Received: 25 February 2022 | Revised: 31 May 2022 | Accepted: 1 June 2022

DOI: 10.1002/cjce.24625

SPECIAL ISSUE ARTICLE

THE CANADIAN JOURNAL OF CHEMICAL ENGINEERING

# Chemical engineering and industrial ecology: Remanufacturing and recycling as process systems

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**Abstract**

Climate change and resource scarcity are just two of the planetary crises that make radical socio-economic change essential if human society is to be sustainable. Chemical engineering is a skill-set that can make a unique contribution to the socio-economic transition, going beyond new technological processes to provide a system-level understanding of economic activities from the perspective of industrial ecology. This paper provides an example by applying process system analysis to the use, re-use, remanufacturing, and recycling of material products. Unlike the 'circular economy' approach, the analysis starts from the stock of goods and materials in use in the economy and models the flows required to build up, operate, and maintain the stock. Metrics are developed to account for the effect of stock growth on demand for materials. The significance of the analysis is illustrated for four metals whose industrial ecologies are at different levels of maturity: lead, copper, aluminium, and lithium. Extending product life through re-use and remanufacturing is crucial for resource efficiency, using labour to reduce demand for energy and non-renewable resources. If end-of-life products are processed to recover individual elements, the cost penalties increase rapidly with the decreasing concentration of valuable materials and increasing number of materials in the mixture. Thus, shifting from a linear economy (make–use–dispose) to closed-loop use of materials involves rethinking product design to reduce the number of materials used. Material substitution to reduce demand for scarce materials needs to look beyond equivalence of function to consider changing patterns of use in the regenerative economy.

**KEYWORDS**

circular economy, critical materials, industrial ecology, material stocks, recycling

# 1 | INTRODUCTION

## 1.1 | Socio-economic transition

We live in 'interesting times'. The starting point for this paper is that human activities are putting the Earth's biosphere into crisis. Climate change, caused by anthropogenic emissions of greenhouse gases, is a well-recognized component of the environmental crisis,[1] but the capacity of the planet to absorb the emissions of human activities and supply the resources on which humans depend has already been exceeded in other ways.[2] These aspects of the unsustainability of current human society and economy come together in the concept of the 'Nexus': that water, food, and energy security are inextricably linked,[3] so that economic activities and some social habits must be changed radically and urgently if we are to leave a sustainable future for our descendants.

Mitigation of greenhouse gas emissions depends largely on moving away from fossil fuels (or, at very least, containing the carbon dioxide formed when they are burned). However, the technologies to exploit alternative energy sources rely on critical raw materials,[4] particularly certain rare earth metals whose supply is unstable and production is energy intensive.[5,6] The dependence of decarbonizing energy supply on the availability of critical raw materials represents another nexus, sometimes called 'The Terawatt Challenge'.[4]

Discussion over how best to manage scarce materials has become dominated by the circular economy paradigm, although the precise meaning of 'circular economy' differs between different authors. Kirchherr et al.[7] reviewed 114 different definitions and concluded that 'the circular economy is most frequently depicted as a combination of reduce, re-use and recycle activities'; in other words, 'circularity' generally means no more than 'valorization' of waste streams from conventional economic activities (including the use of durable and consumable products) to promote 'closed loop' use of materials and products. Furthermore, the emphasis is most commonly on using 'circularity' to achieve competitive advantage and expand economic activity,[7] rather than to reduce resource depletion and environmental impact, or to improve social welfare, or to promote the socio-economic transition to a less unsustainable economy.[8] Corvellec et al.[9] went so far as to conclude that

'… the circular economy is far from being as promising as its advocates claim it to be. Circularity emerges … as a theoretically, practically, and ideologically questionable notion.'

One of the main limitations of the circular economy model lies in its focus on flows—inputs to and waste from economic activities—rather than the stock of materials and products in use in the economy.[8] Building up, operating, and maintaining the stock in an economy (i.e., infrastructure, buildings, plants, vehicles, appliances, etc.) require material inputs and uses energy and labour. Krausmann et al.[10] estimated that about half the materials extracted globally are used to build up or renovate stocks, rather than flowing through the economy to emerge as waste for re-use, recycling, or disposal. Material stocks in the global economy were estimated to have grown by a factor of more than 20 over the 20th century, leading to the observation[10]:

'The 20th century has often been characterised by the emergence of a throwaway society. Paradoxically, it would be better described as a century of massive stockpiling.'

