# 行政院國家科學委員會專題研究計畫　成果報告

## 清淨製程：熱整合與迴流結構的探討(3/3)

計畫類別：個別型計畫
計畫編號：NSC91-2214-E-002-038-
執行期間：91 年 08 月 01 日至 92 年 07 月 31 日
執行單位：國立臺灣大學化學工程學系暨研究所


計畫主持人：余政靖

計畫參與人員：陳逸航


報告類型：完整報告
報告附件：出席國際會議研究心得報告及發表論文
處理方式：本計畫可公開查詢

中　華　民　國 92 年 11 月 3 日

# 行政院國家科學委員會補助專題研究計畫成果報告

※※※※※※※※※※※※※※※※※※※※※※※※※
※ ※
※ 清淨製程:熱整合與迴流結構的探討 (3/3) ※
※ ※
※※※※※※※※※※※※※※※※※※※※※※※※※

計畫類別：■個別型計畫 □整合型計畫
計畫編號：NSC 91-2214-E-002-038
執行期間： 91 年 08 月 01 日至 92 年 07 月 31 日

計畫主持人：余政靖

本成果報告包括以下應繳交之附件：
- □赴國外出差或研習心得報告一份
- □赴大陸地區出差或研習心得報告一份
- □出席國際學術會議心得報告及發表之論文各一份
- □國際合作研究計畫國外研究報告書一份

執行單位：國立台灣大學

中 華 民 國 九十二年 八 月 二十六 日

# 行政院國家科學委員會專題研究計畫成果報告

## 清淨製程:熱整合與迴流結構的探討 (3/3)

## Dynamical Life Cycle Assessment: Implications to Design and Operation of Industrial Processes

計畫編號：NSC 91-2214-E-002-038

執行期限：91 年 08 月 01 日至 92 年 07 月 31 日

主持人：余政靖 國立台灣大學化工系

計畫參與人員：陳逸航 國立台灣科技大學化工系

1、中文摘要

從中度的尺度（meso-scale）來看，清淨製程是化學工業永遠發展的主要技術。本年度的計劃並進一步以巨觀的尺度（macro-scale）來探討永續發長對程序系統工程的影響。由於一大部份的工廠的原料將不再由原料直接煉製而是藉由資源回收而取得，這導致了正向回饋(positive feedback)，我們將探討在此情況下，工廠操作範圍（turndown ratio）的改變以及對未來工廠設計的影響。利用生命週期評估提供一有系統之物流分析，其主要目的在於分析一產品之流程圖及對於外在環境之影響。一般而言，生命週期分析主要是針對物流及能量之穩態特性加以討論，而本文之主要目的在於將系統之動態特性加入生命週期內加以討論。利用廣為熟知之方塊圖引入生命週期內，此時生命週期即具有動態之特性。而一般自然界之資源如：水，紙類，或金屬等，均為可回收再生資源，此一特性即為一迴流結構。迴流結構的動態行為一正向回饋之系統，因此我們可以由動態之結果得知，當一物流有效迴收使用時，整體之動態會變慢。這暗示著當系統愈有效的利用物料時，製程之韌性變差，此時必須考慮系統庫存量使用，以解決製程韌性上的問題，並提出有效的改善策略。

**Abstract**

The life cycle assessment (LCA) offers a systematic approach in identifying the potential in reducing environmental burden throughout the product life cycle. In this work, the dynamic aspect of the LCA is studied. First, the well-known block diagram analysis is incorporated in the LCA and the implications of recycling to process dynamics are explored. The result indicates that, as the result of the positive feedback from material recycling, the overall production dynamics becomes much slower. This implies a lack of flexibility as more and more recycled materials are utilized in product manufacturing and it cannot be foreseen without incorporating dynamics in the LCA. In order to meet the market demand, increased inventories for the raw and recycled materials are needed to compensate the slow recycle dynamic and a larger turn down ratio is necessary for the raw material processing plants. The missing inventory, due to slow dynamics, can be expressed analytically in terms of the recycle ratio and the recycle time constant. It can be used for legislating new recycle policies which can alleviate the increased inventory and large turndown ratio problems for the future processing plants. The results indicate that the dynamical LCA provides a better assessment of product life cycle and, moreover, only the recycle ratio and recycle time constant are needed to complete the analysis.

