A waste minimization approach for process design to promote opportunistic recycling

by Zainuddin Abdul-Manan, Process Systems Engineeering Group, Department of Chemical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia and René Bañares-Alcántara, Universitat Rovira i Virgili, Departament d'Enginyeria Química, Carretera de Salou, Tarragona, Spain.

A proposed design procedure for waste minimization that promotes opportunistic recycling is described. The article begins with a review of the established Douglas' hierarchical design procedure. This is followed by a description of how the waste minimization approach for process synthesis emerged from the established Douglas hierarchical design procedure, highlighting the proposed extension, modifications and the advantages of the waste minimization approach over Douglas' procedure.

The waste minimization hierarchy as outlined by the United States Environmental Protection Agency (USEPA) is a general guideline for pollution reduction that consists of five levels, arranged in order of preference as (a) source elimination, (b) source reduction, (c) recycling, (d) treatment and (e) disposal. Each of the levels represents various waste minimization options. They are arranged in order of preference, from the most preferred option at the top of the hierarchy to the least preferred at the bottom. Figure 1 shows the hierarchy of waste management practices [1]. Waste minimization is concerned with the first, second and third level of the hierarchy [2].

The majority of research on waste minimization has focused on levels (d) and (e) of the waste minimization hierarchy, ie, the development of waste treatment technologies, environmental assessment and auditing methodologies. Relatively little work is concerned with the systematic elimination, reduction and recycling of waste during the design stage. Recycling has been widely accepted as a method to control the release of waste that has been created or introduced in a process. The idea that recycling can also prevent and reduce waste generation might be unfamiliar to those already accustomed to think about recycling at a level below source elimination and source reduction. Attempts to strictly follow the established hierarchical classifications may steer designers away from using recycling as a viable means of eliminating and reducing wastes during design. It is thus useful to view recycling from a broader perspective and to emphasize its key role in eliminating and reducing waste in addition to its traditional role in controlling the release of waste. This type of recycling is referred to in this article as opportunistic recycling.

This article describes a proposed design procedure for waste minimization that promotes opportunistic recycling. The article begins with a review of the established Douglas' hierarchical design procedure. This is followed by a description of how the waste minimization approach for process synthesis emerged from the established Douglas hierarchical design procedure, highlighting the proposed extension, modifications and the advantages of the waste minimization approach over Douglas' procedure in a 'level-by-level' comparison.

(a)	Elimination	Complete elimination of waste	← Highest priority
(b)	Reduction at source	The avoidance, reduction or elimination of waste, generally within the confines of the production unit, through changes in industrial processes or procedures	
(c)	Recycling	The use, reuse and recycling of waste for the original or some other purpose such as input material, materials recovery or energy production	
(d)	Treatment	The destruction, detoxification, neutralization, etc. of waste into less harmful substances	Lowest Priority →
(e)	Disposal	The release of wastes to air, water or land in properly controlled or safe ways to render them harmless; secure land disposal may involve volume reduction, encapsulation, leachate containment and monitoring techniques	

Figure 1: Hierarchy of waste management practices

Douglas hierarchical design procedure

One of the most important considerations during the design of cleaner processes is to generate alternatives for pollution prevention. In preventing waste during process design, Douglas included pollution considerations in his hierarchical design procedure (shown in Table 1)[3, 4]. A design is developed by proceeding through different levels of design abstractions while additional details are added at each level.

To achieve the goal of waste minimization, the idea is to identify potential pollution problems as design is developed, and make decisions not to introduce materials, chemistry, process conditions or techniques that could cause adverse environmental impact at each level of the design hierarchy. Douglas procedure,

This article is based on a paper presented at the 6th World Congress of Chemical Engineering held in Melbourne, Australia in September 2001 and is reprinted here with kind permission of the authors.

however, leaves the waste prevention alternatives for designers to explore. The aim of bringing waste minimization to the front end of the design process and the emphasis on opportunistic recycling inspired the development of the waste minimization (WM) approach hereby presented. This approach is essentially an extension and modification of Douglas hierarchical design procedure.

