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INCORPORATING POLLUTION TAXES AND/OR SUBSIDIES INTO MASTER PLANNING IN SEMICONDUCTOR FOUNDRY PLANTS

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ABSTRACT

The continued development of manufacturing industries along with increasing greenhouse gas emissions has become a critical concern that forces mankind to reduce global warming. Given the long atmospheric lifetimes of Perfluorocarbons (PFCs), it is especially important to reduce the emissions of PFCs which are commonly found in the semiconductor industry. In this study, we propose four master planning models that incorporate pollution taxes, subsidies, and/or progressive pollution taxes into capacity allocation to examine the problem of anthropogenic PFC emissions. The results show that master planning with subsidies and/or progressive taxes provides more flexibility to a foundry plant than that with flat taxes only. Setting emission limits and considering taxation for master planning is the first step toward the success of an environmental policy.

Contribution/ Originality: This study proposes four master planning models for the semiconductor foundry plants by using ecological taxation methods. The paper's primary contribution is finding that the master planning models with subsidies and/or progressive taxes provide more flexibility to a foundry plant than the model with flat taxes only.

1. INTRODUCTION

One of the biggest problems that the world is facing today is that of environmental pollution, which worsens every year and has caused irreparable damage to the earth. In the last 100 years, Earth's average surface temperature increased by about 0.8°C (1.4°F). Two thirds of the increase occurred over just the last three decades. Scientists were certain that it was caused mostly by the increasing concentrations of greenhouse gases produced by human activities such as deforestation and burning of fossil fuels. These phenomena were recognized by the National Academy of Science that consisted of all the major industrialized countries (National Academy of Science (NAS), 2007). To alleviate global warming, the United Nations, the European Union, and many countries have jointly enacted legislation or designed mechanisms such as the Kyoto Protocol (The United Nations Framework Convention on Climate Change (UNFCCC), 1997) and the Copenhagen Accord (UNFCCC, 2009) to curb the total amount of greenhouse gas emissions. Under the Kyoto Protocol, industrialized countries and those in transition to a market economy agreed to limit or reduce the emissions of six greenhouse gases, which are Carbon dioxide (CO_2), Methane (CH_4), Nitrous oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulphur hexafluoride (SF_6).

Among the most potent of non-CO_2 greenhouse gases are the PFCs that have extraordinarily long atmospheric lifetimes of 10000 to more than 50000 years and high Global Warming Potentials (GWP). GWP is a relative measure of how much heat a greenhouse gas traps in the atmosphere. It is estimated that a molecule of Tetrafluoromethane (CF_4), i.e., one of the PFCs, is as effective as 7390 molecules of CO_2 for causing global warming (IPCC, 2013, Chap. 8). This means that if the same mass of CF_4 and CO_2 were introduced into the atmosphere, CF_4 would trap 7390 times more heat than CO_2 over the next 100 years. PFCs, such as Perfluoroethane (C_2F_6), Tetrafluoromethane (CF_4), Fluoroform (CHF_3), Sulphur hexafluoride (SF_6), Octafluoropropane (C_3F_8), Octafluorocyclobutane (C_4F_8) and Nitrogen trifluoride (NF_3), are commonly used in the wafer etching process, tungsten process and cleaning Chemical Vapor Deposition (CVD) tools of the semiconductor industry (see Table 1). Each PFC used in different processes has a different amount emitted to the air. Table 2 shows the GWP values of these PFCs over the next 100 years (Intergovernmental Panel on Climate Change (IPCC), 2013). Except for the natural emissions, CF_4 emissions are mainly attributed to the manufacturing processes in the aluminum and semiconductor industries. Also, much of the C_2F_6 used in the semiconductor manufacturing was released to the atmosphere. By analyzing the stored air, Khalil *et al.* (2003) found that the emission concentrations of CF_4 and C_2F_6 increased about two and ten times, respectively over the past four decades (from 1960 to 2000). Khalil et al. also found that the increasing trend of CF_4 emissions has slowed in recent years, but the reduction in the emission rate in the aluminum industry is partially offset by the increasing use of CF_4 in the semiconductor industry. To mitigate environmental damage from anthropogenic emissions, reducing PFC emissions is especially important given the growth of the semiconductor industry recently.

Table-1. PFCs used in semiconductor manufacturing processes

Manufacturing Process		Gas used in Process
Etching	Metal	CF_4, CHF_3
	Polysilicon	SF_6, NF_3
	Oxide	CHF_3, NF_3, C_2F_6, CF_4, C_4F_8, C_3F_8
CVD	Silicon	C_2F_6, CF_4
	Silicon Oxide	C_3F_8
	Silicon Nitride	NF_3
Tungsten		C_2F_6, NF_3

Table-2. GWP values of PFCs used in semiconductor manufacturing processes over the next 100 years (IPCC, 2013)

Greenhouse Gas	Formula	GWP (100 yr.)
Perfluoroethane	C_2F_6	12,200
Perfluoromethane	CF_4	7,390
Fluoroform	CHF_3	11,700
Sulphur hexafluoride	SF_6	22,800
Perfluoropropane	C_3F_8	8,830
Perfluorocyclobutane	C_4F_8	10,300
Nitrogen trifluoride	NF_3	17,200

