxidizer; WW_i: Waste Water Treatment

control is depicted in Figure 15. The comparison shows that the total annualized costs are always lower in emission markets. This cost reduction was not only true for the entire region, but also for each company individually. Hence, emission trading causes the smallest business interference by the regulatory change. In contrast, command-and-control as well as taxation are likely to create arbitrary losers and winners.

Environmental Impact. Another interesting result is the difference in the actually realized CO_2 reduction. Despite identical reduction targets (110 ktons CO_2 for cap-and-trade, 104 kTons CO_2 for command-and-control, 102 kTons CO_2 for emission-tax). The command-and-control policy exceeds the proposed emission target reaching an actual 27% reduction, almost twice the desired level of 15%. Although further emission reduction is desirable from an environmental point of view, the regulatory goals should be met accurately.

How much would it cost to enforce a 27% reduction with a cap-and-trade regulation? Solving the problem for emission trading with a 27% reduction of emission permits, the total annualized cost were still 7% below than the command-and-control solution. This cost advantage is due to the freedom for plants to choose their investment policies. In summary, two points are important:

Market-based emission control meets specific emission reduction targets tightly.

Market-based approaches achieve desired emission targets at minimal cost to industry.

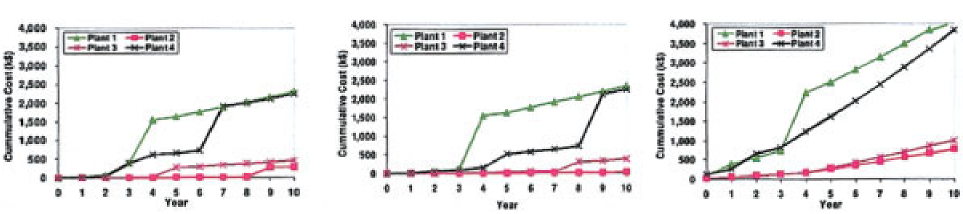
Optimal Design of Market Based Regulations

The tight control over realizable emissions targets poses the following question: "*What is the absolutely cheapest market-based policy leading to a desired emission reduction in a region?*" This question can be answered by solving problem Eqs. 12 – 19 with the annual permit volume, *C(t)*, as a optimization variable. As a solution we obtained the same trajectory depicted in Figure 9. Accordingly, the longer possible delay in cutting the permit volume gives companies the largest lead-time to adjust to the new pollution target. Therefore, reducing the cap in a stepwise fashion is optimal.

The proposed methodology also can determine accurately how a regulator can impose a desired emission reduction target within acceptable compliance cost for that region. The formulation of Eqs. 20 – 29 solves the following optimal regulatory design problem: "*What is the maximum achievable emission reduction given a tolerable compliance cost threshold for the region?*" In this regulatory design problem, the design variable, *C(t)*, is the yearly distribution of emission credits, and is the result of an optimal control problem.

$$Z = \min_{x_j^p, \Delta n_e^p, P_{buy}^p, P_{sell}^p, C(t)} TotalEmissions = \sum_p \sum_t \sum_j x_j^p(t) \cdot E_j^p(t) \tag{20}$$

s.t.



(a): Command-and-control (b): Cap-and-trade (c): Tax

Figure 13. Cumulative cost for each plant under different environmental policies.

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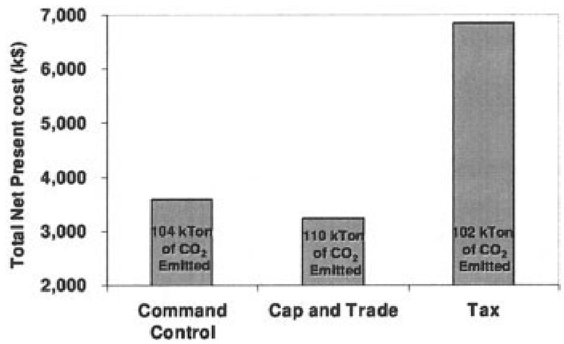

Figure 14. Total regional net present cost and total CO_2 discharges under different environmental regulatory scenarios.

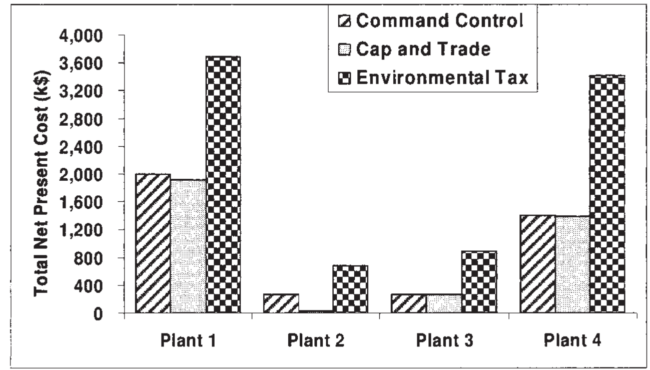

Figure 15. Compilation of each plant's net present total annualized cost of manufacturing under the different environmental regulations.