**2. Introduction**

The life cycle assessment (LCA) is a holistic approach that analyzes the environmental consequences associated with the cradle-to-grave life cycle of a process or product. It focuses on the flows of materials and energy from the extraction of the raw material, to the product manufacturing, to the product use and to the waste management (Allen and Rosselot, 1997). By applying these assessments, the environmental performance of the industry can be improved. Allen and Rosselot (1997) give a good summary on this rapid growing field and journals are also devoted to the subjects (see references). In a more familiar term, it means: (1) doing material and energy balances in a larger context (the biophysical environment) and (2) looking for models for efficient use of resources (Allen and Rosselot, 1997; Bakshi, 2000; Brennecke and Stadtherr, 2000). Any efficient use of resources implies product or material recycling. Moreover, from the industrial ecology perspective, the ultimate goal for sustainable development is to close material cycles which means total recycling (Socolow et al., 1994).

Most of the LCA deals with the static aspect of recycling. The dynamic aspects of LCA have received little attention until recently (Ruth and Harrington, 1997; Cleveland and Ruth, 1999; McLaren et al., 1999). The nature of material recycling results in positive feedback loops. This, in turn, gives a very unique dynamical behavior. The positive feedback is observed in many science and engineering disciplines. Materials recycles and energy integration in chemical processes, increasing-return problems in economy, solid-state laser in physics, spin-glasses and ferromagnatic materials (Arthur, 1990) are typical positive feedback examples. It is well known that the dynamics of a positive feedback system can be drastically different from the original system dynamics (without feedback) (Denn and Lavie, 1982; Luyben, 1993; Morud and Skogestad, 1996). The objective of this work is to study the dynamical aspect of LCA and emphasis is placed on the design and operation of processes.

## 3. Dynamical Aspects of LCA

Without loss of generality, we restrict ourselves to a specific type of raw material in industrial practice and emphasis is placed on the recycling of such material. Allen and Rosselot (1997) lay a framework for the life cycle inventory assessment where recycling may take place at different stages of production. As shown in Figure 2, depending on type of products, the wastes can be recycled for reuse, product re-manufacturing and/or material re-manufacturing and they become raw materials at different manufacturing stages. Therefore, more than one recycle loops may exist and it is obvious that they are all *positive* feedback loops. Once the ratios of recycling are available, we can proceed to compute the associated aggregate energy demand and waste generation. This only shows the steady-state aspect of LCIA and the dynamical behavior can be far different from one’s expectation as a result of the positive feedback.

Dynamic aspects of LCA can be well represented using the block diagram. Instead of showing only steady-state values, simple dynamic elements (e.g., a first order lag with known steady-state gain) can be included in the direct and recycle paths. Consider a well-defined product recycle example, i.e., glass bottle refilling in Fig. 1, where the glass bottles for a soft drink come from new and recycled bottles. The simple product recycle loop can be transformed into an equivalent block diagram as shown in Fig. 2 where $F$ denotes the fresh material (new bottles), $R$ stands for the recycle material (recycled bottles), $P$ represents product (bottled soft drink) and $W$ is the waste. $G_P(s)$, $G_R(s)$ and $G_W(s)$ represent the product manufacturing dynamics, dynamics in the recycle loop and waste generating dynamics, respectively. It will become clear later that the dynamics in the recycle loop ($G_R(s)$) is of special importance. For example, if 80% of the bottles comes from recycling and it takes 6 months to collect and reprocess 63.2% the recycled materials (e.g., it is often called the time constant ($\tau$)), we have the following transfer function:

