The Plastics Sector in China: Issues in Production, Recycling and International Trade

Anantha K. Duraiappah, Zhou Xin and
Pieter van Beukering

Working Paper No 27

March 1999

Authors details

Anantha Duraiappah is senior researcher, and Pieter van Beukering is a researcher at the Institute for Environmental Studies (IVM), Amsterdam. They may be contacted at:

IVM,
De Boelelaan 1115
1081 HV Amsterdam
The NETHERLANDS

	A. Duraiappah	P. van Beukering
Tel:	(31) 20 444 9564	(31) 20 444 9524
Fax:	(31) 20 444 9553	(31) 20 333 9553
email:	anantha@ivm.vu.nl	pieter.van.beukering@ivm.vu.nl

Zhou Xin is a researcher at the Policy Research Centre for Environment and Economy (PRCEE) of the State Environmental Protection Administration. She may be contacted at:

Policy Research Centre for Environment and Economy
State Environmental Protection Administration
No 1 Yuhui Nanlu
Chaoyang District
Beijing 100029
P R of CHINA

The programme of Collaborative Research in the Economics of Environment and Development (CREED) was established in 1993 as a joint initiative of the International Institute for Environment and Development (IIED), London, and the Institute for Environmental Studies (IVM), Amsterdam. The Secretariat for CREED is based at IIED in London. A Steering Committee is responsible for overall management and coordination of the CREED Programme.

Environmental Economics Programme, IIED

IIED is an independent, non-profit organisation which seeks to promote sustainable patterns of world development through research, training, policy studies, consensus building and public information. The Environmental Economics Programme is one of seven major programmes of IIED; it conducts economic research and policy analysis for improved management of natural resources and sustainable economic growth in the developing world.

Environmental Economics Programme
IIED, 3 Endsleigh Street
London WC1H 0DD, UK
Tel +44 (0)171 388 2117; Fax +44 (0)171 388 2826
e-mail: Jacqueline.Saunders@iied.org

Institute for Environmental Studies, (IVM)

IVM is a non-profit research institute, based at Vrije Universiteit, Amsterdam. The Institute's primary objective is to carry out multi- and interdisciplinary research on environmental issues, based on cross-fertilisation of monodisciplinary sciences. Environment and the Third World is one of eight major IVM research programmes.

IVM, Vrije Universiteit
De Boelelaan 1115
1081 HV Amsterdam
The Netherlands
Tel: +31 20 444 9555; Fax: +31 20 444 9553
e-mail:secr@ivm.vu.nl

CREED Steering Committee members include:

Abstracts of CREED publications and details of all CREED projects
are now available on the Internet. Visit the CREED Web site at:

http://www.iied.org/creed

Abstract

The Chinese plastics sector is presently facing an acute shortage of plastic resin. Three options are available: (1) increase domestic production of primary resin; (2) increase domestic production of secondary resin; and (3) increase imports of primary resin. Evaluating option one and three involves a relatively straight forward cost-benefit analysis. Option two, however, poses a slightly more complex problem. Since local recovery rates of waste plastic are insufficient to meet demand, production of secondary resin implies importing waste plastic. Critics of trade in waste argue that imports are in reality a disguise for waste dumping by the exporting country. Moreover, cheap imports of waste tend to crowd out the local recovery system leading to a domestic waste disposal problem. In this paper, a sectoral 'cradle to grave' planning model using material balance flow methodology is formulated with a dual purpose. The first is to investigate which of the three options is economically and environmentally preferable, and the second is to shed more light on the trade in waste and to test the claims put forward by the critics. Preliminary results suggest that option two offers the most economically and environmentally efficient solution but under certain stringent conditions.

Abrégé

L'industrie chinoise des plastiques est actuellement confrontée à un grave manque de résine plastique. Trois options sont envisageables : (1) accroître la production intérieure de résine de base, (2) accroître la production intérieure de résine secondaire et (3) augmenter les importations de résine de base. L'évaluation des options 1et 3 requiert une analyse coût/bénéfice relativement simple. L'option 2, quant à elle, pose un problème relativement plus complexe : puisque les taux locaux de récupération des déchets de plastique sont insuffisants pour que la demande soit satisfaite, la production de résine secondaire implique l'importation de déchets de plastique. Pour ceux qui critiquent le commerce des déchets, de telles importations ne sont en réalité qu'une manière de camoufler un dumping des déchets par le ou les pays exportateurs. Qui plus est, des importations de déchets peu coûteuses tendent à engorger le marché et à marginaliser le système local de récupération, rendant ainsi problématique l'élimination des déchets que génère le pays importateur. Dans ce document, on élabore un modèle de planification « du berceau au cimetière » en faisant appel à la méthodologie des flux de balances matières, et ce avec un double objectif : d'une part, voir laquelle des trois options est préférable au plan économique comme au plan écologique et d'autre part, faire avancer la connaissance du commerce des déchets et mettre à l'épreuve les positions de ses critiques. Les résultats obtenus à titre préliminaire suggèrent qu'encadrée par certaines conditions bien strictes, l'option 2 offre la solution la plus efficace d'un point de vue économique et écologique.

Resumen

El sector de plásticos en China atraviesa un problema agudo de escasez de resina plástica. Existen tres alternativas: (1) incrementar la producción doméstica de resina primaria; (2) incrementar la producción doméstica de resina secundaria; y (3) incrementar la importación de resina primaria. La evaluación de las opciones 1y 3 involucra un simple análisis de costo-beneficio. La opción 2, por otro lado, es más problemática. Las cantidades recolectadas de desechos plásticos no alcanzan a suplir la demanda, por lo cual es necesario recurrir a la importación desechos plásticos para la producción de resina secundaria. Los críticos del comercio de desechos sostienen que la importación de desechos plásticos no es otra cosa que una forma de disponer de los desechos por parte del país exportador. La importación de desechos baratos conduce a una acumulación en los sistemas locales de recuperación y por lo tanto a un problema doméstico de recolección de desechos. Este estudio propone un modelo de planificación sectoral "de la cuna a la tumba", en el cual se usa una metodología de flujo de balance material con un doble propósito. El primero es investigar cuál de las tres opciones es preferible desde un punto de vista económico y ambiental y el segundo es poner de relieve el comercio de desechos y examinar las demandas presentadas por los críticos. Los resultados preliminares sugieren que, en ciertas condiciones estrictas, la opción dos es la más eficiente desde los puntos de vista económico y ambiental.

Contents

Introduction

The demand for plastics in China has grown dramatically over the last two decades, increasing from 1.2 to 8.1 million tons (National Federation of Light Industry 1996). A booming economy and the general tendency to substitute traditional materials with plastics have been the primary forces driving this growth in demand.. The three main demand sectors for plastic products have been agriculture, industry and household, each sector accounting for 23%, 31%, and 40% of total demand respectively.

Traditionally, plastic products in China have been manufactured with a high primary resin content with a small proportion of secondary resin. Primary resin is produced by the petrochemical industry from raw materials such as naphtha and chloride, while secondary resin is produced from waste plastics. At present, 87% of final demand for resin is met by primary resin with secondary resin contributing the remaining 13%.

The quality of the final plastic products are generally classified according to the content mixture of these two resins. The higher the proportion of primary resin, the higher the quality of the end product. However, with advances in technology, the content of secondary resin can be increased in many products without comprising the final quality. Table 1 below gives the breakdown between primary and secondary resin use by the three demand sectors.

Table 1 Share of primary and secondary resin across and within sectors

Category	Primary Resin (000 tons)	Use of primary resin per sector (%)	share of primary resin within sector (%)	secondary Resin (000 tons)	Use of secondary resin per sector (%)	share of secondary resin within sector (%)
Industry	2950	43	86	500	38	14
Household	2000	30	74	700	54	26
Agriculture	1860	27	95	100	8	5
Total	6810	100		1300	100	

source: Beukering et al. (1997)

Industry has the highest demand for primary resin followed by household and agriculture respectively. However, in the case of resin use intensity within each sector, we observe from column four that agriculture uses the highest proportion of primary resin (95%) followed by industry and household. For predicting future demand for the respective resins, we would need to map the statistics from column three and four to the predicted growth in each of the three sectors. For example, based on Table 1, we can predict that if China's economy maintains present growth rates of seven to eight percent, household demand can be expected to grow significantly. This in turn translates to a high growth in demand for secondary resins as the household sector uses the largest proportion of secondary resin.