Equations (2)–(8)

$$NPC^p_{Trading} = \sum_{t=0}^{N} (1+r)^{-t}(P^p_{buy}(t) - P^p_{sell}(t)) \cdot P_{price}(t) \quad (21)$$

$$P^p_{tot}(t) = P^p_{buy}(t) - P^p_{sell}(t) + P^p_{allocated}(t) \quad (22)$$

$$\sum_j E^p_j(t) \cdot x^p_j(t) \leq P^p_{tot}(t) \quad (23)$$

$$P^p_{allocated}(t) \leq w^p \cdot C(t) \quad (24)$$

$$\sum_p P^p_{buy}(t) = \sum_p P^p_{sell}(t) \quad (25)$$

$$P^p_{buy}(t) \leq \sum_{k \neq p} P^k_{sell}(t) \quad (26)$$

$$\sum_p \sum_t \sum_j x^p_j(t) \cdot E^p_j(t) \leq E_{\max} \quad (27)$$

$$\sum_{\forall p} \gamma^p(NPC^p_{Op} + NPC^p_{Cap} + NPC^p_{Trading}) \leq \$3.5m \quad (28)$$

$$C(t) \leq 0.85C(0) \;\; \forall\, t \geq 5 \quad (29)$$

Optimal regulatory design with compliance cost limitations

In this case study, the maximum compliance cost for the region was agreed to equal \$3.5 million in pollution prevention technology over the next 10 years. The solution of the optimal control problem will determine the optimal permit allocation policy, *C(t)*, leading to the lowest regional emission consistent within the manufacturers' budget for pollution prevention. The mathematical problem of Eqs. 20–29 reduces emissions within a maximum permissible compliance budget as specified in constraint (Eq. 28). The minimum achievable regional emission problem gives a total CO_2 discharge of 101.7 kTons. The resulting total air pollution level is 10% less than the previous minimum cost solution reported in problem Eqs. 12–29. Thus, the proposed regulatory design problem demonstrated the lowest possible emissions for the region given the limited budget of \$3.5 million. The minimum emission objective forces all plants to adopt CO_2 reduction immediately. The earlier investments require less trading in the beginning. However, the technology upgrades without exploiting available emission credits is more expensive. The pollution minimization prevents polluters from trading in the early years. The cap trajectory follows the minimum achievable CO_2 emission levels as displayed in Figure 16. This case study demonstrates how to compute the maximum pollution reduction subject to a budget constraint on total regional compliance cost. This formulation offers regulators a systematic tool for designing permit distribution policies to enforce desired emission targets. This idea has never been proposed in the literature to the best of the authors' knowledge.

Conclusions and Future work

The article proposes a systematic framework based on detailed unit operation models to accurately predict treatment options, emissions and optimal investments policies of a region under different regulatory scenarios. The approach shows the successful combination of chemical engineering knowledge with simplified market models to predict the economic and environmental impact of regulatory changes. This work can

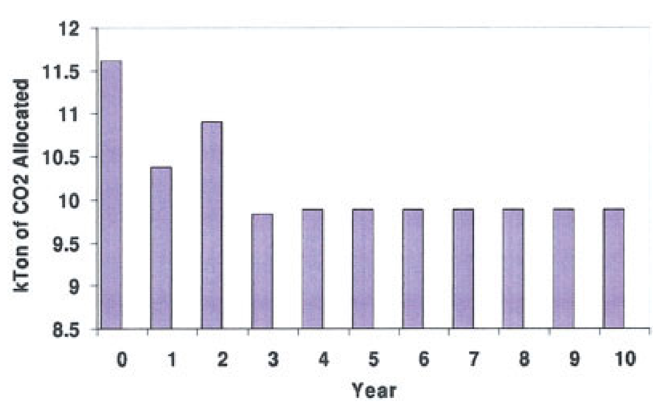

Figure 16. Optimal total allocation of CO_2 permits.

Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.

assist regulators in designing environmental policies that satisfy environmental objectives while limiting the financial burdens to manufacturers.