$$G_R(s) = \frac{K_R}{\tau s+1} = \frac{0.8}{6s+1} \qquad (1)$$

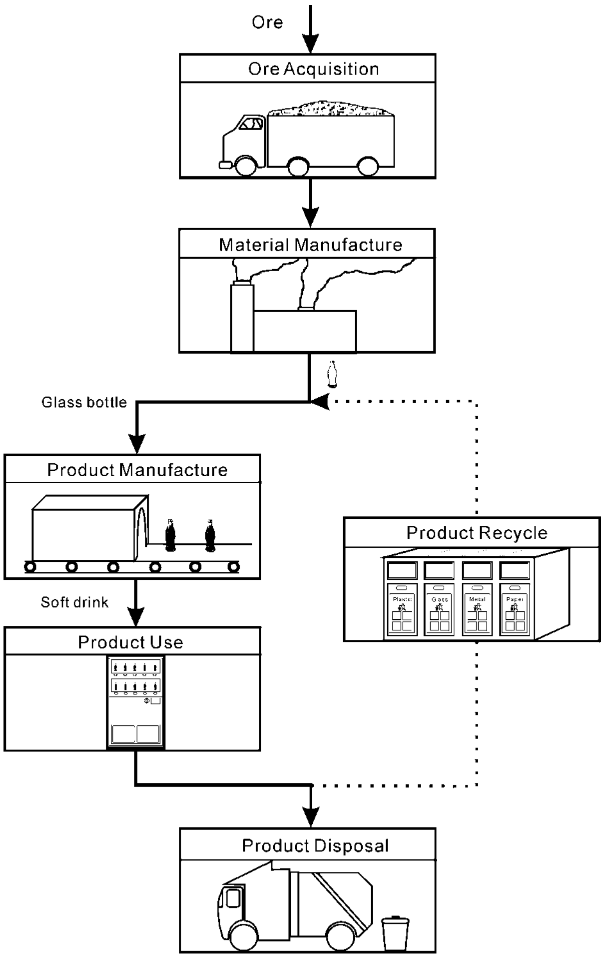


Figure 1. Glass bottle recycling.

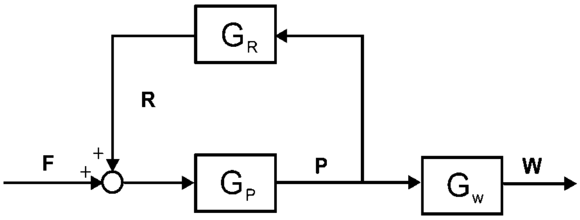


Figure 2. Block diagram for product recycling system.

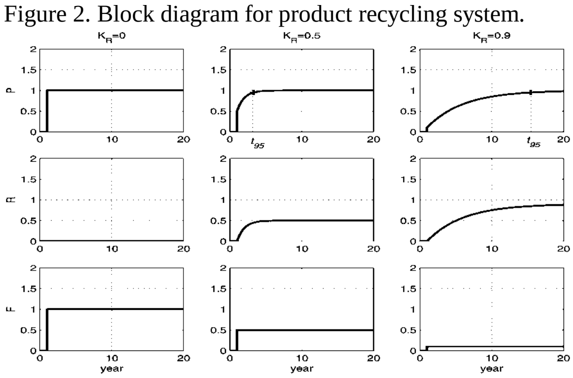


Figure 3. Dynamics of material flows for a step increase in the raw material (F) with recycle time constant of 6 months and different recycle ratios ($K_R$).

Notice that the recycle ratio, $K_R$ , falls between 0 (no recycle) and 1 (complete recycling) and the recycle time constant, $\tau$ , depends on the mechanism of recycling as well as incentives provided. The production dynamics is relatively fast compared to the recycle dynamics and it is generally true to assume that only negligible fraction of bottles is lost during the manufacturing step. Therefore, it is reasonable to assume the following production dynamics: $G_P(s) \approx 1$. With corresponding dynamical elements, we can readily evaluate the recycle dynamics. From the block diagram, we have:

$$\frac{P}{F} = \frac{1}{1-K_R} \cdot \frac{\tau s+1}{\dfrac{\tau}{1-K_R}s+1} \qquad (2)$$

Two observations can be made immediately. First, the positive feedback in the recycle loop makes the *steady-state gain* between the fresh raw material (*F*) and the product (*P*) *larger*. That implies we can make more products by depleting less raw materials. As we are closing the material cycle, the steady-state gain approaches infinity. This is the *positive* side of recycling and it is exactly the essence of closing the material cycle as emphasized in the industrial ecology. Second, the recycling makes the *time constant* between the raw material supply (*F*) and a completed production (*P*) *larger*. That means we will have a slower product manufacturing as the result of utilizing recycled materials. In other words, it will become more and more difficult to meet the consumer demand (e.g., an arbitrary increase in *P*). The reason for that is the recycling process takes time which cannot be speeded up by any sort of manufacturing mechanism. Moreover, as we are closing the material cycle ($K_R \to 1$), the time constant approaches infinity. This is the *negative* side of the material recycling where cannot be foreseen unless the dynamical aspect is considered.