If the market is left to operate freely, greenhouse gas emissions will be excessive, because there are insufficient incentives for companies to reduce emissions. Economists thus recommend that the polluters pay on carbon dioxide and other greenhouse gas emissions (e.g., (Pigou, 1920; Baumol, 1972)) while companies are likely to purchase more energy efficient equipment and the academia investigate low energy consumption technologies (Chang and Chang, 2006; Ou Yang *et al.*, 2009). According to Gupta *et al.* (2006) the equipment cost in a new wafer fab exceeds 75% of the total factory capital costs. Energy efficient equipment and low energy consumption technologies usually cost more for a semiconductor company. On the other hand, sustainable supply chain design is one of the approaches that arises recently to embed economic, environmental, and societal concerns into the supply chain and tries to integrate and optimize firms' operational decisions to reduce environment damage (Frota *et al.*, 2008). This approach may reduce more greenhouse gas emissions with less cost than adopting energy efficient technologies (Benjaafar *et al.*, 2013).

In recent years, the global green tax landscape is evolving rapidly and becoming more complex, as governments increasingly use taxation as a tool to achieve green policy goals and make firms operate more sustainably. Hundreds of pollution taxes are levied and subsidies are offered around the world (KPMG, 2014). In September 2012, Japanese government introduced a new tax to curb greenhouse gas emissions. France imposed a general tax on polluting activities (Taxe Générale sur les Activités Polluantes or TGAP) on a "pay as you pollute" basis. In the US, there are also a large number of sub-national state-based tax incentives related to pollution control and ecosystem protection. In Taiwan, air pollution fees are imposed according to the emission standard regulated by the government. Encouraging industries to reduce greenhouse gas emissions is widely seen as one of the government's policy choices to mitigate the climate change. South Africa's Section 121 Tax Allowance Incentive was designed to encourage the development of energy efficiency improvements. The UK offers a 100 percent first year allowance for specified energy saving plants and machinery. China provides financial subsidies to firms with energy saving evidence through central and provincial government agencies. The design of pollution taxes, subsidies, and economic considerations is central to an environment policy.

In addition, the long manufacturing lead time (around three months) and the high market volatility in the semiconductor industry make it difficult to capture the dynamics of this industry. With large capital investment, equipment idling may lead to high cost of wasted capacity. Hence, advanced planning methods play an important role in this industry. Master planning, which is one of the critical phases in the sustainable supply chain design, is to reserve available-to-promise capacity for customers and aims at the best match of supply and demand. The purpose of this research is to present four master planning models for the semiconductor foundry plants by using ecological taxation methods and evaluate both the economic and environmental performance of the four models in terms of profits, allocation quantities, and emission amounts.

The rest of this paper is organized as follows. In section 2, we will review the literature and models relevant to our study. In section 3, we will describe the modeling background and formulate the sustainable master planning models that restrict greenhouse gases emitted to the environment. In section 4, we present computational results to gain useful insights of the proposed models. Finally, section 5 concludes this paper and suggests topics for future research.

2. LITERATURE REVIEW

In the semiconductor foundry industry, fabrication is activated in response to an actual order, i.e., companies run make-to-order (MTO) operations. As inventory cannot be used to smooth the demand, capacity allocation is vital to the success of a foundry company. Chen *et al.* (2005) developed a capacity planning system that considered the capacity and capability of equipment for multiple semiconductor manufacturing plants. Ponsignon and Mönch (2012) applied heuristic approaches for solving master planning problems by taking demand and capacity constraints into account; Ponsignon and Mönch (2014) also devised two heuristic approaches, a genetic algorithm and a rule-based assignment procedure, for master planning in the semiconductor manufacturing and evaluated the performance of them while considering demand and execution uncertainty. Chiang and Hsu (2014) proposed a master planning model within an integrated order fulfillment system for a MTO foundry fab to maximize corporate profit. The above studies, however, concentrated only on capacity allocation and neglected the examination of environmental issues.

Some scholars addressed the impact of adding external control mechanisms such as carbon taxes or a cap-and-trade scheme on sustainable supply chain management practices. The concept of carbon taxes is to impose an explicit cost on each unit of greenhouse gas emissions to give firms an incentive to reduce pollution, while in a cap-and-trade system, emission permits are given out for free initially, but extra permits can be bought from other firms if needed. Avi-Yonah and Uhlmann (2009) argued that carbon taxes are a better solution to global warming than cap-and-trade due to its simplicity and capability to provide an immediate carbon pricing signal for firms producing greenhouse gases. It will also generate a bigger initial hit to the balance sheet and higher incentive to reduce greenhouse gas emissions (Hoeller and Markku, 1991). Oreskes (2011) suggested that a properly valued carbon tax might be a more effective mechanism than cap-and-trade to reduce greenhouse gas emissions, while Stram (2014) argued that the cap and trade system of European Union Emission Trading Scheme has virtually collapsed. A number of European countries, such as Denmark, Finland, the Netherlands, Norway, Sweden, Switzerland, and the UK, have implemented carbon taxes.