Level 1.	Input information
Level 2.	Input-output structure
Level 3.	Recycle structure
Level 4.	Separation system (a) Vapour recovery system (b) Liquid recovery system

Table 1: Douglas hierarchical decision procedure

The following sections describe the proposed modifications and additions to Douglas' procedure.

The waste minimization approach to design

Note that the sequence of Levels 1 (Input information) and 2 (Input-output structure) of the design hierarchy shown in Table 1 is logically fixed by the availability of information during the early stages of process of process synthesis. These levels needed to be defined before the structure of the recycle and separation systems are recycled and separation systems are tackled, but, a designer may proceed either by specifying the recycle or the separation structure. Thus the hierarchical design procedure may branch in two possible directions:

1. Input information → Input-output structure → Recycle structure → Separation structure (original Douglas approach)
2. Input information → Input-output structure → Reaction system → Separation structure → Recycle structure (proposed waste minimization approach, see Table 2).

To achieve the goal of waste minimization, we propose to synthesize and add details to the separation structure before working on the recycle structure, thus departing from Douglas' established approach of fixing the recycle structure from the abstract [(black) box] reaction and separation blocks. Note that, assuming a black box separation when fixing the reactor recycles implies ignoring the 'internal' separation recycles (eg, separation solvent), and hence, their interactions with the reactor recycles, at least until the separation structure is decided.

Level 1.	Input information
Level 2.	Input-output structure
Level 3.	Reaction system
Level 4.	Separation system (a) Vapour recovery system (b) Liquid recovery system
Level 5.	Global recycle network

Table 2: Waste minimization approach to process design

In contrast, developing the recycle structure based on detailed reaction and separation schemes means that any solvent, inert and waste streams, both from the reaction and separation systems, may now be considered as potential recycles. Simultaneous consideration of the reaction and separation subsystems can promote opportunistic recycling and help achieve our waste minimization goal.

Douglas described how a recycle structure is synthesized from the input-output information. That is, what components to add, remove, replace or recycle are decided at this stage before moving on to detailed separation sequence design. The following examples briefly illustrate the typical design decisions encountered when the recycle structure is being fixed and highlight the advantages of the waste minimization procedure in generating cleaner designs.

Example 1. Ethylene production [4]

The ethylene production process can be represented by the following simplified set of reactions:

$$\underset{\text{(ethane)}}{C_2H_6} \iff \underset{\text{(ethylene)}}{C_2H_4} + \underset{\text{(hydrogen)}}{H_2} \quad (1)$$

$$\underset{\text{(ethane)}}{C_2H_6} + \underset{\text{(hydrogen)}}{H_2} \iff \underset{\text{(methane)}}{2CH_4} \quad (2)$$

Normally steam is added as an inert diluent to reduce byproduct methane because steam is easy to condense and separate. At level 3 (recycle structure) of Douglas hierarchical design procedure, an inert (eg, steam) may be introduced to improve product distribution. Introduction of steam as an inert diluent however leads to an exit water stream that needs to be treated. It is suggested in the article steam be replaced by a different diluent that can be sent to a fuel supply or be recycled less expensively than water.

If the separation structure were defined, we could decide whether any solvent or diluent (in this case, condensed steam) could be used internally either directly or indirectly before being sent to treatment facilities. This could reduce the water usage and waste treatment needs. Alternatively, a component from the separation system may be chosen to replace steam to improve product distribution. The disadvantage of Douglas' approach is that, at this stage, there is no way of knowing whether condensed steam can be used inside the separation or whether a substitute for steam exists, since the separation section is still undefined when the recycle structure is being fixed.

Example 2. Production of acrylonitrile [5]

Acrylonitrile is a building block for synthetic rubber. The once-used acetylene production route has been replaced by the Sohio Process that utilizes cheaper raw materials:

$$\underset{\text{(propylene)}}{2C_3H_6} + \underset{\text{(oxygen)}}{3O_2} + \underset{\text{(ammonia)}}{2NH_3} \rightarrow \underset{\text{(acrylonitrile)}}{2C_3H_3N} + \underset{\text{(water)}}{6H_2O} \quad (3)$$

The reactor effluent consists of inerts (mainly nitrogen from air), unreacted propylene, propane, acrylonitrile, water and impurities. The notoriously difficult separation between propylene and propane is inevitable because propylene is used as a raw material. Conventional distillation is uneconomic due to the low relative volatility between the two hydrocarbons and the fact that propylene (the more volatile of the two) is five times more plentiful than propane. An indirect separation using acrylonitrile as a solvent was proposed by WG Johnson to overcome the separation problem.

