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PROCESS DESIGN AND CONTROL

Dynamical Properties of Product Life Cycles: Implications to the Design and Operation of Industrial Processes

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Life cycle assessment (LCA) offers a systematic approach in identifying the potential in reducing the environmental burden throughout the product life cycle. Generally, it deals with the steady-state aspect of material and/or energy balances under the recycle structure. In this work, the dynamic behavior of the product life cycles 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 a 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 this cannot be foreseen without incorporation of dynamics in the life cycles. To meet the market demand, increased inventories for the raw and recycled materials are needed to compensate the slow recycle dynamics and a larger turndown 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 dynamic analysis provides a better assessment of product life cycles and, moreover, only the recycle ratio and recycle time constant are needed to complete the analysis.

1.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.[1,6] By application of these assessments, the environmental performance of the industry can be improved. Allen and Rosselot[1] give a good summary on this rapid growing field, and journals are also devoted to the subjects (see references). As pointed out by Allen and Rosselot, the LCA consists of three components: (1) inventory assessment (for wastes, emission, raw materials, and energy use), (2) environmental impact assessment, and (3) improvement analysis (to reduce environmental impact). In more familiar terms, 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.[1−3] The book by Allen and Rosselot[1] offers several good examples, e.g., paper versus polyethylene grocery sacks,[8] etc. Any efficient use of resources implies product or material recycling. Therefore, we are dealing with a variety of recycling in LCA, and it is important to trace the material flows in the life cycle inventory assessment. Moreover, from the industrial ecology perspective, the ultimate goal for sustainable development is to close material cycles, which means total recycling (e.g., 100% recycle).[20] It is important to recognize the implications of such a trend to business and engineering practices. It should be emphasized that material recycles are not always favorable to *all* products and, again, LCA provides appropriate evaluation.

Most of the LCA deals with the static aspect of recycling. The dynamic aspects of LCA have received little attention until recently.[5,15,18] 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. Material recycles and energy integration in chemical processes 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).[4,7,9,12,16] The objectives of this work are to study the dynamical behavior of product life cycles, the life cycle inventory in particular, and its implications to process system engineering. Emphasis is placed on the design and operation of processes.

2. Dynamic Behaviors of Life Cycles

2.1. Recycle Structures. Allen and Rosselot[1] lay a framework for the life cycle inventory assessment (LCIA) where recycling may take place at different

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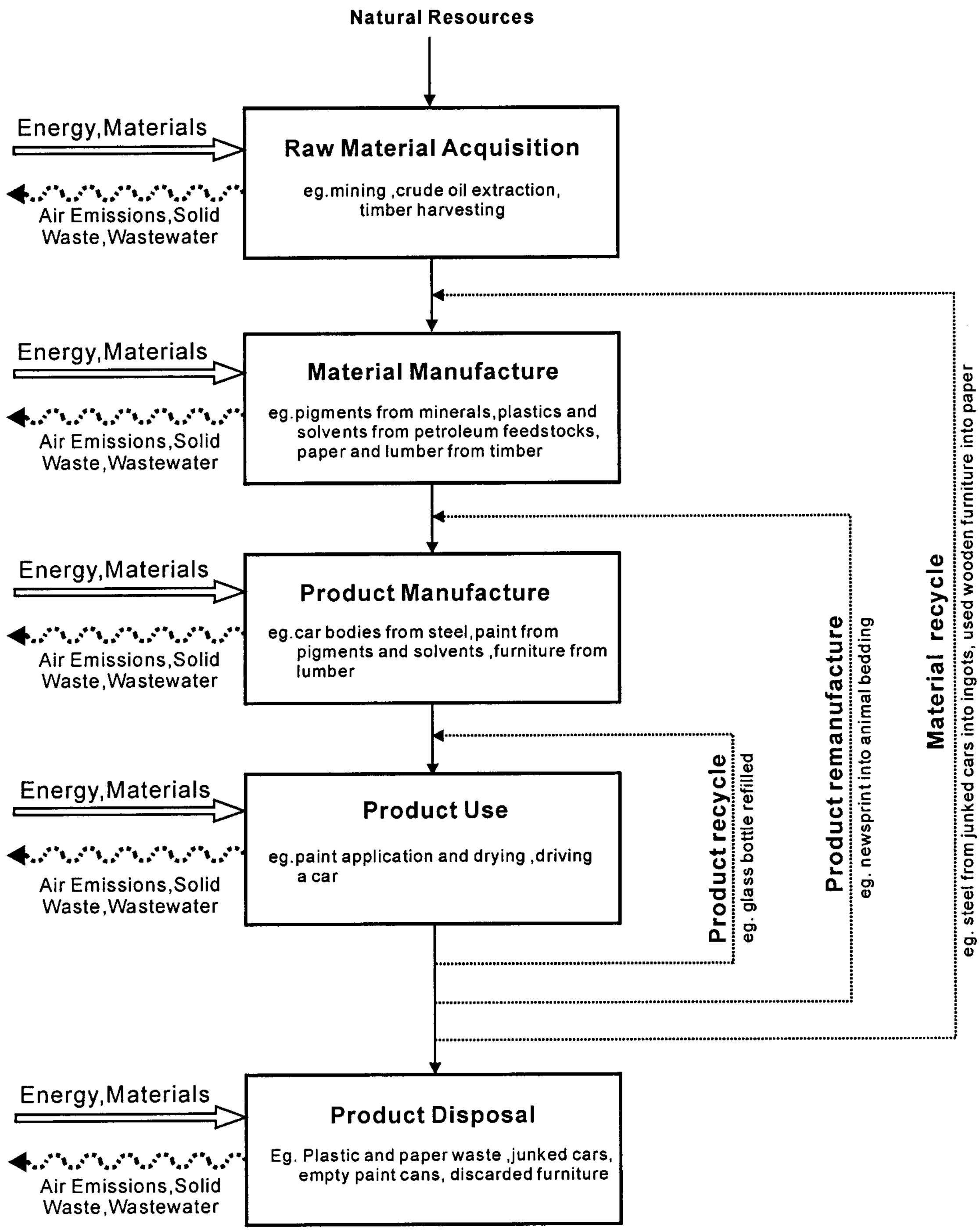