Focussing on stocks can, therefore, provide a perspective that complements the conventional economic focus on flows and lead to a more complete understanding of the changes needed to make the human economy less unsustainable. The stock-centred paradigm is termed 'the performance economy'.[11,12]

## 1.2 | Chemical engineering outside the pipe

The developing global crises require the role of chemical engineering to be rethought. As an urgent example, many of the industries in which many chemical engineers work—notably, oil, gas, and petrochemicals—must address carbon management to mitigate emissions of greenhouse gases and, in some cases, be phased out if we are to avoid catastrophic damage to the biosphere.[1] For the discipline to remain relevant, the skill set that makes up chemical engineering must therefore be deployed in new ways.[13] One response is the growing application of chemical engineering to produce materials from biological sources, for example, through the development of biorefineries (see Section 3.3). This paper goes further to illustrate how the skills of the chemical engineer can be redeployed in the emerging field of industrial ecology. Although not reflected in his published work, John Grace himself was interested in this development.

Industrial ecology has been defined as[14]:

'… the study of the flows of material and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory and social factors on the flow, use and transformation of resources.'

Thus, the concern for management of flows and stocks embodied in the 'circular' and 'performance' economy paradigms has been at the heart of industrial ecology from the outset. Furthermore, 'flow, use, and transformation of resources' sums up the core of

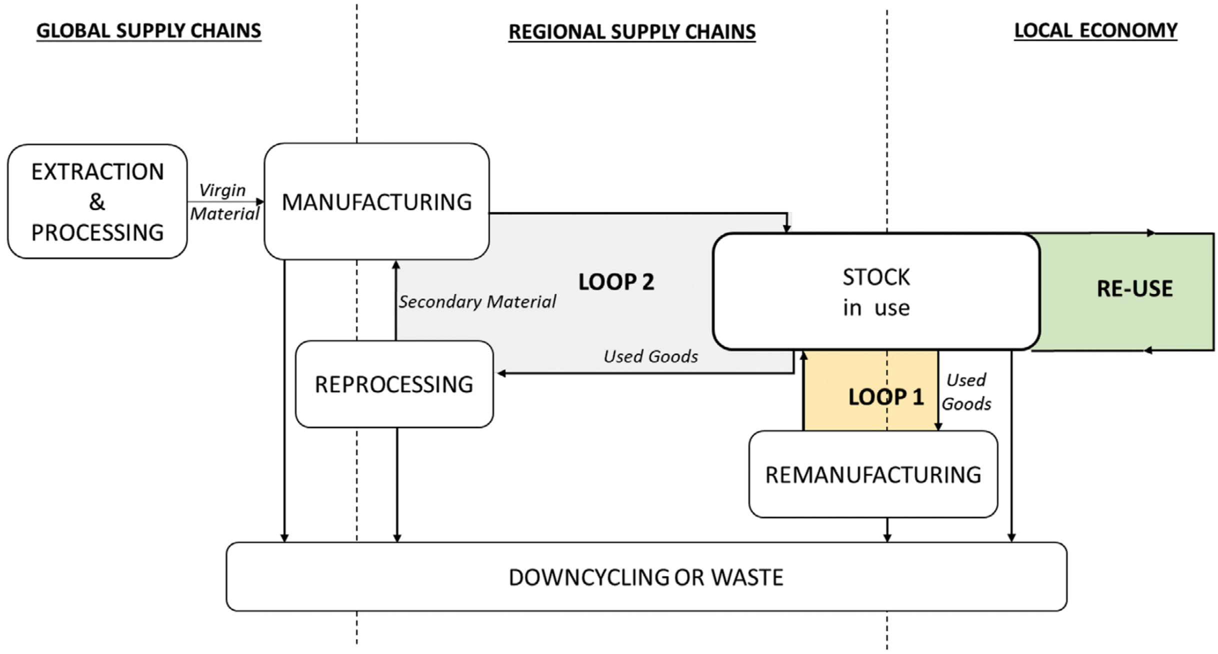


FIGURE 1 Material loops. Adapted from Stahel and Clift[11]