Both the petrochemical and the recycling industries rely on imports to supplement their present production levels to meet local demand for final plastic products. However, the import of foreign waste plastic has been clouded by controversy. Proponents of waste plastics trade argue that trade in recyclable goods offers economic and environment benefits for importing developing countries (Ogilvie 1996, Grace 1978). However, because of the clear

differentiation between the exporting (North) and the importing (South) countries, the issue of Northern exploitation is an issue (UNCTAD 1996).
Critics of the trade argue that trade in waste is simply a cover for waste dumping. The debate revolves around two points. The first is effectively a simple case of getting rid of one's rubbish in another's backyard, and for a brief period in 1996, the Chinese government banned all imports of waste plastic into China. The ban was prompted by the increasing incidents of containers of imported waste plastic which were found to be too highly contaminated to be used for recycling and had to be disposed locally. However, the ban was lifted within six months, mainly as a result of the complaints from the recycling industry which was suddenly faced with a significant shortage of raw materials. The second point relates to the crowding out effect of imported waste. An argument can be made that by increasing the import of waste, substitution from domestic waste to imported waste leads to a breakdown of the local recovery system which in turn inadvertently leads to a local waste disposal problem as well as a social problem caused by unemployment in the informal recovery system. We shall not investigate point one in this paper and shall assume in our analysis that all imported waste fulfills recyclable requirements. This paper investigates in a detailed framework the validity of point two and the economic and environmental significance resulting from the ensuing investigation.

The paper is presented as follows. In section two we highlight the main issues confronting the plastic sector in China. This is followed by a brief description of the plastic cycle. In section four, the main components of the model are provided. Preliminary results from a number of experiments will be discussed in the fifth section. The paper will conclude with some suggestions for extensions to the existing model.

The Main Issues

The Chinese plastic sector is presently facing an acute shortage of plastic resin. In order to relieve the shortage, four main issues need to be addressed. The first concerns the type of resin which is in short supply, ie, primary or secondary resin. Also linked to this issue is the substitution possibilities between the two and the economic and environmental costs associated with the production or importation of the two resins types[1].

The second issue arises if secondary resin production is to be expanded. Can domestic supply of waste plastic meet demand or are imports of waste plastic necessary? And if imports are allowed, what are the implications of this trade on the domestic sector?

The third issue addresses the spatial logistics of the supply and demand for the various goods at the various stages of the plastic cycle. China is a large country and with centres located over a large geographical area. The economic and environmental impacts of transportation logistics involved in getting goods from one point to another will play a crucial role in determining the optimal design strategy for the sector.

The fourth issue focuses on the environmental impacts of the sector. The environmental impacts caused by the petrochemical sector need to be evaluated against the environmental impacts caused by the secondary or recycling sector. Furthermore, the recovery of waste plastic and the effects this has on waste disposal need to be weighed and evaluated. Moreover, the environmental impacts stemming from trade in waste plastics need to be put in perspective with respect to the complete cycle of the plastic sector.

[1] Import of secondary resin is not an option at the present moment as there is no trade flows in this commodity.

The Plastic Cycle

Within the general category of plastics, five main types of plastic products form the bulk of demand in China. These are polyethylene(PE), polyvinlchloride(PVC), polypropylene(PP), polystyrene(PS), and finally polyethylene terephthalate (PET). These five classes of plastic constitute approximately 95% of total demand in China. Each category appears in varying qualities, ranging from high, medium to low. This definition is based on the content mixture of the respective virgin and secondary resins. The higher the content of secondary resin, the lower the quality of the plastic product.

The stages before plastic production, such as oil refining and resin production, together with the stages after production, such as waste plastics recovery and waste management, constitute the plastic cycle. In the following, a highly abstracted version of the full cycle will be given which captures the essentials. The life cycle begins at the petrochemical industry. Because of the high dependency primary resin production has with the petrochemical industry, it is normally presented as an integral part of the petrochemical industry. In the petrochemical industry, the thermal cracking process is used to produce the basic commodities needed for the production of primary resins.

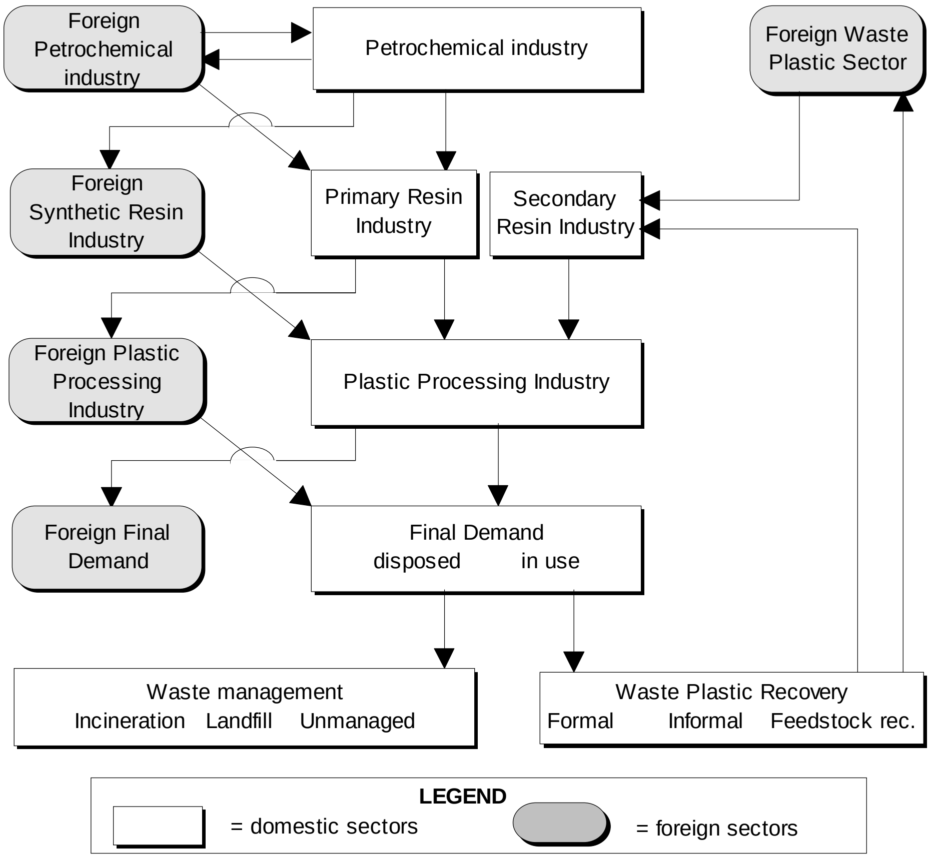
In the thermal cracking process, naphtha is used as an input to produce ethylene, propylene, aromatics and butadiene. The first three are then used in a variety of different processes to produce the different types of virgin resin. Butadiene on the other hand is considered as a by-product of the thermal cracking process and is sold for other uses outside the plastic cycle. Ethylene is polymerised to produce polyethylene (PE). Three different types of PE, i.e., HDPE, LDPE, and LLDPE can be produced depending on the molar weight of the polymer[2]. These different resins are used for very different purposes and are therefore not substitutable. The distinction needs to be maintained throughout the cycle, especially in the waste collection, separation and recycling processes.

The second product of thermal cracking, propylene, is as in ethylene polymerised to form polypropylene (PP). The third product of thermal cracking, aromatics is used to produce Benzene and p-Xylene (PX). Benzene in turn is used in a series of processes to produce polystyrene(PS). PX in turn undergoes another series of processes, together with ethylene to produce polyethyleneterephtalate (PET). In the production of the final plastic product, polyvinylchloride(PVC), ethylene is combined with vinylchloride. Vinylchloride itself is produced from chlorine which in turn is produced from rock salt.

---

[2] The reader is advised to refer to Steinhage et al. to for a detailed description of the chemical science underlying the plastic cycle.

Figure 1 A life Cycle Flow diagram for the plastic sector



The next major step in the cycle involves the production of the final plastic products. The production technology is relatively straightforward. The production process is governed by three techniques: (1) extruding; (2) injection molding; and (3) blow molding. The choice is in principle dictated by the shape and function of the final product.

The third major step in the life cycle is waste generation. Once the products have been delivered to the final demand centres, a certain fraction of total demand finds itself back into the waste stream. The exact ratios are difficult to quantify but based on life spans and the usage of the products, crude estimates can be made for total waste plastic generation by the various demand sectors.

Two options are available for the waste generated: it can be collected and recycled or it can be collected and disposed. In the case of the former, three collections systems are in operation: (1) formal; (2) informal; and (3) waste pickers. The formal system, essentially state-owned enterprises, was the predominant system during the pre-reform period in China. This system has come under increasing threat with reform of the state system and the privatisation of the market. The informal system, which is comprised mainly of small private companies has gained importance over the last decade. The last system, which has been in existence for long time, comprises individual waste pickers who collect waste from all source. During the pre-liberalisation period they supplied waste to the formal sector, but now supply to both the formal and informal sectors. Their comparative advantage lies in their ability to collect and sort contaminated waste in a relatively cost efficient manner.