Figure 1. Typical recycling system.[1]

stages of production. As shown in Figure 1 depending on the types of products, the wastes can be recycled for reuse, product remanufacturing and/or material remanufacturing, and they become raw materials at different manufacturing stages. Therefore, more than one recycle loop may exist, and it is obvious that they are all *positive* feedback loops (e.g., adding material back into the manufacturing system as a result of recycling). Once the ratios of recycling are available, we can proceed to compute the associated aggregate energy demand and waste generation. This is exactly the essence of the LCIA.

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 a material. Figure 1 generally describes 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. For the sake of clarity, let us take a simple example, a soft drink bottle recycling process, to illustrate this. Figure 2 shows a glass bottle recycling system (e.g., similar to the paper sack recycling of Allen and Rosselot[1]) where we have only one recycle loop which goes back to the product manufacturing. If 80% of the bottled product uses recycled bottles and 20% is from the new bottles, from the steady-state perspective, the plants handling the recycling material (e.g., washing, cleaning, and labeling) and the raw material (e.g., producing new bottles) simply stay at 80/20 capacities. However, during transient, the demand for both materials can be significantly different from corresponding steady-state values.

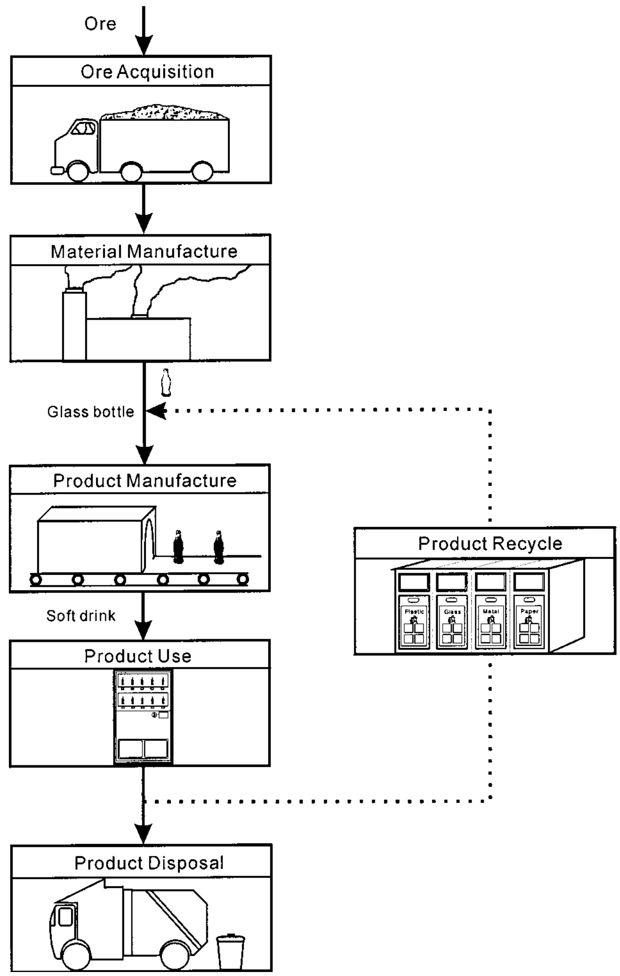

Figure 2. Glass bottle recycling.