A carbon tax is a form of pollution taxes. Tseng and Hung (2014) proposed a supply chain model which showed that the higher the carbon tax level of CO_2 emissions, the lower their amount. Pollution taxes are often grouped with two other economic policy instruments: pollution permits and subsidies. Johnson (2010) proposed a de-carbonization strategy for the electricity sector by imposing carbon fees and using the revenue exclusively to subsidize new, low-carbon generation sources. He *et al.* (2012) compared the effectiveness and efficiency of cap-and-trade and carbon tax policies in a generation expansion planning framework and provided insights on the pros and cons of these policies. Saysel and Hekimoğlu (2013) presented a dynamic simulation model which revealed that policy options such as investment subsidies and carbon taxes could help reduce CO_2 emissions in Turkey; Li and Lin (2013) investigated the impacts of eight different carbon or energy tax policies on carbon emissions reduction in China. Absi *et al.* (2013) introduced carbon emission constraints in multi-sourcing lot-sizing problems, Dissou and Siddiqui (2014) provided a comprehensive analysis of the incidence of carbon taxes on inequality to discuss whether or not the carbon tax is progressive, and Yao *et al.* (2014) developed an energy-efficient subsidy program to ensure the effectiveness of energy consumption. Setting the right tax levels is critical to the success of an environmental policy. However, setting optimal tax and subsidy levels is not within the scope of this study. To facilitate a meaningful and fair comparison, carbon taxes and subsidies were designed to have an equivalent effectiveness on decision variables in He et al.'s model. We will also apply this equivalent effectiveness concept in our models. To the best of our knowledge, there are no articles in the literature that specifically devise master planning models with ecological sustainable concerns for the semiconductor industry. In this study, we propose four master planning models to address the issue of anthropogenic PFC emissions.

3. MODELS

Semiconductor foundry manufacturing consists of four main processes: wafer fabrication, circuit probing, assembly, and final test. Among the four, the wafer fabrication process is the most critical one with the longest flow time. It is a complex process, including wafer cleaning, oxidation, deposition, lithography, etching, diffusion, ion implantation, metallization, inspection, and measurement (see, e.g., Mönch *et al.* (2013)). It takes around three months to complete the whole fabrication. In this research, we study the wafer fabrication process only and propose four master planning models for allocating fabrication capacity to forecasted demand.

Wafer fabrication capacity is usually planned periodically in terms of technology codes (e.g., Chiang and Hsu (2014)) i.e., specifications of technology's factory routing, average layer cycle time, throughout, and other manufacturing information, to generate projected production output targets; to streamline production as well as commit customers with exact delivery date and quantity, the production output targets are planned into daily slots (details of capacity planning are outside of the scope of this research), which become one of the two inputs of master planning (also called allocation planning). The other input of master planning is from demand planning (e.g., Chiang and Hsu (2014)). The demand forecast of a foundry company is usually based on regional sales data and requires sales managers to visit customers frequently. Also, when planning several months ahead, customers have difficulties in specifying exact product requirements to their foundry companies (which may include processing details for hundreds of wafer fabrication steps). Thus, customers usually provide only critical technology code information along with their demand forecast. The forecast data is combined and aggregated as monthly demand, which will be reviewed and revised internally by top managers according to marketing insights and strategy decisions; it will then be disaggregated to weekly demand based on historical trends and statistical forecasting, and divided proportionally into daily demand to match up with capacity's time granularity. Next, capacity can be allocated for maximized profit in master planning, taking into account the environmental concerns, which were not examined in Chiang and Hsu (as mentioned above).

We assume that a semiconductor foundry plant with PFC emissions will be taxed by the government, who has also set the cap or limit of PFC emissions for a foundry plant on a monthly basis (it should not feasible and practical to set PFC emission permits on a daily basis. Thus, in addition to the daily time slot t in master planning, we use the index m to denote the monthly time bucket for the consideration of emission permits, and LMT_m to stand for the cap of PFC emissions in month m and TAX to be the pollution tax per unit of PFC emissions.

According to Kilger and Schneeweiss (2005) master planning is to reserve "committed ATP" capacity for customers in the medium term (e.g., from 6th to 17th month), i.e., it is usually performed monthly. We suppose that the customer demand forecast is known and deterministic, and capacity is stringent and difficult to be expanded quickly. Since on-time delivery is often one of the manufacturing objectives for foundry companies (Taiwan Semiconductor Manufacturing Company (TSMC), 2013) we do not consider in master planning the inventory holding and backorder costs, which are usually handled when orders are promised by firms as they arrive (for details of how order promising follows from master planning, please see Chiang and Hsu (2014). We will formulate four different master planning models with linear programming. The first model with flat pollution taxes only is denoted as MPT, the second model with flat taxes and subsidies as MPTS, the third model with flat and progressive pollution taxes as MPTP, and the fourth model with flat and progressive pollution taxes and subsidies as MPTSP.