Recall that the recycle time constant is 6 months (i.e., $\tau = 6$). If we live in a primitive world without any recycling, $K_R = 0$, the raw material supply can immediately meet the market demand. Fig 3A shows that a step increase in *F* is directly reflected in the production (*P*). However, Fig. 3B indicates that if 50% of the bottles comes from recycling, it takes almost 27.6 months to reach 95% of the steady-state value ($t_{95}$). Even worse, when we approach closing the material cycle, e.g., $K_R = 0.9$ in Fig. 3C, it takes almost 15 years to reflect this change!

## 4. Implications

We have just seen the up side and down side of closing the material cycle. It seems quite obvious that the increased utilization of recycling materials, i.e., an increased $K_R$, is the norm for most process industries in the future. How can the industries cope with such a trend? Using extra inventory is one possible solution to meet the demand.

A production scheme can always be devised to meet the market demand. In terms of the positive feedback system in Fig. 2, it means P(s) has to respond to arbitrary changes instantaneously. In other words, how does the system (e.g., the raw material supply F(s)) respond to a step change in the production P(s)?

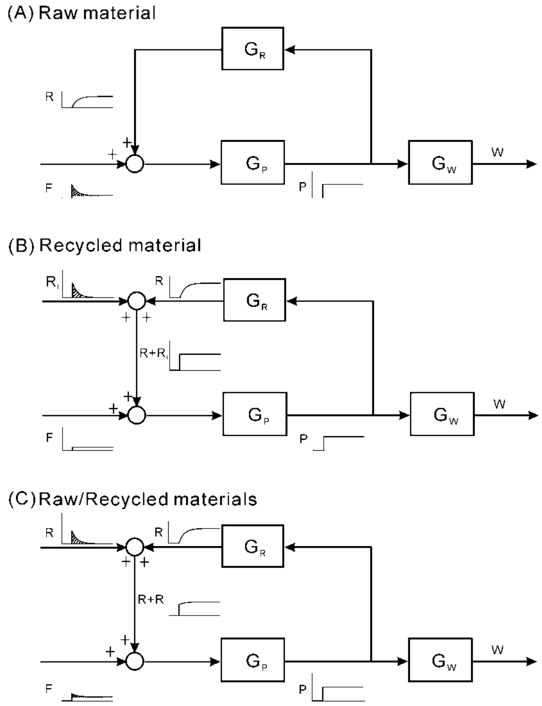


Figure 4. Required inventory to meet market demand from (A) raw material, (B) recycled material and (C) raw/recycle materials.

It can be derived directly from the block diagram. Considering a unit step increase in the demand, we can derive how much inventory is needed for a unit step increase in the demand (i.e., one unit increase in P). Taking the inverse Laplace transformation, the inventory to meet the demand: $F_I = K_R \tau$ (i.e., the shaded area in Fig. 4A). Since the steady-state flow of the supply is $1-K_R$, the inventory can be expressed in terms of residence time, $\tau_F = \tau K_R/(1-K_R)$. It implies that, for every unit step increase in P, we need to stock the raw material for the time of $\tau_F$ with respect to its steady-state value. It is obvious that this is not the current practice. Fig. 5A shows how the raw material supply (F) changes to meet the market demand and the recycle material (R) still goes through a slow increase to reach the steady-state value. Also note that, for F, the ratio of the peak value to the final steady-state value is 5 which far exceeds the turn down ratio of most current continuous processing plants.

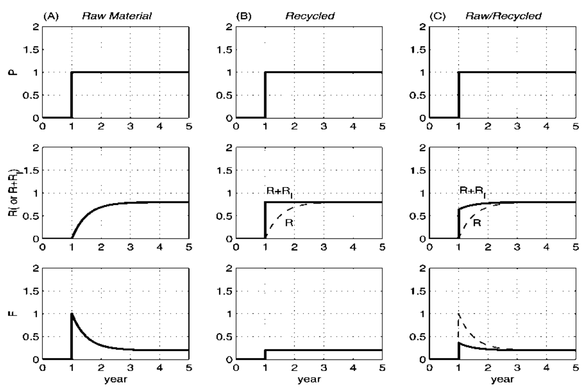


Figure 5. Dynamics of material flows to meet the market demand when the inventory came from (A) raw material, (B) recycled material and (C) raw/recycle materials.

An alternative to meet the market demand is to increase the inventory of recycle material (Fig. 4B). Again, the inventory is $K_R\tau$ and it can be expressed in terms of the residence time. The result shows the residence time is exactly the same as the recycle time constant. The ratio of the peak value for the processing of the recycled material to its steady-state value remains at unity (Fig. 5B).