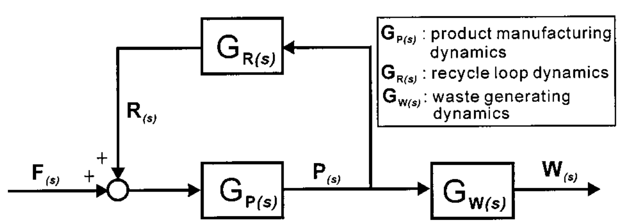

Figure 3. Block diagram for the product recycling system.

2.2. Recycle Dynamics. Dynamic aspects of LCA can be well represented using the block diagram. It is a standard dynamic modeling tool as has appeared in many process control textbooks.[13,14,17,19] Let us, again, use Figure 2 to illustrate how one can include dynamics in the product life cycles. Instead of showing only steady-state values, simple dynamic elements (e.g., a first-order system or first-order lag) can be included in the direct and recycle paths. Consider a well-defined product recycle example, i.e., glass bottle refilling in Figure 2, 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 Figure 3 where F(s) denotes the fresh material (new bottles), R(s) stands for the recycle material (recycled bottles), P(s) represents product (bottled soft drink), and W(s) is the waste. Notice that in the block diagram analysis we normally take the Laplace transformation of the deviation variables (i.e., deviation from its nominal value). For example, F(s) can be obtained from

$$F(\mathrm{s}) = L\,[F^{d}(\mathrm{t})] = L\,[F(\mathrm{t}) - \bar{F}]$$

Here, the operator L stands for the Laplace transformation, the superscript d denotes the deviation variable, and $\bar{F}$ is the nominal values of the raw material. The transfer functions describe the input/output relationships, e.g., $R(\mathrm{s}) = G_{\mathrm{R}}(\mathrm{s})\ P(\mathrm{s})$ as shown in Figure 3. $G_{\mathrm{P}}(\mathrm{s})$, $G_{\mathrm{R}}(\mathrm{s})$, and $G_{\mathrm{W}}(\mathrm{s})$ 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 ($G_{\mathrm{R}}(\mathrm{s})$) is of special importance.

Let us use an example to illustrate the construction of the transfer functions. A company produces 100 000 glass-bottled soft drinks per month. If 80% of the bottles come from recycling, from material balances, we have $\bar{P} = 10^5$, $\bar{R} = 0.8 \times 10^5$, $\bar{F} = 0.2 \times 10^5$, and $\bar{W} = 0.2 \times 10^5$. Notice that here we assume that only a negligible fraction of bottles is lost during the manufacturing step. Immediately, we also obtain the steady-state gains for these three transfer functions. That is, $G_{\mathrm{P}}(0) = 1$, $G_{\mathrm{R}}(0) = 0.8$, and $G_{\mathrm{W}}(0) = 0.2$. Define the recycle ratio as

$$K_{\mathrm{R}} \equiv G_{\mathrm{R}}(0) = \text{recycle ratio}$$

This is the fraction of the product (bottles) that goes back to the recycle system. Notice that the recycle ratio, K_{R}, falls between 0 (no recycle) and 1 (complete recycling) and, in this case, we have $K_{\mathrm{R}} = 0.8$. It is also clear that the steady-state gain of the waste-generating dynamics ($G_{\mathrm{W}}(\mathrm{s})$) is simply $1 - K_{\mathrm{R}}$. Thus far, we have all of the steady-state information for the transfer functions (actually all the information we need is the recycle ratio).

For a first-order system, the only dynamic information we need is the time constant (τ). For the recycle dynamics ($G_{\mathrm{R}}(s)$), it means how long does it take to collect 63.2% of the recycled bottles. For a dated product, this is often referred to as the cycle time, i.e., the average elapsed when the bottles are collected on a specific date. If it takes 6 months to collect 63.2% of the recycled materials, then we have the following transfer function for the dynamics in the recycle loop.

$$G_{\mathrm{R}}(\mathrm{s}) = \frac{K_{\mathrm{R}}}{\tau s + 1} = \frac{0.8}{6s + 1} \tag{1}$$

The recycle time constant, τ, depends on the mechanism of recycling as well as incentives provided. Generally, this is the dominant time constant in the recycle structure (Figure 3). The production dynamics is relatively fast compared to the recycle dynamics, because production rate changes can be made in hours compared to the time constants of months in the recycling. Therefore, it is reasonable to assume the following production dynamics:

$$G_{\mathrm{P}}(\mathrm{s}) = 1 \tag{2}$$

The time constant (τ_{W}) of waste-generating dynamics ($G_{\mathrm{W}}(\mathrm{s})$) generally is smaller than that of the recycle loop. The transfer function can be expressed as

$$G_{\mathrm{W}}(\mathrm{s}) = \frac{1 - K_{\mathrm{R}}}{\tau_{\mathrm{W}} s + 1} \tag{3}$$