The collected waste which is normally a homogenous product then needs to be sorted into: (1) the five categories of plastic mentioned earlier; and (2) different quality levels based on the degree of contamination within each category of plastic. The separated waste is then washed to reduce contamination, after which it undergoes a mechanical recycling process to produce secondary resin. At this point we would like to stress that the distinction between plastic types as well as quality levels within each category at all levels of recycling is necessary in order to produce final plastic goods of varying quality. In other words, each class and quality category is treated as a heterogeneous product.

Once they are produced, the secondary resins together with the virgin resins are then used to manufacture final products. And the cycle repeats itself. One has to note that the number of times a plastic can be recycled is limited and at some point it needs to be disposed. This is implicitly captured by the waste generation fraction we mentioned earlier. Another option, albeit technically sophisticated and economically expensive is the feedstock process which is presently only performed on an experimental level in China. This is where homogenous waste plastic is put through a process by which oil as an end product is produced. However, with technological innovation, this option may turn out to be an economically viable option in the future.

To limit its size, this paper does not provide a full report on the level and origin of all the data used in the study. The data were collected from literature sources, interviews with ministries and experts as well as a full field survey among 120 recyclers in various regions in China. For a comprehensive overview of this information we refer to the main report of the project.

Optimised Spatial Material Balance Flow Model (OS-MBF)

A static cost minimisation sectoral planning model is used as the base for the OS-MBF model. Sectoral models were first developed to help in the designing of industrial sectors in developing countries (Kendrick and Stoutjedijk 1978). However, the early models were primarily formulated as economic planning models with little attention paid to environmental impacts. But as the importance of environmental issues increased, it became imperative to look at a range of issues in addition to the economics of production, including the environmental impacts of production; the economics of disposal and recycling; and the environmental impacts of disposal and recycling (Beukering and Duraiappah 1998). In order to facilitate the incorporation of these new issues into the design strategy of a sector, the base model has been extended to incorporate a 'cradle to grave' analysis together with the associated environmental impacts caused by the complete product cycle (Duraiappah, 1993). The mathematical model will not be described in detail in the main section of the paper but is provided in the appendix. Only the germ cell of the philosophy driving the modeling framework is presented below.

The OS-MBF model developed for this study captures the complete life cycle of the plastic industry, beginning with the thermal cracking of naphtha to the final disposal of waste plastic. By incorporating a life cycle within a traditional sectoral modeling exercise, it is possible to track the use and production of the various materials (life cycle analysis); and to evaluate the trade-offs that occur within and between economic and environmental variables at each stage of the cycle (sectoral analysis). Moreover, the technological input-output structure of sectoral models lends itself well to the multi-process and multi-product characteristics of the plastic cycle. Furthermore, the model decision platform provides a basis for comparisons between the different objectives of decision makers.

To begin, activity centres for the plastic sector are identified. Based on the dynamics of the demand and supply of the sector, the following three main activity centres were identified: (1) primary resin production centres; (2) demand and waste collection centres; and (3) recycling and final product production centres. The centres are not mutually exclusive. These activity centres were located strategically across the country taking into account of the primary demand centres, raw material supply centres and finally foreign import facilities. In this manner, transportation logistics, both from an economic cost and environmental impact perspective are taken into consideration in the decision making framework. This distinction allows us to capture the spatial dimension to the problem.

Next, the set of all technological options for the complete cycle are identified. Associated with each process is a unique input-output vector, also known as a technology matrix, which describes the various inputs used and the outputs produced. Through the technology matrix, the level of raw, intermediate, final and pollutant goods used and/or produced can be computed. The processes are linked through a series of mass balance equations which in essence stipulate that total mass of material used must be equal to total mass of material produced. The technology matrix in essence provides the basis for an analysis of trade-offs between the use of primary versus secondary resin. In the optimisation procedure depending

on the objective of the optimisation exercise, the optimal design strategy comprising an unique combination of technologies is identified.
Associated with processes are capacities. All processes have capacity limits. In order to specify capacities, we first link processes with a particular machine unit. We achieve this mapping by first identifying machine units and the capacity of each unit in each respective activity centre. The next step is to introduce a machine-process utilisation matrix by which we link the process with a particular machine unit. More than one process can use a machine unit and in many cases it is this feature of the production process which highlights existing bottle necks in the sector and policy options to mitigate or eradicate these inefficiencies. The units can vary depending on the degree of complexity of the model (Kendrick and Stoutjedijk 1978). The important point here is that a limit is imposed such that infinite production levels are not allowed and which can lead to misleading or unrealistic results. In the version of the model presented here, we have used existing capacity in the various processes in the Chinese plastic sector as the upper limits.

Once the technology matrix is defined, the next step involves linking the various stages in the cycle through a series of material balance flow equations. In essence, these equations state that the total mass of products produced at a point must be equal to the total mass of inputs used in the process. The level of inputs can be a combination of products produced within the centre, shipped from another centre or imported. In the case of the latter two, the transportation logistics are also taken into account in addition to the economics of production.

From the emission and material levels resulting from the technology matrices, the environmental dimension can be composed. There are two options of modelling the environment in the model. Environmental services are introduced as a scarce but variable parameter or an upper bound on environmental use is fixed. The latter is the more commonly used route as it is the simplest. However, it involves a degree of arbitrariness as the constraints are determined in many cases in an *ad hock* manner.[3] T he former method, albeit more difficult, theoretically provides a design strategy which is the most cost effective, both from an economic and environmental perspective.

In order to determine the environmental impact, the concentration levels of each pollutant need to be determined taking into account the physical properties of the site. For example, an air pollutant emitted during sea freight will do less harm than the combustion of plastics in a densely populated area. Also climatic conditions can be very influential. It is beyond the purpose of this model to take into account this level of detail. Therefore, standard values are applied. In other words, transfer coefficients are used to translate emissions to concentrations, assuming factors such as population density, and age distribution. Next, these environmental

[3] There are various ways in which environmental effects can be aggregated. In the “distance-to-target” approach weights are derived from the extent to which actual environmental performance deviates from some goal or standard (Powell et al. 1995). Alternatively, multi-criteria techniques can be used to determine the weights. In this method, scores are derived from panels of experts and interested parties (Beinaut 1995). These two approaches have several disadvantages. As experts generally over-represent their own interests, the weights applied are rarely representative for the society as a whole. Another handicap is the fact that the ultimate environmental score is not reported in monetary values. Consequently, integration with the financial analysis is impossible. For a more elaborate exposé on valuation, we refer to van Drunen and van Beukering (1999).

impacts are translated into monetary values, again making strict assumptions such as income levels and property values.

The concept of economic valuation of environmental externalities is mainly applied in policies in industrialised countries. Especially in the United States economic valuation is a common practice due to its juridical system where environmental claims are often expressed in monetary terms (i.e. the oils spill of the Exxon Valdez in Alaska in 1989). Developing countries generally prefer to base their environmental systems on environmental standards. The ground principles of this approach are very different from economic valuation. Economic valuation was selected as the main environmental approach in this project, for various reasons which will be explained below. In the main report of the project alternative valuation methods are explained and compared.

The monetisation of environmental impacts by the various pollutants is called economic valuation. In this approach, the economist's monetary measure of economic value is the Willingness-to-Pay (WTP). The WTP is defined as the maximum amount of money a person is willing to pay to obtain a good or service. An individual's WTP for a good is a reflection of his preferences for this good relative to other goods. It suggests that a person also has a certain WTP for environmental goods.

There are various techniques to measure the WTP. First, the values can be based directly on market values of productivity. For example, if extensive emissions of air pollutants from a coal fired electricity plant adversely affect agricultural yields in the region, the crop losses can be used as a measure of the environmental damage of the electricity plant. Second, values can be based on market prices for surrogate products or services. For example, deforestation may lead to a shortage of fuel wood. An alternative fuel which may need to be imported may again represent the external environmental costs of deforestation.

In both examples, market prices are directly or indirectly indicative for the environmental impact. Often, environmental goods are not retrievable from market prices, for example the value of biodiversity or human health. In this case, individual preferences (WTP) may be revealed through interviewing techniques.

This approach is used for several reasons. First, it allows us to combine the derived external values with internal "financial" costs thereby enabling a full cost-benefit analysis. Second, economic valuation albeit conducted under strong assumptions reduces the degree of arbitrariness as compared to emission regulatory standards (Duraiappah, 1994).

A large pool of literature is available on EVA. From this literature, standard values have been derived for each pollutant (Beukering *et al.* 1998). These standard values allow us to translate emissions directly into costs bypassing the concentration computation stage. It should be mentioned that this simplification may lead to a certain level of inaccuracy. Yet, in the sensitivity analysis the impact of this potential error will be tested.