chemical engineering. Therefore, industrial ecology represents a natural way by which the way of thinking called 'chemical engineering' can contribute to the socio-economic transition to a sustainable society; it takes chemical engineering 'outside the pipe' to a much broader role in assessing systems within which materials and products are used.[15] The purpose of this paper is to illustrate the application of 'chemical engineering outside the pipe' to inform industrial strategy and policy on re-use, remanufacturing, and recycling. The system perspective is fundamental: sustainability is itself a system property[16] so that sustainability is a property of possible systems within which any particular material can be used, not an inherent material property.[17]

## 2 | CLOSED-LOOP PRODUCT SYSTEMS

### 2.1 | Re-use, remanufacturing, and recycling

Figure 1 shows the three 'loops' that can extend the service life of goods and materials in the economy[11,12,18] with their geographical scales:

Re-use refers to direct re-use such as cleaning garments, activities such as refilling returned containers, and also cases where ownership changes, for example, via a second-hand market. These activities are usually carried out locally.

Remanufacturing (loop 1) includes repair and remanufacture of used goods and 'upgrading' to meet new performance standards or fashion. Remanufacturing may be a local activity such as repairing appliances or vehicles. Complex items may be taken to regional service centres, but global movement of goods for remanufacturing is limited.

Recycling and reprocessing (loop 2) refer to reprocessing or dismantling to recover materials or components that may be recycled in the same product system ('closed-loop recycling', as in Figure 2) or passed to loop 2 of a different product system ('open-loop recycling'), often with lower performance requirements or lower economic values ('downcycling'). Recycling is commonly carried out on a larger scale than remanufacturing, in a regional or global product system. Downcycling may be local but may also occur at regional or global scales, exemplified by the large quantities of used clothing shipped to Africa from Europe.

Production of both virgin and secondary materials and components is usually more energy-intensive and less labour-intensive than remanufacturing.[11,12,19] Therefore, to both reduce resource use and generate employment, re-use and remanufacturing (loop 1) are usually preferable to reprocessing (loop 2), with primary production the least desirable.[12,20] The priority order for improving resource efficiency is[11,21]:

1. Extend service life to reduce material throughput, which is specifically advocated in the European Union[5];

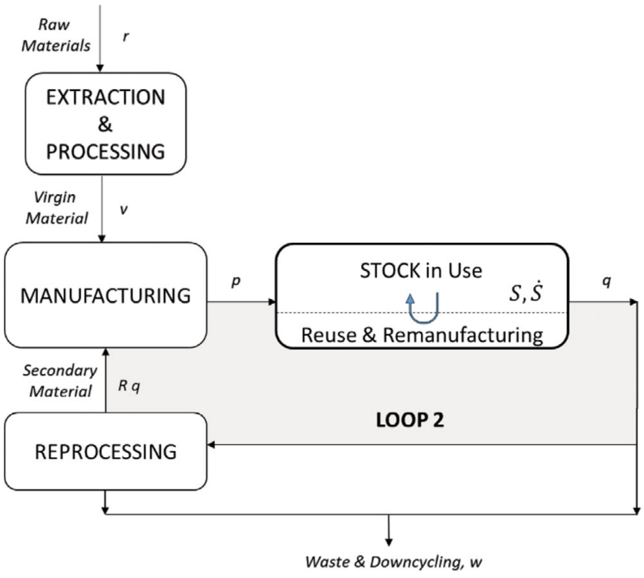


FIGURE 2 Product system for durable goods

2. Intensify use of stock to reduce stock needed;
3. Increase re-use of existing stock;
4. Increase the proportion of worn or damaged products remanufactured;
5. Increase the proportion of post-use products and materials reprocessed.