Model 1: MPT

We consider a finite planning horizon that spans over 12 months. Suppose each demand includes only one customer c. We let D_{cfgmt} denote the customer c's demand forecast that can be satisfied with technology code g at factory f in time period t of month m, and QTY_{cfgmti} be the required quantity of order i from customer c satisfied with technology code g at factory f in time period t of month m. Demand is to be served with capacity CAP_{fgmt} that is supplied at factory f with technology code g in time period t of month m. The goal is to find the optimized committed ATP profile "ALP_{cfgmt}" that maximizes forecasted corporate profit (minus pollution taxes). The per wafer forecasted margin M_{cfgmt} can be obtained by subtracting the per wafer manufacturing cost from the per wafer forecasted selling price for demand D_{cfgmt}. Note that the same technology code g may have a different forecasted margin for a different customer c, at a different factory f, in a different time period t of a different month m for a wafer foundry company. In a foundry plant, the expensive implanter equipment often represents the bottleneck operation and thus its capacity needs to be taken into account in particular in the model. The bottleneck machine consumption (in hours) per wafer and total bottleneck machine consumption limit are denoted by CMW_{cfgmt} and CM_{fgmt}, respectively.

We use EM_{fgsh} to represent per wafer emission amount of chemical h at stage s with technology code g at factory f, and TEM_{fg} to be the sum of EM_{fgsh} with technology code g at factory f, i.e.,

$$TEM_{fg} \equiv \sum_{s \in S} \sum_{h \in H} EM_{fgsh} \tag{1}$$

We assume that unsatisfied orders are lost and unmet forecasts are ignored for the rest of the horizon. Table 3 shows the notation of the basic master planning model (MPT).

Table-3. Notation of the master planning model

Indices	
c	index for customers, $c = 1,2,\ldots,C$
i	index for orders, $i = 1,2, \ldots\ldots I$
f	index for factories, $f = 1,2,\ldots,F$
g	index for technology codes, $g = 1,2,\ldots,G$
h	index for chemicals, $h \in H = \{C_2F_6, CF_4, CHF_3, SF_6, C_3F_8, C_4F_8, NF_3\}$
s	index for process stages, $s \in S =$ {Etching , CVD, Tungsten}
t	index for time periods, $t \in T(m)$
m	index for months or quarters, $m = 1,2,\ldots,M$ (planning horizon)
$T(m)$	set of working time periods in month m
Parameters	
D_{cfgmt}	demand forecast (in wafers) from customer c to be manufactured with technology code g at factory f in time period t of month m
QTY_{cfgmti}	required quantity (in wafers) of order i from customer c at factory f satisfied with technology code g in time period t of month m
CAP_{fgmt}	available capacity (in wafers) associated with technology code g at factory f in time period t of month m
M_{cfgmt}	per wafer forecasted margin associated with demand D_{cfgmt}
CMW_{cfgmt}	capacity consumption (in hours) per wafer of the bottleneck machine associated with technology code g at factory f in time period t of month m
CM_{fgmt}	maximum available capacity (in hours) of the bottleneck machine with technology code g at factory f in time period t of month m
R_{cfg}	an indicator which takes on the value of 1 if customer c's products with required manufacturing technology code g are supported at factory f
EM_{fgsh}	emission amount (in tons) per wafer of chemical h at stage s associated with technology code g at factory f
TEM_{fg}	total PFCs emission amount per wafer with technology code g at factory f
TAX	pollution tax per unit of PFCs emissions
LMT_m	cap of PFCs emissions in month m
Decision Variables	
ALP_{cfgmt}	amount of capacity committed to demand D_{cfgmt}

Formally, MPT is expressed as follows:

$$\text{Maximize } Z = \left(\sum_{c=1}^{C} \sum_{f=1}^{F} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{t \in T(m)} M_{cfgmt} \cdot ALP_{cfgmt} \cdot R_{cfg} \right) - TAX \cdot \left(\sum_{c=1}^{C} \sum_{f=1}^{F} \sum_{g=1}^{G} \sum_{m=1}^{M} \sum_{t \in T(m)} TEM_{fg} \cdot ALP_{cfgmt} \cdot R_{cfg} \right) \tag{2}$$

subject to

$$\sum_{c=1}^{C} ALP_{cfgmt} \cdot R_{cfg} \le CAP_{fgmt} \quad \forall f, g, m, t \in T(m) \tag{3}$$

$$ALP_{cfgmt} \cdot R_{cfg} \leq D_{cfgmt} \quad \forall c, f, g, m, t \in T(m) \tag{4}$$

$$ALP_{cfgmt} \cdot R_{cfg} \geq \sum_{i=1}^{I} QTY_{cfgmti} \quad \forall c, f, g, m, t \in T(m) \tag{5}$$

$$\sum_{c=1}^{C} ALP_{cfgmt} \cdot CMW_{fgmt} \cdot R_{cfg} \leq CM_{fgmt} \quad \forall f, g, m, t \in T(m) \tag{6}$$