An important advantage of economic valuation is the fact that it enables a comparison of the benefits of some environmental improvement with the associated costs. If the benefits, as measured by the WTP for these benefits, are less than the costs then the conclusion would be that the individual prefers to have this improvement to not having this improvement. For example, suppose a program designed to reduce air pollution would result in less cases of an adverse health effect associated with air pollution, say asthma attacks. If some person is willing to pay US$ 75 for preventing these adverse health impacts while the costs of the program to him would be only US$ 50, then one can conclude that he would prefer the situation with the reduced air pollution even though this would mean he has less (US$ 50) to spend on other goods.

The fact that the actual estimation of the weights of the various environmental impacts – and thus the WTP – is a rather time-intensive procedure, is a major disadvantage of economic valuation is that methodology. Generally, extensive surveys have to be organised to gather data. Part of this effort can be avoided by applying benefit transfer[4] to existing values from other studies.

Another disadvantage resulting from the comprehensiveness of economic valuation is the fact that the final result is accompanied by a significant degree of uncertainty. Also, the fact that economic valuation expresses values in monetary terms, for example for human health, makes it a rather politically sensitive approach.

In constructing the economic valuation, we found that pollutant emissions from the plastic cycle had significant contribution to five environmental impacts: (1) global warming potential; (2) eutrophication; (3) human toxicity; (4) solid waste; and (5) acidification. The values applied for these five environmental effects were compiled from a series of existing studies (Beukering *et al.* 1998). Through benefit transfer, these values which mainly refer to Europe and the United States, have been corrected for Chinese conditions by, for instance, applying a factor representing relevant aspects such as the income differences between the countries, population density and the value of property such as house and land.

To close the model, an objective function is specified. The objective function we used ranged from a standard economic cost minimisation strategy to a total cost, ie., economic plus environmental costs, minimisation strategy. In either case, based on the policy makers objective, the model solution provides an optimal design strategy. The question at hand is which strategy provides the most cost effective solution. This now leads us to some preliminary results provided by the OS-MBF model developed for the plastic sector in China.

---

[4] The definition of benefit transfer is ‘an application of monetary values from a particular valuation study to an alternative or secondary policy decision setting, often in another geographical area than the one where the original study was performed’ (Navrud 1994).

Results

The driving force behind an optimisation model is the objective function. To understand the trade-offs between environmental and economic goals, the model is analysed with different objective specifications. For this paper, the following two strategies were formulated:

1. The *economic* strategy. The traditional sectoral modeling strategy whereby an economic cost minimisation objective function is adopted.
2. The *sustainable* strategy. In this version, total cost minimisation is adopted, ie, environmental cost is included in addition to the economic costs components.

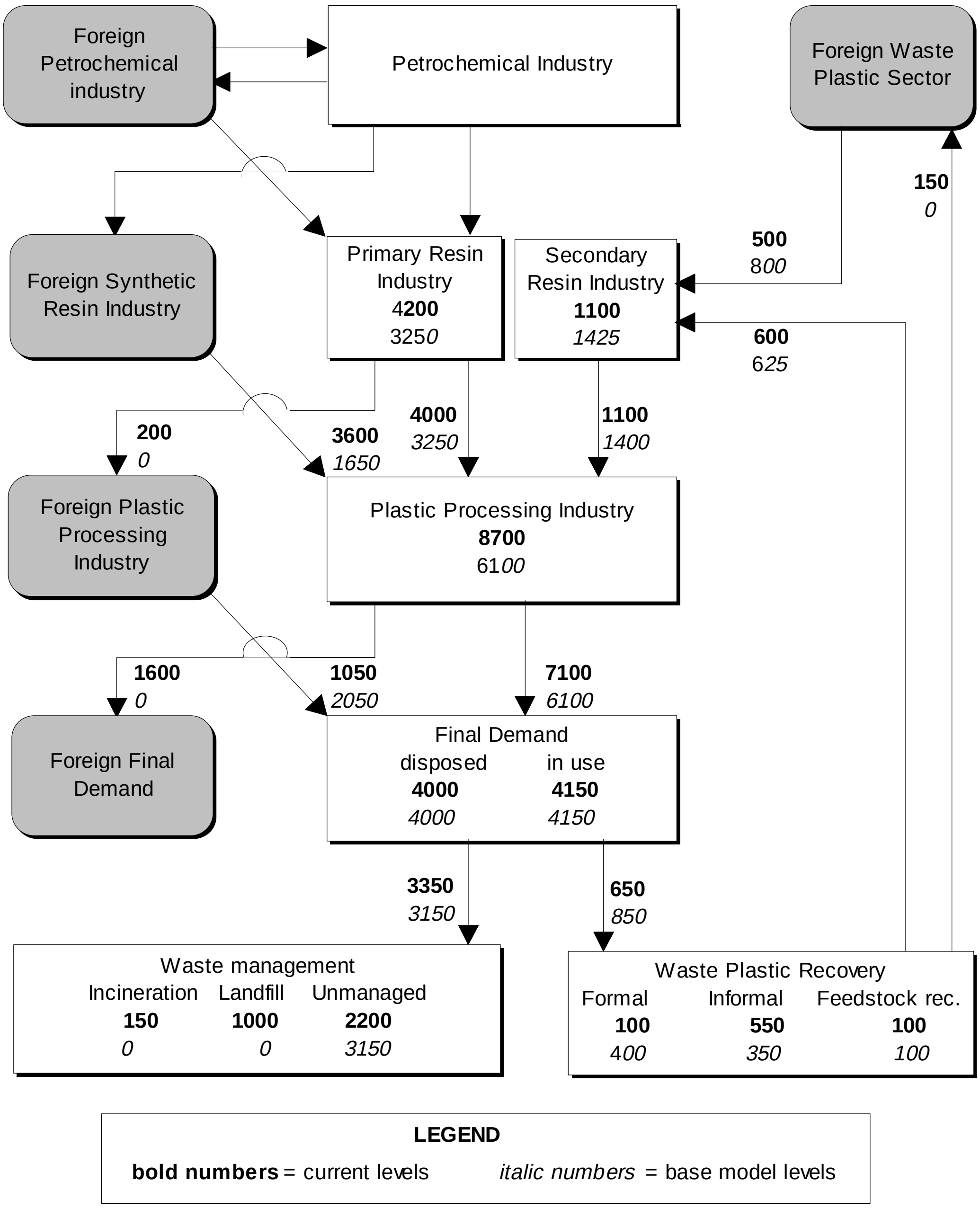
Moreover, as imports of waste plastic is a major issue in China, we used the model to analyse the optimal strategies under two trade regimes; (1) full trade; and (2) an import ban on waste plastic. In total, we ran seven experiments. The first four have been mentioned above. The fifth run involved changing some of the technical parameters governing the input mix of virgin and secondary resin in the manufacture of final products. This was primarily done to test what at first sight seemed strange results from the first four experiments. The final two runs were to check the sensitivity of the results to changes in imported waste plastic prices.

We begin by comparing the economic full trade strategy with the present situation in China's plastic sector. As the focus of the study is on the plastic sector, we begin the comparison from the primary resin production stage and not from petro-chemical production.

From Figure 2 below, we observe close simulations with actual mass flows except for the following: (1) the production of final goods; (2) import of primary resin; and (3) production of primary resin. There are two reasons for the lower production in final goods. The first is relatively straightforward: in this exercise, we omit exports and this in turn implied a lower demand for final goods. The second reason is slightly more complex and is linked to the lower import of primary resin as well as the lower level of domestic production of primary resin - point two and three above.

The reason for the above observations was traced back to the technology matrix and capacity bottlenecks. The technology matrix was developed in a manner which allowed various combinations of secondary resin with primary resin to produce various qualities of final products. The matrix is fixed and therefore no substitution is allowed between the resins if a shortage is witnessed in either category. This may be considered as a shortcoming of the model but in actuality turned out to be a crucial characteristic which highlighted a number of major problems in the Chinese plastic sector.

Figure 2. A Life Cycle Flow diagram for the plastic sector (1000 tons)



Closer investigation of the model results highlighted a capacity constraint at the secondary resin production stage. The sector unable to produce secondary resin and import the commodity had no other alternative but to import final goods to meet demand. Subsequently, domestic production as well as import of primary resin were reduced. The question which immediately arises in light of this result is why then is the plastic sector importing such a large amount of primary resin? It is in response to this puzzle that experiment five, a sensitivity analysis on the technology matrix, was formulated.

In order to solve the puzzle, we modified the technology matrix in a manner whereby the level of primary resin used in the production of final goods was increased. Table 2 below gives the input mix before and after modification of the technology matrix.