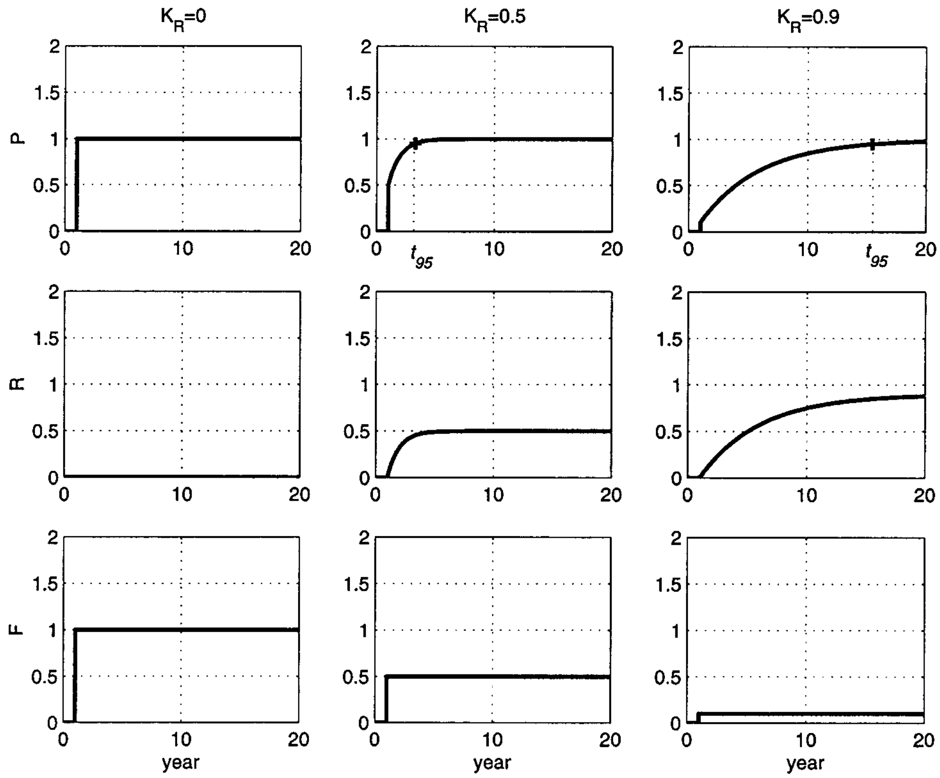

Figure 4. Dynamics of material flows for a step increase in the raw material (F) with a recycle time constant of 6 months and different recycle ratios (K_R).

Because we are interested in the effects of recycle dynamics on the production system, the influence of G_W to the environment will not be explored further. With corresponding dynamical elements, we can readily evaluate the recycle dynamics. From the block diagram, we have

$$P(s) = G_P(s)\,(F(s) + R(s)) = G_P(s)\,(F(s) + G_R(s)\,P(s)) \tag{4}$$

Rearranging eq 4, one obtains

$$\frac{P}{F} = \frac{G_P}{1 - G_P G_R} \tag{5}$$

Substituting the transfer functions (eqs 1 and 2) into eq 5, we have

$$\frac{P}{F} = \frac{1}{1 - K_R} \frac{\tau s + 1}{\dfrac{\tau}{1 - K_R}s + 1} \tag{6}$$

Two observations can be made immediately.

1. 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 ($K_R \rightarrow 1$), the steady-state gain approaches infinity ($1/(1 - K_R) \rightarrow \infty$). Certainly, this is the *positive* side of recycling, and it is exactly the essence of closing the material cycle as emphasized in the industrial ecology.

2. 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 a 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 ($K_R \rightarrow 1$), the time constant approaches infinity [$\tau/(1 - K_R) \rightarrow \infty$; i.e., it takes an extremely long time to meet the demand]. This is the *negative* side of the material recycling which cannot be foreseen unless the dynamical aspect is considered.

Again, let us use the product recycle example to illustrate this. 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. Figure 4A shows that a step increase in F is directly reflected in the production (P). However, Figure 4B 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 Figure 4C, it takes almost 15 years to reflect this change (e.g., reaching 95% of the steady-state value)!

3. Implications to Process Industries

We have just seen the upside and downside 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.