$$\left(\sum_{c=1}^{C} \sum_{f=1}^{F} \sum_{g=1}^{G} \sum_{t \in T(m)} TEM_{fg} \cdot ALP_{cfgmt} \cdot R_{cfg} \right) \leq LMT_m \quad \forall m \tag{7}$$

$$ALP_{cfgmt} \geqq 0 \quad \forall c, f, g, m, t \in T(m) \tag{8}$$

Objective function (2) shows that profit of a foundry company is deducted by the pollution taxes paid to the government. Constraints (3)-(6) are the same as expressions (2)-(5) of the allocation planning stage in Chiang and Hsu (2014) except that the monthly time buckets are introduced here. Note that R_{cfg} is used to denote whether or not customer *c*'s products with technology code g can be manufactured at factory *f*. A customer's product was qualified in a specific plant with requested technology code at the product engineering phase. It's quite cost and time consuming to change the manufacturing plant or technology code. Thus, a customer places an order only after the product was qualified already. Constraint (3) ensures that the ATP capacity committed to customers be less than or equal to the available capacity. Constraint (4) specifies that the committed ATP quantity cannot exceed the customer demand forecast, while constraint (5) ensures that it should at least satisfy the order quantity placed. Since master planning is to reserve capacity for forecasted demand in the medium term (e.g., from 6th to 17th month) when only a small number of orders arrive at this stage, $CAP_{fgmt} \geq \sum_{c=1}^{C} \sum_{i=1}^{I} QTY_{cfgmti}$ is usually true. Constraint (6) requires that the total consumption of bottleneck machine hours should be less than or equal to the maximum bottleneck capacity. Constraint (7) states that the sum of daily PFC emission amounts cannot be larger than the monthly emission cap.

Model 2: MPTS

Economic incentives to reduce environmental damage can be used through subsidies as well. A subsidy is a form of financial compensation for polluters to reduce PFC emissions. Thus, in model 2 (MPTS), we assume that in addition to the pollution taxes on PFC emissions, subsidies will be given to foundry plants with unused emissions. We use MB_m to denote the remaining emission permits in month *m*, as given by expression (10) below, and *SI* as the subsidy per unit of unused emission permits. The total compensation can be obtained from multiplying $\sum_{m=1}^{M} MB_m$ by *SI*. MPTS is expressed by

Maximize $Z =$

$$\left(\sum_{c=1}^{C}\sum_{\mathrm{f}=1}^{\mathrm{F}}\sum_{\mathrm{g}=1}^{G}\sum_{m=1}^{M}\sum_{t\in T(m)} M_{cfgmt}\cdot ALP_{cfgmt}\cdot R_{cfg}\right)-TAX\cdot\left(\sum_{c=1}^{C}\sum_{\mathrm{f}=1}^{\mathrm{F}}\sum_{\mathrm{g}=1}^{G}\sum_{m=1}^{M}\sum_{t\in T(m)} TEM_{fg}\cdot ALP_{cfgmt}\cdot R_{cfg}\right)$$
$$+\left(SI\ \cdot\ \sum_{m=1}^{M} MB_m\right) \qquad (9)$$

subject to
$$\left(\sum_{c=1}^{C}\sum_{f=1}^{F}\sum_{g=1}^{G}\sum_{t\in T(m)} TEM_{fg}\cdot ALP_{cfgmt}\cdot R_{cfg}\right)+MB_m = LMT_m \qquad \forall m \qquad (10)$$

and (3)-(6) , (8) , (9) , and $MB_m \geqq 0\ \forall m$

Constraint (10), instead of (7), is used to ensure that the consumed emission permits plus unused permits be equal to the total permits.

Model 3: MPTP

A progressive tax is a tax applied when the taxable base increases above a certain level. It is frequently used in personal income taxes. We incorporate it along with flat taxes into the master planning model, which is named as MPTP. We suppose that the producer pays a higher tax rate, denoted by TAX_h, for his greenhouse gas emissions when the emission amount exceeds LMT_m. The tax rate is TAX when the emission amount is less than or equal to LMT_m, and will climb to TAX_h when the amount is greater than LMT_m. MPTP is expressed by

$$\text{Maximize Z=}\left(\sum_{c=1}^{C}\sum_{\mathrm{f}=1}^{\mathrm{F}}\sum_{\mathrm{g}=1}^{G}\sum_{m=1}^{M}\sum_{t\in T(m)} M_{cfgmt}\cdot ALP_{cfgmt}\cdot R_{cfg}\right)-TAX\cdot\left(\sum_{m=1}^{M}\left(LMT_m+\frac{MA_m-|MA_m|}{2}\right)\right)$$
$$-TAX_h\cdot\left(\sum_{m=1}^{M}\left(\frac{|MA_m|+MA_m}{2}\right)\right) \qquad (11)$$

subject to

(3)-(6), (8), and (9),

where

$$MA_m \equiv \sum_{c=1}^{C}\sum_{\mathrm{f}=1}^{\mathrm{F}}\sum_{\mathrm{g}=1}^{G}\sum_{t\in T(m)} TEM_{fg}\cdot ALP_{cfgmt}\cdot R_{cfg} - LMT_m \qquad \forall m$$

(12)

We see that for any month m, if

(1) $\sum_{c=1}^{C}\sum_{\mathrm{f}=1}^{\mathrm{F}}\sum_{\mathrm{g}=1}^{G}\sum_{t\in T(m)} TEM_{fg}\cdot ALP_{cfgmt}\cdot R_{cfg} > LMT_m$, i.e., $MA_m > 0$, then

$$\frac{MA_m-|MA_m|}{2}=0,\quad \frac{|MA_m|+MA_m}{2}=MA_m,$$

implying that there are both flat and progressive taxes for month m in (11).