## 2.2 | Product system: Stocks and flows

The priorities set out above emerge from analysis of closed-loop management of durable manufactured goods (such as appliances, vehicles and buildings, or other infrastructure) for the simple case of a mature sector where the stock of goods is saturated and changes little over time.[11] The following analysis, based on the product system model shown in Figure 2, extends the treatment to sectors where the quantity of stock changes significantly over time. We consider the case where the stock is growing, but the model also applies where increasing intensity and efficiency reduces the total stock, that is, growth is negative.

Raw materials are processed to provide a specific element or substance that is used in product manufacture at rate $v$ (typically measured as kg or tonnes per year), along with secondary recycled material. The products passing into use contain a flow $p(t)$ of the substance. The stock of goods in use contains a quantity $S(t)$ of the substance, which grows with time at rate $\dot{S}$. Re-use and remanufacturing keep stock in use by extending its service life, $T$. The analysis can be modified to more complex cases, including goods with a range of service lives (i.e., residence times),[22–24] but the general conclusions are unaffected. For simplicity, it is presented here for the case where all goods have the same life, equivalent to plug flow in a process system. Therefore, remanufacturing (loop 1) is included in the use phase; that is, the proportion of the total stock out of use for remanufacturing at any time is assumed to be small, so that stock is available for use throughout essentially the whole of its service life. Goods leaving the use phase in the life cycle contain a flow $q(t)$ of the substance in question. Part of the end-of-life goods are recovered for reprocessing (loop 2). The efficiency of loop 2 depends on the fraction of end-of-life goods recovered for reprocessing and the efficiency of reprocessing. Combining these two influences into a single parameter, the fraction of $q(t)$ returned as a secondary material into the next generation of goods is defined as the recycle ratio or recovery fraction, $R$. End-of-life goods not recycled and material rejected from reprocessing remove the substance from the system at a rate $w(t)$, to be downcycled or lost to the economy as waste.

The focus here is on how management of the stock affects demand for virgin material, $v(t)$. The stock variables—that is, $S(t)$ and $\dot{S}$—are treated as independent variables, determined by demand for the service provided by the stock. The product life, $T$, and recycle ratio, $R$, are properties of the system, determined by product design and use and by management of end-of-life goods, respectively. The flows—$p(t)$, $q(t)$, $r(t)$, $v(t)$ and $w(t)$—are dependent variables, determined by the demand for material to maintain the growing stock given the division of flows within the system; in process system terms, $p(t)$ is regulated to maintain the growth in $S(t)$. To provide a simple example, the following analysis assumes that $\dot{S}$, $T$, and $R$ are constant.

## 2.3 | Growth and replacement of stock

The Appendix presents a simple analysis of the movement of material through the use phase in its life cycle, subject to the assumptions set out above. It is shown that

$$p(t) = q(t) + \dot{S} \tag{A1}$$

$$p(t) = \frac{S(t)}{T} + \frac{\dot{S}}{2} \tag{A10}$$

$$q(t) = \frac{S(t)}{T} - \frac{\dot{S}}{2} \tag{A11}$$

From the balance around the manufacturing stage

$$v(t) = p(t) - R\,q(t) \tag{1}$$

Therefore,

$$\frac{v(t)}{p(t)} = 1 - \frac{R\,q(t)}{p(t)} \tag{2}$$

The fraction of secondary material in new goods entering use follows as

$$f = 1 - \frac{v(t)}{p(t)} = \frac{R\,q(t)}{p(t)} = R\,\frac{2-\alpha}{2+\alpha} \tag{3}$$

where $\alpha$ is a dimensionless growth rate of stock representing the fractional growth of stock during the lifetime of a single item

$$\alpha = \dot{S}\frac{T}{S} \tag{4}$$

Figure 3 shows the fractional contribution of secondary material, $f$, as the function defined by Equation (3) of the dimensionless growth rate of stock, $\alpha$, and the recycle ratio for end-of-life products, $R$. It is noteworthy that $f$ is always smaller than $R$ and the difference depends on the sector growth rate, $\alpha$. In fact, there is a range of values for $f$, above the curve for $R = 1$, that is unattainable. This rather obvious conclusion has important implications for public policy on the management and recycling of durable goods. Recycling targets are commonly framed in terms of the proportion of secondary material in 'new' goods,[25,26] because $f$ is usually easier to monitor than $R$, but without reference to whether the stock of material in the sector is growing. Figure 3 shows why this approach can have perverse consequences by increasing demand for secondary material. From Equations (3) and (4)