3.1. Increased Inventory: Raw Material. A production scheme can always be devised to meet the

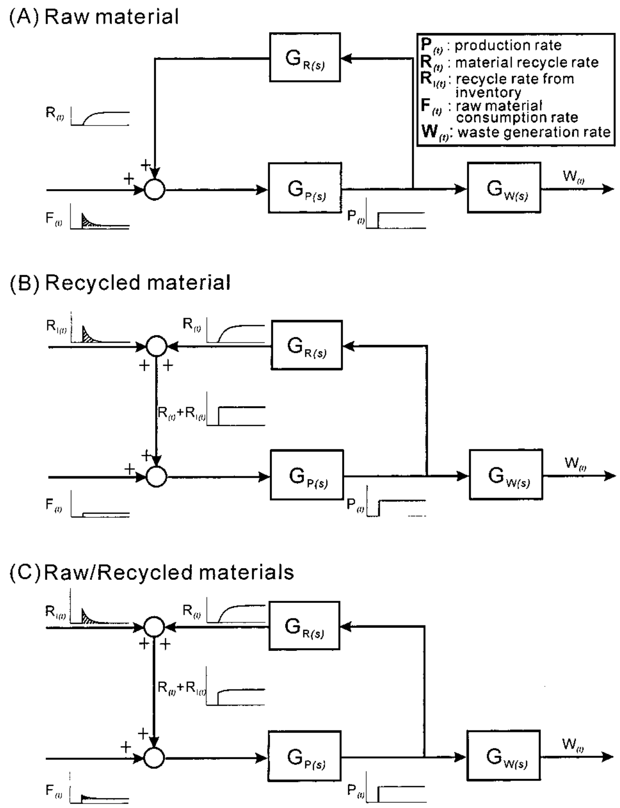

Figure 5. Required inventory to meet market demand from (A) raw material, (B) recycled material, and (C) raw/recycled materials.

market demand. In terms of the positive feedback system in Figure 3, this 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)? It can be derived directly from the block diagram. Considering a unit step increase in the demand, from eq 6, we have

$$F(\mathrm{s}) = (1 - K_\mathrm{R})\frac{\frac{\tau}{1-K_\mathrm{R}}s + 1}{\tau s + 1}P(\mathrm{s}) = (1 - K_\mathrm{R})\frac{\frac{\tau}{1-K_\mathrm{R}}s + 1}{\tau s + 1}\frac{1}{s} = \frac{1-K_\mathrm{R}}{s} + \frac{K_\mathrm{R}\tau}{\tau s + 1} \quad (7)$$

Equation 7 indicates that the raw material supply is composed of two parts: the steady supply part [i.e., $(1 - K_\mathrm{R})/s$] and the inventory supply part [i.e., $K_\mathrm{R}\tau/(\tau s + 1)$]. Figure 5A describes qualitatively the dynamic response of F(s) for a step increase in P(s). We can go on to find out how much inventory is needed for a unit step increase in the demand (i.e., one unit increase in P). The inverse Laplace transformation of the inventory part in eq 7 gives

$$F(\mathrm{t}) = L^{-1}\left(\frac{K_\mathrm{R}\tau}{\tau s + 1}\right) = K_\mathrm{R}\mathrm{e}^{-t/\tau} \quad (8)$$

For the raw material, the inventory to meet the demand then becomes

$$F_\mathrm{I} = \int_0^\infty F(\mathrm{t})\,\mathrm{d}t = K_\mathrm{R}\tau \quad (9)$$

The result shows that, to meet the market changes, we need an extra inventory of $K_\mathrm{R}\tau$ (i.e., the shaded area in Figure 6A) for a unit step increase in P. Because the steady-state flow of the supply is $1 - K_\mathrm{R}$, the inventory can be expressed in terms of time.

$$\tau_\mathrm{F} = \tau\frac{K_\mathrm{R}}{1 - K_\mathrm{R}} \quad (10)$$

This means that, for every unit step increase in P, we need to stock the raw material for the time of τ_F with respect to its steady-state value. For the soft drink company example with $K_\mathrm{R} = 0.8$ and $\tau = 6$, a 20% increase in sales implies that 20 000 more bottles ($\Delta P = 0.2\bar{P} = 20\ 000$) have to be made, and this implies an extra inventory of 96 000 new bottles ($F_\mathrm{I} = K_\mathrm{R}\tau\Delta P$). Because the steady-state supply of the new bottles for this increase is only 4000 new bottles [$\Delta F = (1 - K_\mathrm{R})\Delta P$], this corresponds to an inventory of "24 months" ($\tau_\mathrm{F} = F_\mathrm{I}/\Delta F = 96000/4000 = 24$) such that instantaneous market demand can be met. It is obvious that this is not the current practice. Figure 6A 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 [$1/(1 - K_\mathrm{R})$], which far exceeds the turndown ratio of most current continuous processing plants.