Table 2 Input mixture for production of final goods

	High Quality		Medium Quality		Low Quality	
	before	after	before	after	before	after
Primary Resin	90%	100%	20%	50%	30%	30%
Secondary Resin	10%	0%	80%	50%	70%	70%

The results, shown in Tables 3 and 4, confirmed our suspicions; the import of primary resin rose significantly while the import of final goods decreased. Because the cost of importing primary resin is much less than the cost of importing final goods, we observed a drop in total cost in spite of the additional environmental cost incurred due to higher domestic production of final goods. In effect, the plastic sector in China had adopted a strategy whereby a higher level of primary resin was used in order to reduce the dependence on the import of final goods to meet final demand.

Table 3 Cost comparisons with different sets of input-output coefficients for the production of final goods (billion Yuan)

	Base Economic	Base Sustainable	Modified Base Economic	Modified Base Sustainable
raw material cost	18.2	14.1	19.2	14.7
transport cost	1.94	1.71	1.93	1.65
import cost	38.9	44.8	35.2	41.8
environmental cost	3.88	0.97	4.27	1
by product revenue	3.8	3.52	3.8	3.52
total cost	55.2	58	52.5	55.6
actual total cost	59	58	56.8	55.6

Table 4 Imports of commodities with standard and modified technology matrix (million tons)

Imports	Base Economic	Base Sustainable	Modified Base Economic	Modified Base Sustainable
Primary Resin	0.6	1.6	1.0	2.2
Waste Plastic	0.8	0.8	0.5	0.5
Final Goods	2.1	2.1	1.3	1.3

We call the strategy adopted above a second best solution because, although it is a more cost effective strategy than importing final goods, technology allows the industry to reduce cost further by allowing an increase in the portion of secondary resin in many final products without compromising quality. If industry takes advantage of this factor, it can reduce cost in two ways. First, increasing the supply of secondary resin is a cheaper option than either increasing domestic primary resin production or importing it. Second, the production of secondary resin is environmentally less intensive than primary resin production processes. These results are clearly demonstrated in the following section.

Policy Options

In Table 5 below, the various cost components across the economic and sustainable strategy under a free and restricted trade regime are shown. But before we begin to discuss results and policy prescriptions we should explain the difference between total cost and actual total costs. In the sustainable strategy scenario, the two are the same. However in an economic strategy, there is a difference between the two which is accounted for by the environmental cost component. In the economic strategy, only economic cost is minimised; environmental cost is left out in the minimisation process. However, in actuality, this cost will be incurred and the actual cost figure reflects the true costs associated with the plastic sector.

Table 5 Costs for various strategies under free and restricted trade regimes (in billion Yuan)

	Base Economic	Base Sustainable	No Import Economic	No Import Sustainable
raw material cost	18.2	14.1	18.3	12
transport cost	1.94	1.71	1.67	1.47
import cost	38.9	44.8	53.2	61.2
environmental cost	3.88	0.97	4.5	1.3
by-product revenue	3.8	3.52	3.8	2.87
total cost	55.2	58	69.3	73
actual total cost	59	58	73.8	73

note: differences in total are due to rounding out errors.

What is evident from the four simulations is the cost efficiency of both the economic and sustainable strategies under the free trade regime - a cost saving of approximately 26 percent. The results also indicate a lower impact on the environment under the free trade regime irrespective of the strategy adopted. In other words, the import of waste plastic is both economically and environmentally beneficial for the Chinese plastic sector.

The high cost accruing from the import ban was traced to higher import levels of final goods to meet local demand. The import ban on waste plastic causes a shortage of raw materials for the production of secondary resin as domestic supply of waste plastic is insufficient to meet demand of the secondary resin production sector. The lower production of secondary resin in turn creates a bottleneck in the production of final goods because secondary resin is used in various combinations together with primary resin to produce final products. As the import of secondary resin decreases[5], the only option is to import final products to meet local demand. This pushes up import costs and subsequently total costs. In reality however, the sector would have substituted secondary resin with primary resin, increase domestic production of domestic goods and reduce import of final goods thereby reducing final costs, as illustrated in Tables 3 and 4 above. But what the simulation highlights is the cost advantages which can be reaped if a higher level of secondary resin production is pursued.

The most obvious response would be to increase the domestic supply of waste as a substitute for imported waste. However, this may only mitigate the shortage to a certain extent, because only a certain proportion of plastic can return to the waste stream. The other portion remains in use and it would be unrealistic to assume a 100% recovery rate[6]. The other possibility is to increase the efficiency in waste collection from the present six percent to previous levels of 20% (Beukering and Li 1998). However, this will still be insufficient to meet total demand and the only other viable option is to allow the import of waste and simultaneously provide incentives to increase the capacity of the secondary plastic producers.

A possible counter proposal or an alternative to the above policy prescription which critics of trade in waste may suggest, is to increase the capacity of the domestic primary resin production sector. This in fact is the dilemma currently encountered by the Chinese plastic sector. Increasing domestic production of primary resin capacity would indeed resolve the problem but at a comparatively higher cost as confirmed by Table 5. On the other hand, if we take advantage of the technical possibilities, a lower cost option is possible. Going back to the input-output technology matrix, we know that to produce final products, a combination of primary with secondary resin is in most cases possible. Therefore, substituting primary resin with secondary resin can in theory reduce cost while still meeting final demand. Therefore, increasing primary resin production at the present moment is an economic and environmentally costly endeavour as compared to increasing the production of secondary resin.

Sensitivity analysis

We next looked at the sensitivity of the plastic cycle in China for changes in the import price of waste plastics as well as capacity limits in the secondary resin production centres (plastic recycling industry). We tested the sensitivity of the model results to a price increase of 50% (sensitivity analysis 1) and a price decrease (sensitivity analysis 2). Although this is unusually high for sensitivity tests on primary materials, fluctuation of this magnitude are rather common in the international secondary market. Two additional sensitivity experiments were conducted. The first involved increasing the capacity of the secondary resin sector by 20% but with price

---

[5] In the present model version, we do not allow imports of secondary resin as this does not take place under present conditions and is seen as very unlikely to do so in the future.

[6] The recovery rate of plastics, which is defined as the share of the total plastic consumption in a particular year which is recovered from the waste stream for recycling purposes, declined from 20% in 1980 to 6 % in 1996 (Beukering and Li, 1998).

fixed at the base level (sensitivity analysis 3) while in the second a price decrease of 50% together with a 20% increase in capacity of secondary resin was implemented (sensitivity analysis 4). The results are shown in Table 6.

Table 6 Results of the Sensitivity Analysis

	Base scenario (P_{wp} = 1, C_{wp} = 1)	*units*	sensitivity analysis 1 (P_{wp} = 1.5, C_{wp} = 1)	sensitivity analysis 2 (P_{wp} = 0.5, C_{wp} = 1)	sensitivity analysis 3 (P_{wp} = 1, C_{wp} = 1.2)	sensitivity analysis 4 (P_{wp} = 0.5, C_{wp} = 1.2)
domestic primary resin	3,226,421	*metric tons*	0.00%	-0.25%	0.72%	0.39%
imported primary resin	1,646,306	*metric tons*	-0.06%	-1.01%	-3.64%	-4.08%
domestic secondary resin	1,429,741	*metric tons*	-0.14%	0.00%	18.48%	18.48%
imported waste plastics	805,108	*metric tons*	-0.28%	23.10%	34.63%	52.85%
domestic waste plastics	624,633	*metric tons*	0.01%	-29.78%	0.62%	0.62%
domestic final goods	6,096,086	*metric tons*	-0.05%	-0.37%	3.74%	3.48%
imported final goods	2,068,813	*metric tons*	0.14%	1.08%	-11.03%	-10.26%
total costs	58.1	*billion Yuan*	2.17%	-2.36%	-3.26%	-6.37%
environmental costs	0.9	*billion Yuan*	0.00%	-0.03%	0.63%	0.61%

P_{wp} factor by which the import price of waste plastics is multiplied for the sensitivity scenario
C_{wp} factor by which the plastic recycling capacity is multiplied for the sensitivity scenario

Let us begin by observing the sensitivity of the model to a 50% increase in the import price of waste plastics. The changes were minimal with an increase of two percent in total costs. This increase in cost was primarily caused by an increase in the import of final goods. The dynamics of the sector seem to suggest that this option is relatively more cost effective at the margin than importing waste at the previous levels to produce secondary resin which is needed subsequently to produce final goods domestically. This conclusion is supported by the lower domestic secondary resin production figure illustrated in Table 6

We next reduced the import price of waste plastic by 50%. The results illustrated major changes in the material flows. The import of waste plastics increased by approximately 23% while the use of domestic waste decreased by 30%. This result suggests that the local recovery sector is sensitive to international market prices for waste plastic and if these prices fall, the domestic secondary resin production sector will substitute domestic waste with imported waste. The crowding out effect advocated by critics of trade in waste plastic poses a real threat to the domestic waste sector which policy makers must address when policy prescriptions are formulated. However, a word of caution must be mentioned here. Our analysis does not take into account the social costs which accrue to the economy when unemployment goes up in the recovery sector. This is a real cost which must also be addressed when policies relating to trade in waste plastic are discussed.