$$f = R\frac{\frac{2S}{\dot{S}} - T}{\frac{2S}{\dot{S}} + T} \tag{5}$$

One way for a manufacturer to increase $f$ is to reduce $T$, that is, requiring an unrealistically large fraction of secondary material in 'new' products can have the perverse effect of incentivizing short product life. Regulations and targets should therefore focus on $R$ rather than $f$: Policy measures should be directed explicitly at increasing the proportion of used goods recovered for reprocessing. Once the goods are in loop 2, normal economic pressures will act to improve the efficiency of reprocessing.

The European Commission[6] has ranked critical materials in order of decreasing $f$. Lead, copper, aluminium, and lithium provide examples of four materials whose industrial ecologies are at different stages of development. The system properties for these materials are

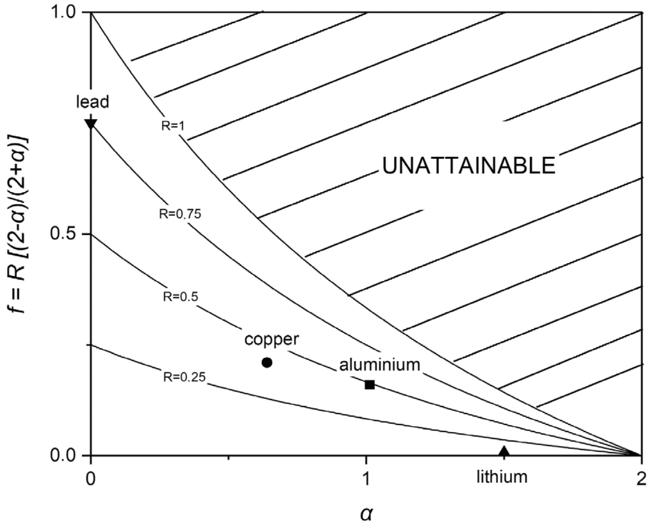


**FIGURE 3** Proportion of secondary material available as a function of recycle ratio and sector growth rate

summarized in Table 1. Lead has the highest value for $f$ because it is used in mature sectors, with high $R$ and low $\alpha$: $f \approx 0.75$, that is, 75% of the lead in new products in Europe is recovered material.[6] For automotive lead-acid batteries in particular, rates of collection and recycling are much higher than for other batteries, limited mainly by the export of used vehicles outside the European Union.[27] Aluminium represents an intermediate case: Recycling systems are in place ($R$ is relatively high, at about 50%), but the stock is growing ($\alpha$ is high) (e.g., Liu et al.[28] and Davis et al.[22]) so $f \approx 0.16$, that is, only about 16% of the aluminium in new products is secondary material.[6] A similar situation is found for copper.

Lithium is a leading example of a material subject to rapidly growing demand, mainly for use in lithium-ion batteries (LIBs; see Section 3.3.), but for which recycling is still lagging.[29–33] The development of recycling systems for lithium is complicated because the economic driver arises from other battery materials, particularly cobalt[27,29,30]; therefore, the increasing price of lithium has driven expansion of primary production rather than increasing recycling. The rate of recycling of lithium is uncertain. There is an extensive but poorly traced international trade in lithium, both as a commodity and in end-of-life products.[34] Refurbishment and downcycling of used batteries[33] also contribute to the uncertainty. A figure of $R = 0.05$, possibly overestimated, has been assumed here. Even with this generous estimate, the fractional contribution of secondary lithium in new goods is very small: $f \approx 0.007$.