3.2. Increased Inventory: Recycled Material. An alternative to meet the market demand is to increase the inventory of the recycle material. Again, the dynamic analysis is helpful. Consider the block diagram in Figure 5B. If the inventory of the recycle material [R_I(s)] is the only way to make up the difference, from the block diagram in Figure 5B and assuming $G_\mathrm{P}(\mathrm{s}) = 1$, we have

$$R_\mathrm{I}(\mathrm{s}) = P(\mathrm{s})\,(1 - G_\mathrm{R}) - F(\mathrm{s}) \quad (11)$$

For a unit step increase in P(s) [i.e., $P(\mathrm{s}) = 1/s$] and assuming that F(s) stays at the new steady-state value [i.e., $F(\mathrm{s}) = (1 - K_\mathrm{R})/s$], one obtains

$$R_\mathrm{I}(\mathrm{s}) = \frac{K_\mathrm{R}\tau}{\tau s + 1} \quad (12)$$

Similar to the previous case, the inverse Laplace transform is employed to find the inventory for the recycled material.

$$R_\mathrm{I} = K_\mathrm{R}\tau \quad (13)$$

When eq 13 is compared with eq 9, it immediately becomes clear that we need an inventory of $K_\mathrm{R}\tau$ to make up the slow recycle dynamics, and this is the total processing materials needed irrespective of where it comes from (e.g., from raw material or recycled material). Figure 5B describes how the inventory in the recycle loop provides enough processing material to meet the market demand. Again, the inventory can be expressed in terms of the residence time.

$$\tau_\mathrm{R} = K_\mathrm{R}\tau/K_\mathrm{R} = \tau \quad (14)$$

The result shows that the residence time is exactly the same as the recycle time constant. This means that, for a unit step increase in P, we need to stock the recycled material for the time of τ with respect to its steady-state

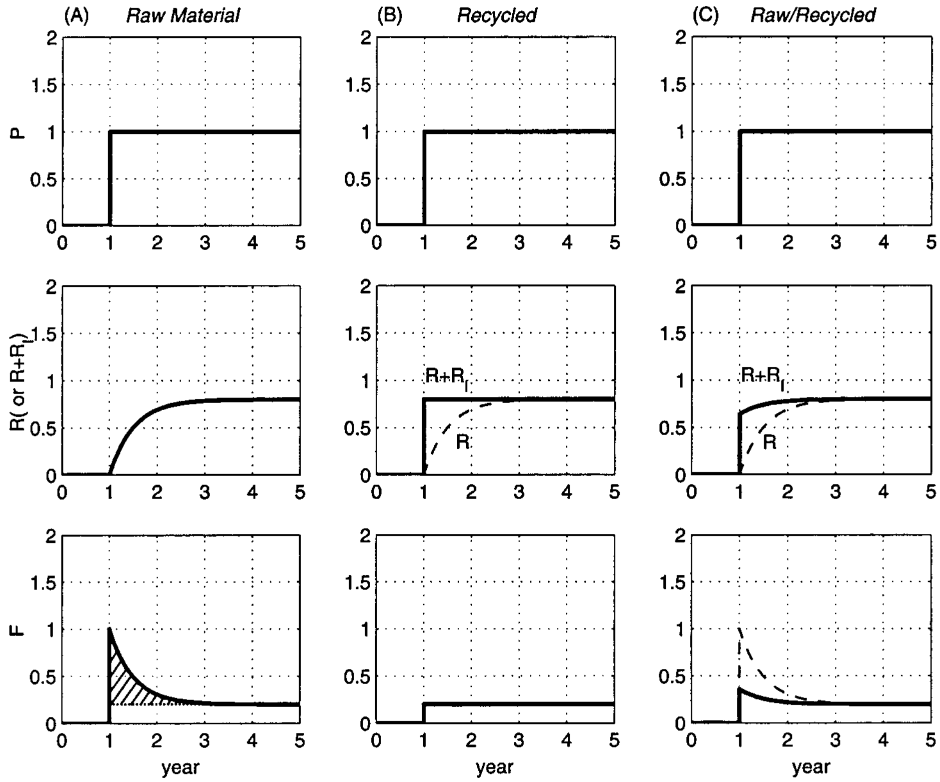

Figure 6. Dynamics of material flows to meet the market demand when the inventory came from (A) raw material, (B) recycled material, and (C) raw/recycled materials.

value. Again, for the case of an 80% recycle ratio (i.e., $K_R = 0.8$) and a 6 month recycle time constant, we need to have an inventory of "6 months" such that instantaneous market demand can be met. Figure 6B reveals the flows of the raw material, the recycle material, and the product. The ratio of the peak value for the processing of the recycled material to its steady-state value remains at unity, as shown in Figure 6B. That implies that the recycled material processing plant should be operated at a fixed capacity throughout. In other words, we foresee little problem in the turndown ratio for the recycled material processing plants.