One recurring observation was noted in the two sensitivity scenarios discussed above as well as in the first four simulations: the secondary resin sector was always operating at full capacity. In fact it was highlighted in the previous sections that it was the limited capacity at the secondary resin production centres that was dictating the sectoral design. In order to investigate the relative importance of this factor, we decided to run two further sensitivity tests. In sensitivity analysis three the capacity is increased by 20% while the imported waste plastic price remains the same as in the Base run. In sensitivity analysis four, the capacity was increased as in sensitivity analysis three but with the price of imported waste reduced by 50%.

We observe a relatively large drop in the import of final goods. As the supply of secondary resin is no longer a limiting factor, the plastic sector is able to produce a larger quantity of final goods domestically. The drop in total costs stems directly from the lower import cost of final goods vis-à-vis the import cost of waste plastics. The environmental cost goes up slightly as there is a higher domestic activity level . However, the increase in environmental cost is more than compensated by the decrease in import cost. These savings in costs are even higher if the import price of waste plastics is half of the current level as clearly shown by sensitivity analysis 4. Another interesting and crucial result demonstrated by sensitivity analysis four is the rejection of the crowding out effect hypothesis. The results clearly illustrate that a drop in price of imported waste does not have an effect on the use of domestic waste - the quantity of imported waste goes up but not at the expense of domestic waste. In other words, the domestic recovery sector is operating at full capacity and all domestic recyclable waste is being recycled.

Spatial Dimension of the Model

We now turn our attention to the spatial dimension of the strategies discussed above. In order to prevent an overload of information, we restrict our analysis to the sustainable strategy. Spatial information is important for a number of reasons. First, it highlights where present bottlenecks are and where future investments should be made. Second, transport costs usually form a substantial part of total costs and major costs reductions can be achieved if demand and supply links are strategically matched.

The transportation logistics are depicted in three figures. The shipments patterns which are indicated by dotted lines indicate shipment within the centres. There are a number of centres which are a combination of primary resin production, secondary resin and final product manufacturing centres and finally demand centres. An overview of the various activity centres is given below and their respective locations in China are shown in Figure 3.

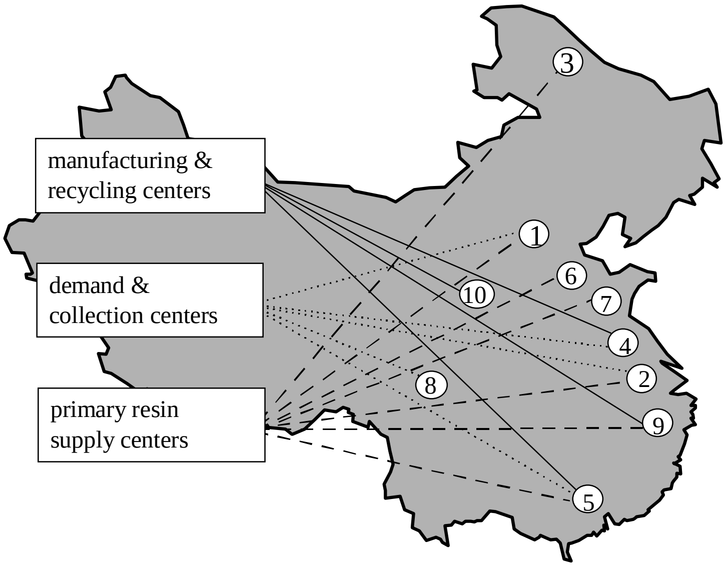
- *Activity Centres*:
  Beijing, Shanghai, Daqing, Nanjing, Guangzhou, Tianjin, Zibo, Nibo, Baoding, Chongqing;

- *Primary Resin Production Centres*:
  Beijing, Shanghai, Daqing, Nanjing, Guangzhou, Tianjin, Zibo;

- *Recycling and Final Production Centres*:
  Nibo, Nanjing, Guangzhou, Baoding;

- *Final Demand Centres*:
  Beijing, Shanghai, Nanjing, Guangzhou, Chongquing.

Figure 3 Geographical distribution of activity centres in China

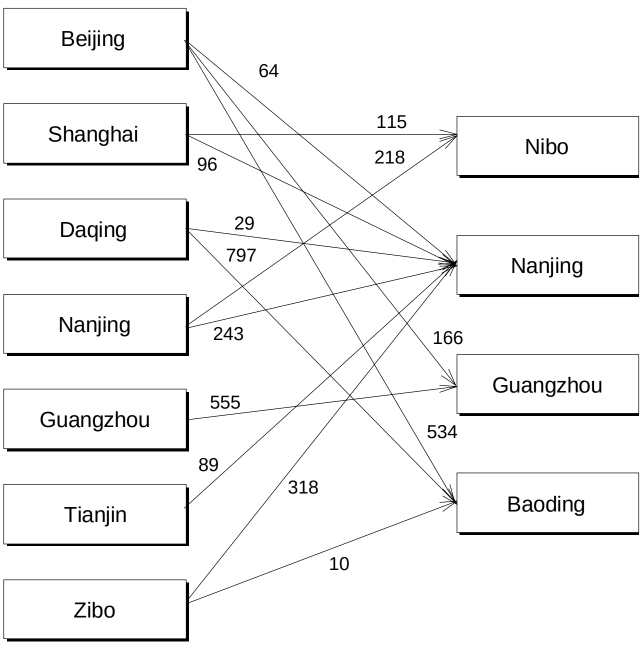


Activity Centers

1. Beijing
2. Shanghai
3. Daqing
4. Nanjing
5. Guangzhou
6. Tianjian
7. Zibo
8. Chongqing
9. Ningbo
10. Baoding

The figures given below are for the sustainable strategy under the original technology matrix. Three sets of results are shown. The first set shown in Figure 4, describes the transportation of primary resin from the production centres to the final product manufacturing centres.

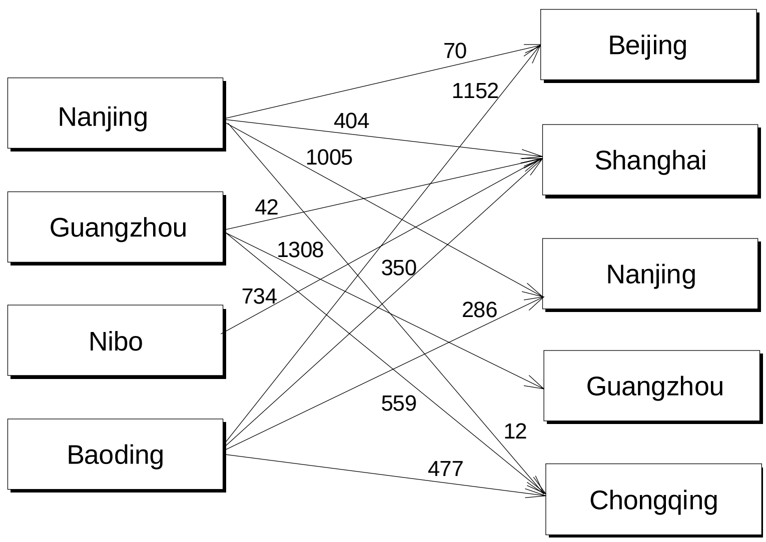
Figure 4 Material flows of primary resin within China



Two interesting observations are noted. The first is the supply link between Beijing and Guangzhou and the second is the link between Daqing and Nanjing. The distance between these two centres are significant and one would have expected production centres located strategically closer to supply the primary resin to the two final goods production centres. The reason was traced to a combination of transport logistics and capacity constraints. Taking into consideration distances between centres, it would seem logical for Guangzhou to get supplies from Shanghai or Nanjin, which are both nearer. However, capacity constraints in these two centres plus the lower transport cost to the demand centres of Ninbo and Nanjin make it cost effective to let Beijing supply Guangzhou. A policy option to reduce this dependence is to increase the capacity in Guangzhou itself or as the next alternative Shanghai or Nanjin.. The same dynamics prevail for the Daqing-Nanjing link.