This article also provides mathematical programming formulations for designing optimal strategies for the induction of new environmental friendly technology. While the proposed method cannot generate new reaction and separation steps by itself, it allows the assessment of new process technology as soon as it is incorporated into the database of treatment and recycles models. Even at the preliminary research and design stage, a new abatement technology, its pollution reduction efficacy and its cost can be considered before it is introduced to industry. The proposed combinatorial synthesis methodology would identify the optimal time to purchase as well as number and capacity of new units for the novel process at each manufacturing site. Alternatively, regulators could systematically design and predict the effect of regulatory incentives or penalties to facilitate the expeditious introduction of technological innovations for pollution prevention.

The quantitative analysis reveals that the flexibility of the emission-trading model benefits plant managers in three aspects. First, they can optimally time their investments decisions in accordance with their production plans and available cash flow. Second, they may earn ongoing benefits from technological improvements by selling surplus emission credits. Finally, desired air emission reduction targets for a whole region were more accurately met under the *cap-and-trade* environmental policy than any other approach. Consequently, the market-driven environmental policy offers the regulator a very tight control instrument to enforce desirable levels of tolerable pollution. In conjunction, these three advantages are likely to stimulate pollution prevention efforts in industry currently missing in the prevailing command-and-control environmental regulations.

Determining the ideal tax rate requires a good estimate of the manufacturers' *hidden* marginal abatement costs. The corporate proprietary cost structure may be difficult for a regulator to estimate without methods described in this article. A mathematical program for identifying the necessary environmental tax for a desired pollution prevention target was proposed and solved. In addition, necessary iterations for determining the optimal tax levels to enforce a desired emission target cause regulatory uncertainty for the industry. Environmental taxation may therefore be hard to implement politically.

A unique innovation of the work is the notion of an *optimal design of environmental regulatory policies.* Mathematical programming formulations calculated the optimal distribution of emission credits to impose industrial air emission reduction at minimum cost to manufacturers. These problems provided solutions to optimal permit management for minimum emissions within limited regional compliance cost and analytical determination of environmental tax levels for desired ecological targets.

This article considered simplified market models using a multi-objective utility maximization assumption to predict corporate decisions. In the future, improved models should consider price flexibility as a function of multiplayer demand-and-supply scenarios. Another interesting feature to be included in future work is the consideration of uncertainty in the market and price forecasts.

Acknowledgments

Financial support from NSF Grant DMI-0328134 and the Environmental Manufacturing Management (EvMM) fellowship from the UIC Institute for Environmental Science and Policy are gratefully acknowledged.

Notation

Indices

e = equipment type
j = treatment step
p = plant
t = time

Parameters

C_e = price of equipment e
r = rate of interest
S_e = size of equipment e
γ^p = plant p individual cost minimization weight

Variables

c = operating cost
C = total cap allocated
C_T = total capacity of treatment type T in year t
Cpt_T^p = operating capacity of treatment type T in year t
ΔC_T = capacity increment of treatment type T in year t
E_j = emission produced in plant p
$e^p_{\max}$ = individual plant emission thresholds (tons/yr)
E_{max} = maximum tolerable regional emission
$n_e(t)$ = number of equipment of type e available in year t
Δn_e = number of equipment of type e purchased in year t
NPC = total net present cost
$NPC_{Operating}$ = net present operating cost
$NPC_{Capital}$ = net present capital investments
NPC_{tax} = net present tax cost
$NPC_{Trading}$ = net present emission trading investments
$P_{allocated}$ = permit allocated
P_{sell} = permits sold
P_{buy} = permits bought
P_{price} = price of emission credit
w^p = fraction of cap allocated to plant p
x = binary decision variable
Φ = tax price

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Appendix: Recycle and Treatment Options for Each Plant

This appendix summarizes the results of applying the *CPS* methodology to the four plants in the case study. Table A1 lists the compositions of 13 byproduct streams in four plants, plant-1 to plant-4. Most liquid effluents contain extraction and

Table A1. Composition of Different Waste Categories and Number of Structural Alternatives for their Management for the Four Plants in the Region

	Waste Flow Rate (Ton/Yr)												
	Plant-1				Plant-2			Plant-3			Plant-4		
Compounds	W1-1	W1-2	W1-3	W1-4	W2-1	W2-2	W2-3	W3-1	W3-2	W3-3	W4-1	W4-2	W4-3
Methanol	0	0	50	0	0	0	100	0	0	80	0	0	55
Acetone	40	70	70	10	100	70	150	40	90	80	0	40	30
Acetonitrile	0	0	0	0	0	0	250	100	0	50	0	0	0
Ethanol	0	0	0	0	0	40	0	0	30	0	0	0	0
Water	0	50	230	360	0	10	0	0	50	60	60	130	225
Benzene	50	0	0	0	50	0	0	40	0	0	0	0	0
Ethylene Dichloride	60	0	0	0	60	0	0	80	0	0	60	0	0
O-Toluene	0	0	0	0	59	0	0	0	0	0	0	0	0
No. of Treatment Paths	5	4	2	2	10	4	5	10	5	5	9	3	5
No. of Policies		80				200			250			135	