3.3. Increased Inventory: Raw Material/Recycled Material. The previous two cases assume that the processing plants can be operated under different ratios 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. That means the ratio of raw material to the recycled material is kept at a constant value, $(1 - K_R)/K_R$. Under this circumstance, what will be the inventory for both types of processing materials? In the dynamical LCA, this implies $F(s)/[R_I(s) + R(s)] = (1 - K_R)/K_R$ for the block diagram shown in Figure 5C. Again, both $F(s)$ and $R_I(s)$ can be backcalculated by assuming a unit step increase in $P(s)$. From Figure 5C, we have

$$F(s) = \frac{1 - K_R}{s} + \frac{(1 - K_R)K_R\tau}{\tau s + 1} \tag{15}$$

and

$$R_I(s) = \frac{K_R K_R \tau}{\tau s + 1} \tag{16}$$

Again, the inverse Laplace transform is used to compute the inventories for both the raw and recycled materials, and we obtain

$$F_I = (1 - K_R)K_R\tau \tag{17}$$

and

$$R_I = {K_R}^2\tau \tag{18}$$

Probably, a better measure of the inventory is the residence time. Dividing the corresponding inventories by the material flows, we have

$$\tau_F = \tau_R = K_R\tau \tag{19}$$

Equation 19 indicates that the residence times for the extra inventory are the product of the recycle ratio and recycle time constant, and they are the same for both cases. Because the recycle ratio is always less than 1, 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, an 80% recycle ratio and a 6 month recycle time constant, we need to have inventories of "4.8 months" for both the raw and recycled materials to meet the market demand. Figure 6C shows that the flow of the raw material overshoots its steady-state value while the flow of the recycled material undershoots its steady-state value. The ratio of the peak demand to the final steady-state values is 1.8 (i.e., $1 + K_R$) for the raw material. For the recycled material, the initial demand is 80% of its steady-state value (i.e., K_R). For the recycled material processing, the turndown ratio is "1.25", which is quite acceptable. However, for the raw material supply, the turndown ratio will eventually reach a value of "2" when we approach closing of the

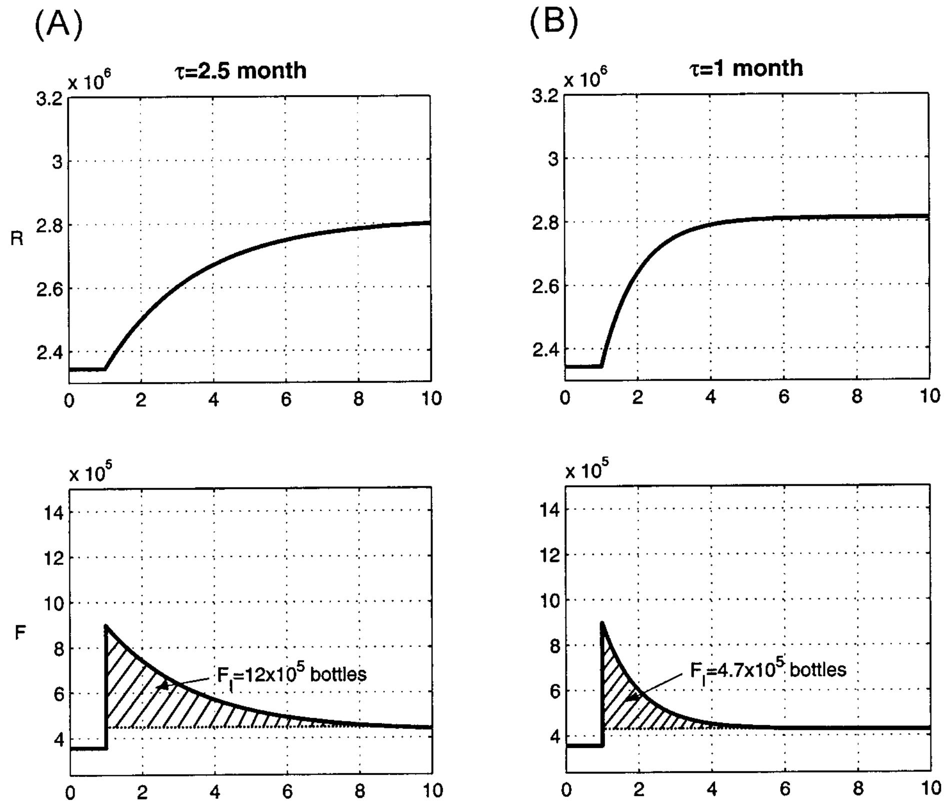

Figure 7. Dynamics of material flows and additional inventory (F_I) for a 20% increase in sales under (A) current ($\tau = 2.5$) and (B) suggested ($\tau = 1$) time constants.

material cycle (i.e., $K_R \rightarrow 1$). Again, this is a high limit for most engineering designs.