(2) $\sum_{c=1}^{C}\sum_{\mathrm{f}=1}^{\mathrm{F}}\sum_{\mathrm{g}=1}^{G}\sum_{t\in T(m)} TEM_{fg}\cdot ALP_{cfgmt}\cdot R_{cfg} \le LMT_m$, i.e., $MA_m \le 0$, then

$$\frac{MA_m - |MA_m|}{2} = MA_m, \quad \frac{|MA_m| + MA_m}{2} = 0,$$

implying that there are flat taxes only for month m in (11).

Model 4: MPTSP

It is possible for government to include in an environmental policy all of the three policy instruments considered in this paper: flat pollution taxes, subsidies, and progressive pollution taxes. The resulting master planning model for a foundry plant is named as MPTSP, which is expressed by

$$\text{Maximize Z=} \left(\sum_{c=1}^{C} \sum_{\text{f}=1}^{\text{F}} \sum_{\text{g}=1}^{G} \sum_{m=1}^{M} \sum_{t \in T(m)} M_{cfgmt} \cdot ALP_{cfgmt} \cdot R_{cfg} \right) - TAX \cdot \left(\sum_{m=1}^{M} \left(LMT_m + \frac{MA_m - |MA_m|}{2} \right) \right)$$
$$-TAX_h \cdot \left(\sum_{m=1}^{M} \left(\frac{|MA_m| + MA_m}{2} \right) \right) + SI \cdot \left(\sum_{m=1}^{M} \left(\frac{|MB_m| + MB_m}{2} \right) \right) \quad (13)$$

subject to (3)-(6), (8), and (9),

where MA_m and MB_m are given in (12) and (10), respectively. By considering whether or not $\sum_{c=1}^{C} \sum_{\text{f}=1}^{\text{F}} \sum_{\text{g}=1}^{G} \sum_{t \in T(m)} TEM_{fg} \cdot ALP_{cfgmt} \cdot R_{cfg} > LMT_m$, as in model 3, we can verify that the objective function (13) is valid.

4. RESULTS

We will provide a case study of a semiconductor company to examine the performance of the proposed four master planning models. The experiment design and corresponding data are described in section 4.1. Computational results of the four models are stated in section 4.2. The models can be solved to optimality by any LP software or optimization solver. For this research, we used the modeling and optimizing language Lingo 13.0 and the simple database Microsoft Access 2010. Also, all the computations were executed on a personal computer with an Intel Core i7-2600 2.80 GHz processor and 8 GB RAM, operated by the Microsoft Windows 7 professional system. All the four models were solved within six seconds. Discussion of the results is provided in section 4.3.

4.1. Experiment Design

The environment where the company operates is a classical MTO operation. The data was collected from it with some modifications (see also Chiang and Hsu (2014)). We consider three customers, three technology codes at a factory, and a planning horizon of twelve months. Each month is assumed to have 30 working days. Tables 4 and 5 list the experimental data of capacity and demand forecast, respectively used in the four models for a horizon from 6^{th} to 17^{th} months.

Table-4. Experimental data of capacity

Month	6Th	7Th	8Th	9Th	10Th	11Th	12Th	13Th	14Th	15Th	16Th	17Th	Total
Technology 1	40950	40950	40950	40950	40950	40950	42950	42950	42950	43550	43550	43550	505200
Technology 1	46800	46800	46800	46800	46800	46800	46800	46800	46800	46800	46800	46800	561600
Technology 1	46200	46200	46200	46200	46200	46200	46200	46200	46200	46200	46200	46200	554400
Total	133950	133950	133950	133950	133950	133950	135950	135950	135950	136550	136550	136550	1621200