The use of acrylonitrile as a solvent eliminates the solvent recovery step and results is a simpler process (US Patent 2,980,727 by WG Johnson). This example shows the advantages of fixing the recycle structure only after the separation synthesis. Had the recycle structure been fixed first, acrylonitrile would be classified solely as a product to be removed from the process. The problem would need reworking when it is found later (during the separation synthesis) that acrylonitrile is also a potential solvent.

We can conclude that if we decide to add, remove or recycle certain components before the separation synthesis, we may have to answer the following questions later and possibly have to rework the problem:

1. Should a component be removed from the reactor or reused downstream? Can any component from the reactor be directly (or indirectly) reused downstream as an inert, solvent, etc? Can further separation be avoided by reusing it downstream?
2. Is it necessary or convenient to add a new component in the reactor? Can any component from the separation section be reused in the reactor?
3. How does the separator recycle influence the reactor recycle? Can the recycle purges be independently designed? What would be the effects of independent recycle designs on plant performance and operability?

It is evident that in all cases a definite answer can only be obtained by delaying any recycle decisions until the separation structure is fixed. Detailing the separation structure before recycling, as proposed in the waste minimization approach, allows us to analyse all recycle streams simultaneously so that the possibility of waste exchange and recycle interactions can be assessed.

Four advantages can be expected from the waste minimization approach:

- improving the scope for recycling and the ability to explore and exploit the waste minimization alternatives,
- avoidance of design rework,
- effective prevention of trace accumulation that may cause operability problems, and
- reduction of excessive purge losses and release by eliminating unnecessary exit points.

There are two important points to draw from the preceding discussion. First, Douglas' model was originally developed to be applicable for the general design case regardless of the design 'theme' and is therefore not specifically directed towards recycling. Second, any recycle decisions made before fixing the separation structure via the Douglas synthesis model can still be revised and reworked. The modified model is an adaptation to process synthesis for waste minimization, that has been designed to promote recycling. At best, it may prevent missed opportunities for recycling while guiding the design for better operability. At worst, it may only avoid design rework.

Concluding remarks

Opportunistic recycling is commonly employed during retrofit to minimize waste. However, its systematization is a subject that has received little attention during process design. In this article, the Douglas hierarchical design procedure has been modified and extended to create a procedure for process design that is conducive to waste minimization particularly through opportunistic recycling. Just as in Douglas' approach, a design is developed by proceeding through successive levels of design abstraction while additional details are added at each level. To achieve the goal of waste minimization, the idea is to identify potential pollution problems as design is developed, and make decisions not to introduce materials, chemistry, process conditions or techniques that could cause adverse environmental impact at each level of the design hierarchy.

The design procedure for waste minimization which promotes opportunistic recycling includes the following key new features:

- recognition of the multiple roles that a given species may assume (eg, a given species can either be a product and a recycle), giving rise to alternative flowsheets.
- intra and inter-level recycling for the reaction and separation sections of the process and search for inert diluents, substitute materials and potential internal solvents.
- analysis and evaluation of alternative mixing points in the overall process context.
- visualization of recycle and mixing scopes for enhanced separation and generation of cleaner alternative separation structure using ternary diagrams.

References

1 *USEPA (1991), European Community Council Resolution on Waste Policy, (91/156/eec) edition.*
2 *Crittenden, B and Kolaczkowski, S (1995), Waste Minimization: A Practical Guide. Institution of Chemical Engineers, 1995.*
3 *Douglas, J M (1988), Conceptual Design of Chemical Processes. McGraw-Hill, 1988.*
4 *Douglas, J M (1992), Process Synthesis for Waste Minimization. Ind. Eng. Chem. Res., 31, 238-243, 1992.*
5 *Ruud, D F , Powers, G J and Siirola, J J (1973), Process Synthesis. Prentice-Hall, Englewood Cliffs, NJ, 1973.*

❑