4. Implications to Recycle Policies

The reason for the extra large inventories and/or large turndown ratio is due to the slow supply of the recycled material (because the speed of recycling depends on the consensus of our society). The problem will become even worse as we approach our ultimate goal: closing of the material cycle (i.e., $K_R \rightarrow 1$). This leads to a very unfavorable practice in process industries and, eventually, the price will be paid by the consumer. The missing inventory, for a unit step increase in the market demand, can be expressed analytically as "$K_R\tau$". In other words, this additional inventory (e.g., the shaded area in Figure 5) is needed to provide responsiveness for the positive feedback system (e.g., instantaneous response to production changes). It is interesting to note that this is simply the product of the recycle ratio (K_R) and the recycle time constant (τ).

Because encouraging material recycling is always an important policy of many local and national governments, we anticipate a steady increase in the recycle ratio (e.g., fraction of the product recycled). Unfortunately, as pointed out earlier, this simply makes the dynamic system less responsive and a larger inventory is needed in the future. However, 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, τ, is a good measure of the speed for recycling. Shortening of the recycle time constant can effectively speed up the overall system dynamics and, subsequently, can alleviate the increased inventory problem. Consider an industrial product recycle example. The sales of Taiwan beer in the summer are 2 700 000 bottles/month with a recycle ratio of 86.8%. Currently, the recycle time constant is around 2.5 months ($\tau = 2.5$). To meet a 20% increase in the demand, we need 1 200 000 new bottles from the additional inventory, i.e., $F_I = K_R\tau\Delta P = (0.868)(2.5)[(0.2)(2\ 700\ 000)] = 12 \times 10^5$. On the other hand, if the cycle time is reduced to 1 month, the additional inventory is only 40% of the original figure, i.e., $F_I = 4.7 \times 10^5$, as shown in Figure 7. This example clearly demonstrates the effectiveness of shortening of the recycle time constant in alleviating the positive feedback problem. Moreover, there is plenty of room for improvement (e.g., $\tau \rightarrow 0$). Provided with incentives, policies can be made such that we are able to approach closing of the material cycle while maintaining the responsiveness of the manufacturing mechanism.

5. Conclusion

In this work, dynamics properties of product life cycles are explored. The block diagram analysis provides a framework to describe the dynamical behavior of the product life cycle and, moreover, only a simple dynamic element is required. The analyses show that (1) recycling decreases the gain between the raw material and the product (i.e., more efficient use of natural resources) and (2) recycling slows down the response between the raw material supply and the production (i.e., the production system will respond slowly to the market demand). To compensate for the lack of responsiveness, large inventories of raw/recycled materials are needed. Different inventory arrangements are devised to provide instantaneous response to the market demand. The results indicate that, generally, we need extra inventory for the production plant and a large turndown ratio for the raw material processing plant. More important, these quantitative results can be expressed analytically in terms of two important parameters: the recycle ratio and the recycle time constant. The implications from dynamic analyses indicate that it is necessary to provide incentive to shorten the recycle time constant especially when we are approaching closing of the material cycle. Moreover, the proposed approach can be applied to analyze the air emissions, waste generation, and energy requirements in the temporal mode.

Acknowledgment

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Nomenclature

$F(t)$ = raw material consumption rate in the time domain
$\underline{F}(s)$ = Laplace transformed raw material consumption rate
$\bar{F}$ = nominal value of the raw material consumption rate
F_I = additional inventory for raw material
$G_P(s)$ = transfer function of production dynamics
$G_R(s)$ = transfer function of recycle dynamics
$G_W(s)$ = transfer function of waste generation dynamics
K_R = recycle ratio or steady-state gain of $G_R(s)$
K_W = steady-state gain of $G_W(s)$
$P(t)$ = production rate in the time domain
$\underline{P}(s)$ = Laplace transformed production rate
$\bar{P}$ = nominal value of the production rate
$R(t)$ = material recycle rate in the time domain
$\underline{R}(s)$ = Laplace transformed material recycle rate
$\bar{R}$ = nominal value of the material recycle rate
R_I = additional inventory for recycle material
t_{95} = time for reaching 95% of the steady-state value
$W(t)$ = waste-generation rate in the time domain
$\underline{W}(s)$ = Laplace transformed waste-generation rate
$\bar{W}$ = nominal value of the waste-generation rate

Greek Symbols

τ = recycle time constant or cycle time
τ_W = time constant for waste generation

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