Table-5. Experimental data of demand forecast

Month	6Th	7Th	8Th	9Th	10Th	11Th	12Th	13Th	14Th	15Th	16Th	17Th	Total
Customer 1	50400	49300	50400	50650	50400	50000	50400	50650	51800	50400	50500	50800	605700
Technology 1	14400	13500	14400	14400	14400	14400	14400	14650	14400	14800	14400	14400	172350
Technology 2	20100	20100	20100	20100	20100	20100	20100	20100	20100	20100	20100	20100	241200
Technology 3	15900	15700	15900	16150	15900	15700	15900	15900	16300	16500	16000	16300	192150
Customer 2	52200	52200	52100	52200	52200	51900	53100	52400	53050	53100	53100	53100	630650
Technology 1	15150	15150	15250	15150	15150	14850	15450	15250	16050	15650	15450	15150	183700
Technology 2	22800	22800	22600	22800	22800	22800	22800	22900	22800	23100	23400	23700	275300
Technology 3	14250	14250	14250	14250	14250	14250	14850	14250	14200	14350	14250	14250	171650
Customer 3	38400	38500	38700	38750	38600	37900	38600	38500	38800	38400	39200	38750	463100
Technology 1	10800	10900	10950	11000	11000	10300	11000	10900	11100	10800	11600	10800	131150
Technology 2	12300	12300	12300	12450	12300	12300	12300	12300	12300	12300	12300	12300	147750
Technology 3	15300	15300	15450	15300	15300	15300	15300	15300	15400	15300	15300	15650	184200
Total	141000	140000	141200	141600	141200	139800	142100	141550	142650	142900	142800	142650	1699450

Table-6. Experimental data of tax and subsidy values

MPT	MPTS		MPTP		MPTSP		
TAX	*TAX*	*SI*	*TAX*	TAX_h	*TAX*	TAX_h	*SI*
0	0	0	0	100	0	100	0
500	500	500	500	600	500	600	500
100	100	100	100	1100	100	1100	100
1500	1500	1500	1500	1600	1500	1600	1500
2000	2000	2000	2000	2100	2000	2100	2000
2500	2500	2500	2500	2600	2500	2600	2500
3000	3000	3000	3000	3100	3000	3100	3000
3500	3500	3500	3500	3600	3500	3600	3500
4000			4000	4100			
4500			4500	4600			
5000			5000	5100			
5500			5500	5600			
6000			6000	6100			
6500			6500	6600			

We are interested in investigating the economic and environmental performance of the four models with respect to different tax rate and subsidy settings. We will use the same tax and subsidy values in each experiment, as explained in section 2. Table 6 lists different *TAX*, *SI*, and TAX_h values used, where TAX_h is greater than *TAX* by 100 in each experiment. Following the 2013 TSMC corporate social report (TSMC, 2014) we set the emission amount per wafer between 0.156 to 0.302 tons in our experiments.

4.2. Computational Results

We present the results of computational experiments by running the four models. Figures 1, 2, and 3 show the results in terms of profit, allocation quantity, and emission amount, which are given in thousands of dollars, pieces, and tons, respectively.