Previous two cases assume that the processing plants can be operated under different ratio of raw/recycled materials during the transient. This may not be the case for some industries. Therefore, it is reasonable to assume that the ratio of materials utilized remains the same for the time scale considered. Under this circumstance, what will be the inventory for both type of processing materials? The results are: $F_I = (1-K_R)K_R\tau$ and $R_I = K_R^2\tau$ . The residence time for the inventory becomes: $\tau_F = \tau_R = K_R\tau$ . Since the recycle ratio is always less than one, to the extreme, the residence time approaches the recycle time constant. Notice that this is a more likely scenario for most processing plants. Again, for the product recycle example, we need to have inventories of "4.8 months" for both the raw/recycled materials to meet the market demand (Fig. 5C). The ratio of the peak demand to the final steady-state values is 1.8 (i.e., $1+K_R$) for the raw material.

The reason for the extra large inventories and/or large turndown ratio is due to the slow supply of the recycled material (since the speed of recycling depends on the consensus of our society). The problem will become even worse we are approaching our ultimate goal: closing the material cycle (i.e., $K_R \to 1$). This leads to a very unfavorable practice in process industries and, eventually, prices will be paid by the consumer. The missing inventory is "$K_R\tau$ ". In this work, we provide a less known fact that the *speed* of recycling is also important. That is how soon you put the bottles, newspapers etc. into the recycle system. In particular, the recycle time constant, $\tau$ , is a good measure of the speed for recycling. Shorten the recycle time constant can effectively speed up the overall system dynamics and, subsequently, can alleviate the increased inventory problem. Moreover, there is plenty of room for the improvement (e.g., $\tau \to 0$ ). Provided with incentives, policies can be made such that we are able to approach closing the material cycle while maintaining the responsiveness of the manufacturing mechanism.

## 5. Conclusion

In this work, process dynamics is incorporated into the life cycle assessment (LCA). The block diagram analysis provides a framework to describe the dynamical behavior of product life cycle and, moreover, only a simple dynamic element is required. The results indicate that, generally, we need extra inventory for the production plant and large turndown ratio for the raw material processing plant. The implications of dynamic LCA indicates that it is necessary to provide incentive to shorten the recycle time constant especially when we are approaching closing the material cycle. Furthermore, the dynamical LCA can be employed to analyze the air emissions, waste generation and energy requirements in the temporal mode.

## 6. References


1. Allen, D. T.; Rosselot, K. S. *Pollution Prevention for Chemical Processes*, Wiley, New York (1997).
2. Arthur, W. B. "Positive Feedbacks in the Economy", *Scientific American* 1990, Feburary, 80.
3. Bakshi, B. R. "A Thermodynamic Framework for Ecologically Conscious Process System Engineering", *Comput. Chem. Eng*. 2000, 23, 1767.
4. Brennecke, J. F.; Stadtherr, M. A. "A Course in Environmentally Conscious Chemical Process Design", *Comput. Chem. Eng*. 2000, 23, 1375.
5. Cleveland, C. J.; Ruth, M. "Indicators of Dematerialization and the Material Intensity of Use", *J. Ind. Ecology* 1998, 2 (3), 15.
6. Denn, M. M.; Lavie, R. "Dynamics of Plants with Recycle", *Chem. Eng. J*. 1982, 24, 55.
7. McLaren, J.; Wright, L.; Parkinson, S.; Jackson, T. "A Dynamic Life-Cycle Energy Model of Mobile Phone Take-back and Recycling", *J. Ind. Ecology* 1999, 3(1), 77.
8. Luyben, W. L. "Dynamics and Control of Recycle Systems. 1. Simple Open-Loop and Closed-Loop Systems", *Ind. Eng. Chem. Res.* 1993, 32, 466.
9. Morud, J.; Skogestad, S. "Dynamics Behaviour of Integrated Plants", *J. Process Control* 1996, 6, 145.
10. Ruth, M. "Dynamics of Material and Energy Use in US Pulp and Paper Manufacturing", *J. Ind. Ecology* 1997, 1(3), 147.
11. Socolow, R. C.; Andrews, F.; Berkhout, F.; Thomas, V. *Industrial Ecology and Global Change*, Cambridge University Press, Cambridge**,** 1994.