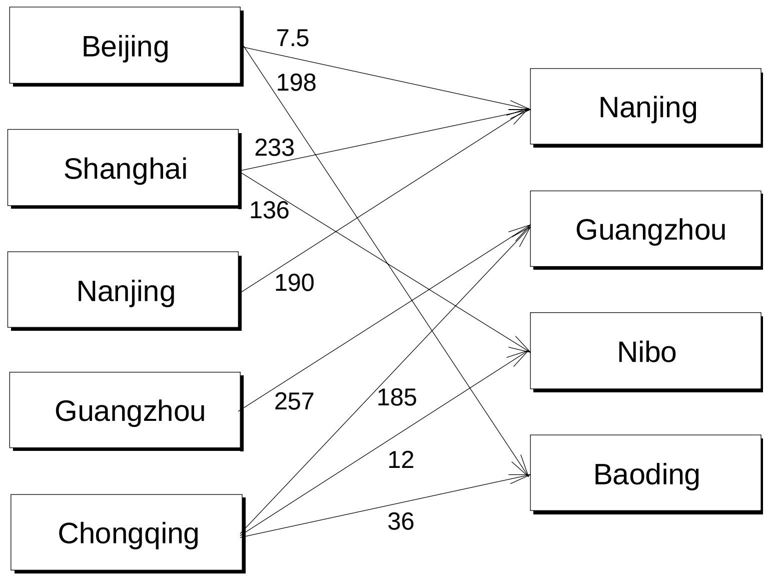
Figure 5 below describes the shipment patterns of final products from the manufacturing centres to the final demand centres. No real surprises were observed in the shipment patterns although at first observation it would seem odd to see Chongqing being supplied by Baoding. However, on closer scrutiny of the results, the closest supply centre, Guangzhou is already operating at capacity and no other alternative is possible except Baoding, the next closest centre. A policy option would be to increase the capacity in Guangzhou but a word of caution should be mentioned here. As the demand by Chongqing is relatively large, the increase in capacity in Guangzhou must be substantial. Therefore, the decision to invest in Guangzhou must be made in the context of the transportation costs plus the possibility of future expansion in demand. This in turn would require the model to be extended from the present static model to a inter-temporal model.

Figure 5 Material flows of final products within China



The last transportation link shown in Figure 6 is the supply of the separated waste plastic to the recycling centres. The shipment patterns were determined solely by transport costs, with the nearest being supplied first followed by the next and so on. But what is interesting is the quantity of waste which is supplied to the recycling centres.

Figure 6 Material flows of recyclable waste plastics within China



We implicitly assumed that all recyclable waste is recycled. Mapping the quantity of waste shipped to Guangzhou plus its own waste to the capacity available for mechanical recycling, we computed an excess of approximately 80,000 tons of different types of recyclable waste plastics. Therefore, it seems that there is an acute shortage of recycling capacity which goes to support our earlier findings. This is in essence the reason for substituting secondary resin with primary resin for a number of plastic products.

Conclusion

One crucial and important factor was continuously highlighted by the various model simulations. The limited existing capacity of secondary resin production is causing bottlenecks in the plastic sector. The shortage is in fact forcing the final goods manufacturing sector to use a higher proportion of primary resin in their final goods than economically and technically permissible. This in turn has been one of the reasons for the large import of primary resin. The plastic sector is presently pursing what we call a “second best” strategy. The fact that it is using imports of primary resin to produce final goods rather than importing the final products themselves is one step in the right direction. The next step would be to take advantage of technical properties for plastic goods with regard to the content mixture of primary and secondary resin. In other words, there is an upper bound for substituting primary resin with secondary resin and this constraint should be maximised. We identified three ways in which the sector can move from a “second best” to a “first best” solution. These are:

- Increasing the capacity of mechanical recycling
- Allowing imports of waste plastic
- Improving the waste recovery rate.

By adopting option one above, the total costs of the plastic cycle in China can be reduced significantly by increasing the capacity of the domestic recycling industry. Although the additional recycling capacity is mainly met by imported waste plastics, the overall import costs will reduce, since the increase in imports of waste plastics will mainly replace relatively expensive imported final goods. Second, the overall costs could be reduced even further if the recovery sector could be improved and expanded. China has experienced a significant reduction in its recovery rate over the last decade due to privatisation. As a result, certain recyclable materials remain unexplored. Policies could stress this recovery potential.

The model presented in this study was formulated with the primary objective of investigating and shedding light on the present status of the plastic sector. We now know that secondary resin, both domestic and imported, can be used more extensively in the sector and is a strategy which produces a more economically and environmentally superior solution compared to the current dependence on primary resin. The next step in the analysis is therefore to: (1) design the investment plan for the sector, in other words, the size, timing and location of investments; and (2) identify the optimal recovery rate for waste plastic and the channels which should be supported and given the proper incentives. Each activity requires a separate model as the complexity of each endeavour is high and impossible to be incorporated within a single all encompassing model.

References

Beinaut, E. 1995. *Multiattribute Value Functions For Environmental Management*. PhD thesis. Tinbergen Institute Research Series No. 103. . Vrije Universiteit, Amsterdam.

Beukering, Pieter van, and Duraiappah, A.K. 1998. "The Economic and Environmental Impacts of Waste paper Trade and Recycling in India: A Material Balance Approach.". *Journal of Industrial Ecology* l.2 (2): 21-40.

Beukering, Pieter van, Drunen, Michiel van, Dorland, Kees, Jansen, Huib, Ozdemiroglu, Ece and Pearce, David. 1998. *External Economic Benefits and Costs in Water and Solid Waste Investments: Methodology, Guidelines and Case Studies*. Report number R98/11. Institute for Environmental Studies, Amsterdam.

Beukering, P.J.H. van, and Yongjiang, Li. 1998. *The Plastics Cycle In China: With Special Emphasis On International Trade And Recycling*. Background paper for the Workshop, The Plastic Cycle in China Chinese Academy of International Trade and Economic Cooperation (CAITEC), 20 January 1998.

Beukering, P.J.H. van, Yongjiang, Li, Yumin, Zhao and Xin, Zhou. 1997. *Trends And Issues In The Plastics Cycle In China With Special Emphasis On Trade And Recycling.* CREED Working Paper Series No.16. IIED, London. and IVM, Amsterdam.

Duraiappah, A.K. 1993. *Investing in Clean technology: An Exercise in Methodology*. Netlap Publication Series. UNEP, Bangkok.

Grace, R., Turner, R.K and Walter, I. 1978. . "Secondary materials and international trade." *Journal of Environmental Economics and Management* 5: 172-186.

Kendrick, D.A. and Stoutjesdijk, A.J. 1978, *The Planning Of Industrial Investment Programmes; A Methodology.* John Hopkins University Press, Baltimore.

Markandya, A . 1994. "Economic Valuation: An Impact Pathway Approach". In *Externalities of Fuel Cycles*. Vol 9. European Commission DGXII, Brussels.

National Federation of Light Industry 1996. *Internal Data* From National Federation Of Light Industry. Beijing

Ogilvie, S.M. 1996. *Opportunities and Barriers to Plastics Recycling*. AEAT-0114. Prepared by the Recycling Advisory Unit of the National Environmental Technology Centre for the Department of Trade and Industry. NETC, Oxfordshire.

Powell, J. C., Pearce, D. and Brisson, I. 1995. *Valuation for Life Cycle Assessment of Waste Management Options*. CSERGE Working Paper WM 95-07. University of East Anglia, Norwich.

Steinhage, C.C.M. et al.: 1990. Milieuinventarisatie verpakkingsmaterialen, CPM TNO.

UNCTAD. 1996. *Statistical Review of International Trade in Paper and Plastic Waste*. UNCTAD Commodities Division, Geneva.

Appendix

SETS

I	Activity Centres / Beijing, Shanghai, Daqing, Nanjing, Guangzhou, Tianjin, Zibo, Chongqing, Ningbo, Baoding /
PI(I)	Primary Resin Production Centres /Beijing, Shanghai, Daqing, Nanjing Guangzhou, Tianjin, Zibo/
DI(R)	Demand, Collection and Separation Centres /Beijing, Shanghai, Guangzhou, Chongqing, Nanjing /
FI(I)	Washing, Recycling and Final Production Centres /Ningbo, Guangzhou, Nanjing, Baoding /
P	**Processes**
PPR(P)	Primary Resin Production
PSR(P)	Secondary Resin Production
PFP (P)	Final Goods Production
PCL(P)	Waste Collection Processes
PSP (P)	Waste Separation Processes
PDSP(P)	Waste Disposal Processes
M	**Machine Units**
MPR(M)	Primary Resin Production
MSR(M)	Secondary Resin Production
MFP(M)	Final Goods production
C	**Commodities**
CRPI(C)	Raw Material Commodities used in primary resin production centres
CIPI(C)	Intermediate Commodities used in primary resin production centres
CFPI(C)	Final Goods produced in primary production centres
CRDI(C)	Raw Material Commodities used in Collection, Separation centres
CIDI(C)	Intermediate Commodities used in Collection, Separation and disposal
CFDI(C)	Final Goods produced in Collection, Separation and disposal centres
CWDI(CRDI)	Waste Goods produced by sectors
CRFI(C)	Raw Materials used in final production centres
CIFI(C)	Intermediate goods used in final production centres
CFFI(C)	Final Goods produced in final production centres
S	**Demand sectors for plastic goods**

VARIABLES

z	Activity Levels
x	domestic shipments
u	domestic purchases
v	imports

w	waste level
e	emissions
md	middle distillate used
rc	raw material costs
vc	import costs
dc	disposal costs
br	byproduct revenue

DATA

a	input-output technology matrix
d	fixed demand
α	recovery ratio
k	capacity available
mud	distillate used for transportation
mut	transport cost per unit transported
p	prices
j	capacity utilisation rate

SET OF EQUATIONS

Primary Resin Production Centres

1. Material Balance Constraint for Raw Materials

$$\sum_{p} api_{c,p} z_{p,pi} + u_{c,pi} + v_{c,pi} \geq 0 \qquad c \in CRPI, pi \in I$$

The total amount of raw material used in each primary resin production centre must be matched by domestic purchases plus imports. The api coefficient tells us the amount of a particular raw material which is needed by a particular process to produce one unit of output. The units are in physical units. U is domestic purchases while v is the import level.