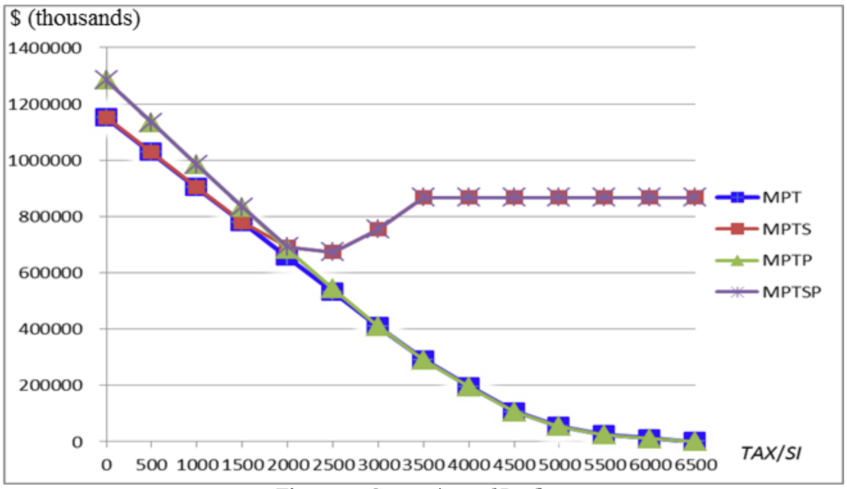

Figure-1. Comparison of Profits

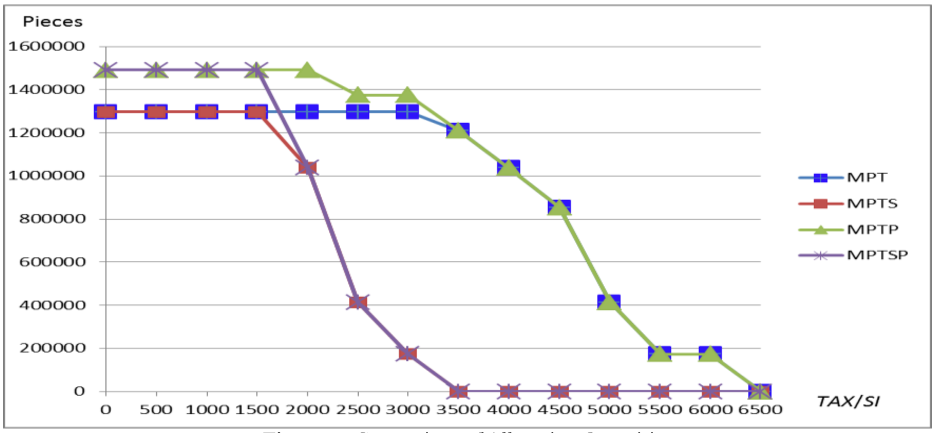

Figure-2. Comparison of Allocation Quantities

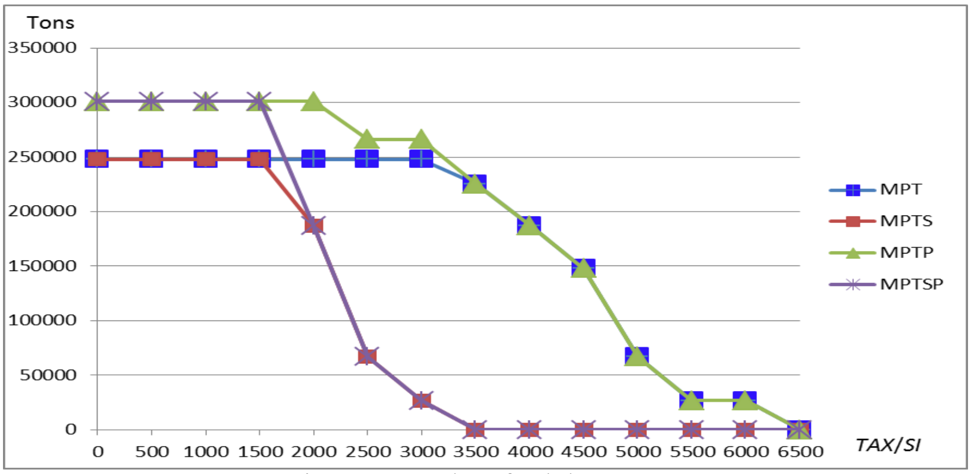

Figure-3. Comparison of Emission Amounts

From Fig. 1, we observe that profit and *TAX* are negatively correlated for MPT and MPTP, which makes sense intuitively. This is also true of MPTS and MPTSP when *TAX* is small. When *TAX* and *SI* are low, MPTP and MPTSP are likely to earn more profits by keeping on allocating capacity and emitting PFCs beyond the limit, as seen from Fig. 2 and 3 (Fig. 3 is similar to Fig. 2, for a foundry plant will yield more PFC emissions if it allocates more capacity to customers). On the other hand, when *TAX* and *SI* are high, MPTSP seems to earn more profits as well by allocating less capacity which results in fewer emissions. This shows the advantage of including progressive taxes and subsidies in master planning.

In the experiments, when *TAX* and *SI* are less than or equal to 1500, MPTP and MPTSP allocate the same capacity and earn the same profits. As *TAX* and *SI* are greater than 1500, it does not pay off to allocate capacity to the wafers with low margins; hence, MPTS and MPTSP perform the same as they allocate the same capacity to customers and progressive taxes do not come into play. When *TAX* and *SI* are greater than or equal to 3500, MPTS and MPTSP do not allocate capacity and thus receive subsidies from the government. Different levels of the pollution taxes and subsidies can allow the government or a decision maker to consider "what-if" analysis so as to determine the extent of the environmental "footprint" of an industry (the semiconductor industry in our models).

4.3. Discussion

It appears from the above results that the more policy options or instruments a master planning model is given, the better the profit obtained. For example, MPTP outperforms MPT if *TAX/SI* is small, and MPTS outperforms MPT if *TAX/SI* is large; MPTS also yields a smaller amount of PFC emissions than MPT if *TAX/SI* is large. Moreover, MPTSP performs the best for a foundry plant, since it allows the use of all three policy options: flat pollution taxes, subsidies, and progressive pollution taxes. When *TAX/SI* is small, it allocates capacity beyond the emission limit, thus paying progressive taxes to the government; on the other hand, when *TAX/SI* is large, it does not allocate enough capacity to customers, thus receiving some subsidies from the government.

We can interpret the results in another way. We know from linear programming that relaxing a constraint allows one to consider more choices, resulting in better objective function values. In our models, relaxing the PFCs emission constraint allows a foundry plant to use more policy options given by the government, resulting in improved profits. Hence, MTPSP can be regarded as the best proposed master planning model.

5. CONCLUSIONS AND POLICY IMPLICATIONS

In this research, we study a greenhouse gas emission problem that is relevant for master planning in the semiconductor industry. We consider taxation for capacity allocation to resolve the trade-off between economic growth and environmental protection. Specifically, we incorporate flat taxes, subsidies, and/or progressive taxes into master planning. We demonstrate that the planning model with subsidies and/or progressive taxes provides more flexibility than the model with flat taxes only.

The main contribution of this study is on considering four ecological taxation methods and evaluating both the economic and environmental performance of the corresponding four models. From the experiments, we find that setting tax rates and subsidy values is key to the models studied. If they are set low, firms would prefer to allocate more capacity to customers, thus perhaps paying progressive taxes to the government, and the environment hurts. On the contrary, if they are set higher than necessary to reduce emissions, firms would allocate less capacity, thus receiving some subsidies from the government, and the economy grows slowly. Designing optimized taxation and subsidy policies seems to be an attractive avenue of future research. However, we believe that the current study lays the foundation for such future research.

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