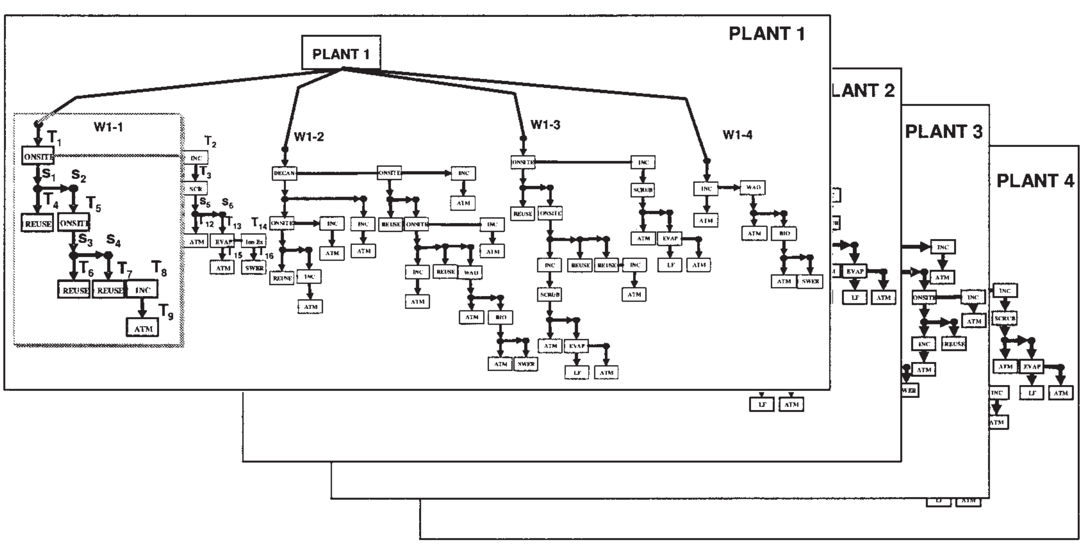

Figure A1. Partial view of the superstructure of four plants: (ONSITE - Onsite Recycle; Inc. - Incineration; REUSE-Reuse; DECAN-Decantation; EVA-Evaporation; IonE-Ion Exchange; SCR-Scrubber; WAO-Wet Air Oxidation; BIO-Biological Treatment; LEA-Leaching; LF-Landfill; ATM-Atmosphere; SEW-Sewer). Treatment paths for waste stream $W_{1\text{-}1}$ in plant-1 are enlarged for better readability.

wash solvents typical in synthetic organic medicinal plants that need to be recycled or treated before discharge. Other aqueous wastes contain organic contaminants. These solvents have been grouped in different waste categories as shown in Table A1. The complete treatment paths for all plants created by the *CPS algorithm* are depicted in Figure A1. Each has a distinct superstructure because their waste stream compositions are different. As an example, the superstructure for plant-1 implicitly includes $5 \times 4 \times 2 \times 2 = 80$ different treatment paths, while plant-2 has 200 paths. For clarity, we present the treatment options for the liquid waste category $W_{1\text{-}1}$, of plant-1 that contains a mixture of three solvents as summarized in Table A1. The sequence of steps T_1-T_5-T_6-T_7-T_8-T_9 constitutes a single treatment path, and is highlighted in Figure A1. Because of its abundance and its high market value, benzene is selected for onsite recycle, a task achieved in a single distillation step (T_1). The distillate, S_1, is almost pure benzene and can therefore be reused (T_4). The bottom product, S_2, can either be submitted to another onsite recycle step (T_5) or incinerated (T_{10}). In this path, another distillation step is selected to recover the remaining ethylene dichloride (S_4) from the acetone (S_5). Ethylene dichloride is reused (T_6), and the acetone can be either be reused (T_7) or incinerated (T_8). The off-gases are sent to atmosphere (T_9).

In a similar way, the superstructures for the other plants are automatically generated by the Combinatorial Process Synthesis methodology. According to Figure A1, there are $80 \times 200 \times 250 \times 135 = 540{,}000{,}000$ different feasible treatment policies for the whole region.

Manuscript received Oct. 12, 2005, and revision received Mar. 8, 2006.