2. Material Balance Constraint for Intermediate Materials

$$\sum_{p} api_{c,pi} z_{p,pi} + \sum_{\substack{pi' \\ pi' \neq pi}} x_{c,pi',pi} + v_{c,pi} \geq \sum_{\substack{pi' \\ pi' \neq pi}} x_{c,pi,pi'} \qquad c \in CIPI, pi \in I$$

Total amount of intermediate products produced domestically by all processes plus interplant shipments from other plants plus imports must be greater than the total amount of intermediate products supplied to all other plants.

3. Material Balance Constraint for Final Goods

$$\sum_{p} api_{c,pi} z_{p,pi} \geq \sum_{fi \in I} x_{c,pi,fi} \qquad c \in CFPI, r \in R$$

The total amount of each type of primary resin produced at each centre must be greater than the sum of shipments to all final production centres.

Collection, Separation and Disposal Centres

4. Total domestic waste generated by each sector

$$w_{c,di} = \sum_{s \in S} \sum_{c \in cffi} \alpha_{s,cwdi} d_{c,i,s} \qquad i \in di, c \in CWDI$$

The total amount of a particular waste generated in each demand centre is equal to the sum across sectors of sectoral recovery rate of the particular waste type ($\alpha_{s,cwdi}$) multiplied by the total demand or use of all plastic types by the three sectors in the demand centres. In essence, we have each sector producing a homogenous waste which comes from an aggregation of all plastic types which are consumed.

5. Raw Material Balance

$$\sum_{p} adi_{c,p} z_{p,di} + u_{c,i} \geq 0 \qquad c \in crdi, i \in di$$

Total amount of raw materials used must be met by purchases. The main activities here are collection, separation and washing of recyclable waste plus of course the disposal of final waste.

6. Constraint on domestic purchase of waste

$$u_{cwdi,di} \leq \sum_{pcl} adi_{cwdi,p} z_{p,di} \qquad C \in cwdi, di \in DI$$

Domestic purchase of waste (defined by sector of origin) must be less than the total amount collected by the various collection systems.

7. Constraint on collection of waste

$$\sum_{pcl} adi_{cwdi,p} z_{p,di} \leq w_{c,d} \quad c \in CWDI, di \in DI$$

The total amount of all waste types collected by all the collection systems must be less than the total waste generated by the respective sectors.

8. Intermediate Balance

$$\sum_{p} adi_{c,p} z_{p,i} = 0 \qquad c \in cidi, i \in di$$

Net intermediate production level plus shipments from other plants must be greater than or equal to shipments to all other plants.

9. Final Good Balance

$$\sum_{p} adi_{c,p} z_{p,i} \geq \sum_{fi \in I} x_{c,di,fi} \qquad c \in cfdi, i \in di$$

Total amount of separated but dirty waste must be greater than the total amount shipped to all the recycling centres plus exports.

<u>Final Recycling and Production Centres</u>

10. Raw Material Balance

$$\sum_{p} afi_{c,p} z_{p,fi} + u_{c,fi} + v_{c,fi} \geq 0 \quad c \in crfi, i \in fi$$

Total amount of raw material used in the final production centres must be matched by domestic purchases and as well as imports. Note that one of the raw materials at this stage is the separated but still dirty waste plastics which are bought from the collection and separation centres.

11. Intermediate Balance

$$\sum_{p} afi_{c,p} z_{p,fi} + \sum_{\substack{fi' \\ fi' \neq fi}} x_{c,fi',fi} \geq \sum_{\substack{fi' \\ fi' \neq fi}} x_{c,fi,fi'} \quad c \in cifi, fi \in i$$

Intermediate goods at this stage will be clean sorted waste plastic goods. Note no import of this is allowed. Import of waste is captured in the raw material balance in equation 8 above. That waste also undergoes the cleaning process together with the domestic sorted waste.

12. Raw material constraint

$$u_{c,fi} \leq \sum_{di \cup pi} x_{c,di \cup pi,fi} \qquad c \in cfdi \cup cfpi, fi \in i$$

The purchase of waste plastic products must be less than the total shipment from all the collection and separation centre. Note that the final products of the collection centres and the final product from the primary resin production centres are the raw materials for the final production and recycling centres.

13. Final Good Balance

$$\sum_{p} afi_{c,p} z_{p,fi} \geq \sum_{di} x_{c,fi,di} + e_{c,i} \quad c \in cffi,\, fi \in i$$

Total shipment of final goods to final demand centres must be less than the total amount produced at the production centres.

14. Market Demand

$$\sum_{fi} x_{c,fi,di} + v_{c,di} \geq db_{c,di} \qquad c \in cffi, di \in i$$

Shipments from all final production centres together with imports must meet final market demand.

15. Capacity Constraint at all production centres

$$\sum_{p} b_{m,p,i} z_{p,i} \leq k_{m,i} \qquad m \in MPR, i \in I$$

Total amount of capacity used by all the processes which use a particular machine unit must be less than the total capacity available of that particular machine unit.

16. Middle distillate used in transportation

$$md = \sum_{i \in I} \sum_{c \in C} v_{c,i} \mu^{d}_{v,i} + \sum_{i \in I} \sum_{j \in I} \sum_{c \in C} x_{c,i,j} \mu^{d}_{i,j}$$

Total amount of middle distillate used is equal to middle distillate used in transporting: (1) all imported goods; (2) all intermediate shipments; and (3) final goods. The last two are capture by the second term in the equation above while the first term relates to imports.

17. Total Emissions

$$\sum_{i} \sum_{p} api_{c,p} z_{p,i} + api_{c,\text{"}md\text{"}} md = e_{c,i} \qquad c \in CE$$

Total emissions for each pollutant is equal to emissions by all processes at all activity centres plus emissions from middle distillate used in transportation.

18. Transport Costs

$$trc = \sum_{i \in I} \sum_{c \in C} v_{c,i} \mu^{t}_{v,i} + \sum_{i \in I} \sum_{j \in I} \sum_{c \in C} x_{c,i,j} \mu^{t}_{i,j}$$

Transport cost is equal to transport of all imported goods to activity centres plus interplant shipments between activity centres plus transport of all final goods to activity centres. μ is the transport cost per ton per activity centre link. The distance between the centres is already computed within the coefficient.

19. Raw Material Costs

$$rc = \sum_{i \in I} \sum_{c \in CRPI \cup CRDI \cup CRFI} u_{c,i} \quad p_{c,i}^{d}$$

Raw material costs is equal to the various raw materials purchased domestically multiplied by the domestic price of the raw materials. $p_{c,z}^{d}$ is the price for raw commodity c in activity centre i. We capture price differences in the various centres if any.

20. Import Costs

$$vc = \sum_{i \in I} \sum_{c \in CRPI \cup CIPI \cup CRFI \cup CFFI} v_{c,i} \quad p_{c,i}^{v}$$

The import cost is equal to the import levels of the various commodities which can be imported multiplied by the import prices faced at the various production centres.

21. Disposal Cost

$$dc = \sum_{di \in DI} \sum_{p \in pdsp} dis\cos t_{p,di} z_{p,di}$$

The disposal cost is equal to the amount of waste disposed multiplied by the unit cost of disposal. Discost tells us the cost of disposing one unit of waste by a particular process in each disposal centre. The summation gives us total costs for all processes and all centres.

22. By product Revenue

$$br = \sum_{i \in I} \sum_{c \in Cbp} api_{c,p} z_{p,i} p_{c}^{d}$$

By product revenue is equal to the amount of by product commodity c produced by all the processes in all the respective plants multiplied by the price for that commodity.

23. Total Costs

Total Cost(TC) = RC+VC+TRC+DC+EC-BR