For a substance, such as lead, used in mature sectors where $\alpha$ is small ($\alpha \approx 0$), Equation (1) reduces to the steady-state case[11]:

**TABLE 1** Parameters of the product systems for selected substances

| | Lead (2020) | Copper (2011) | Aluminium (2009) | Lithium (2020) |
|---|---|---|---|---|
| $S$, Mt | 137 | 356 | 665 | 0.31 |
| $\dot{S}$, Mt/yr | $\cong 0$ | 10 | 29 | 0.058 |
| $T$, yr | 7 | 23 | 23 | 8 |
| $p$, Mt/yr | 17 | 20 | 53 | 0.090 |
| $q$, Mt/yr | 17 | 10 | 24 | 0.032 |
| $w$, Mt/yr | 5 | 6 | 12 | 0.032 |
| $\alpha$, – | $\cong 0$ | 0.64 | 1.0 | 1.5 |
| $R$, – | 0.75 | 0.41 | 0.48 | $\cong 0.05$ |
| $f$, – | 0.75 | 0.21 | 0.16 | $\cong 0.007$ |
| Data source | [35] | [10] | [10,28] | [29,30,32,35] |

Abbreviations: Mt, million tons; yr, year.

$$v \approx q\,(1-R) = (1-\ R)\frac{S}{T} \tag{6}$$

As summarized in Section 2.1, the priorities to reduce the input of virgin material ($v$) are to extend the life of goods in use ($T$) and to increase $R$ by increasing the fraction of used goods recovered for reprocessing and improving the efficiency of material recovery from reprocessing.

By contrast, in a rapidly growing sector, where $\dot{S} \gg S/T$ (i.e., $\alpha \gg 1$), demand is dominated by stock growth. In this case, Equations (A1) and (1) confirm that

$$v \approx p \approx \dot{S} \tag{7}$$

In this limiting case, demand for virgin material can only be reduced by reducing the stock growth rate, $\dot{S}$.

Copper ($\alpha = 0.64$), aluminium ($\alpha = 1.0$), and lithium ($\alpha = 1.5$) represent intermediate cases between $\alpha \approx 0$ and $\alpha \gg 1$. The fractional demand for virgin material is intermediate between predictions of Equations (6) and (7). Both increasing $R$ and reducing $\dot{S}$ have pronounced effects on the input of virgin material ($v$).

# 3 | PRODUCT DESIGN AND END-OF-LIFE STRATEGIES

## 3.1 | Extending product lifetime and reducing stock

Equation (3) and Figure 3 provide a conceptual framework for assessing the sustainability of resource use in a growing system. Strictly speaking, economic growth is inherently unsustainable, as it implies unbounded access to limited resources on a finite planet.[36] One of the main goals of sustainable development is to ensure universal access to a decent quality of life while reducing resource depletion to a level compatible with societal, demographic, technological, and economic outlooks.[8,37] Resource exploitation is a large component of conventional measures of economic activity, such as gross domestic product (GDP),[38] so this implies limiting economic growth. The 'post-growth' agenda has explored the implications of focusing on the provision of social welfare rather than economic growth per se from a macro-economic perspective.[39–41] The analysis developed here complements that approach by taking a process-based perspective.

We distinguish between 'demand growth', that is, the growth of societal demand for the function provided by the material stock, and conventional 'economic growth,' which expresses the growth in economic activity, measured in financial terms, associated with production of goods. Economic growth is related to the stock growth, $\dot{S}$, and depends on the recycle ratio, $R$, and also on the fraction of secondary material, $f$, via the dimensionless growth rate of stock, $\alpha$. These, rather than the material flows, define the product system. A given value for $\alpha$ can result from different values of $S$, $\dot{S}$, and $T$, not all equivalent in sustainability. Economic and demand growth can be decoupled, to reduce $\dot{S}$ and so improve sustainability, by extending product lifetime, $T$, and also increasing the intensity of use of the stock through measures such as shared ownership.[11,12]

Re-use and remanufacturing are ways to extend product life (see Section 2.1). Product remanufacturing finds its rationale in the way environmental impact and added value build up along the supply chain. Clift and Wright[42] showed that this build-up commonly takes the convex form shown schematically in Figure 4: the early stages in primary production are associated with the greatest environmental intensity and least economic value, so that remanufacturing reduces environmental impact but commonly at greater added value (i.e., greater product cost). Particularly for remanufacturing, labour is a major component of added value. Labour is an inherently renewable

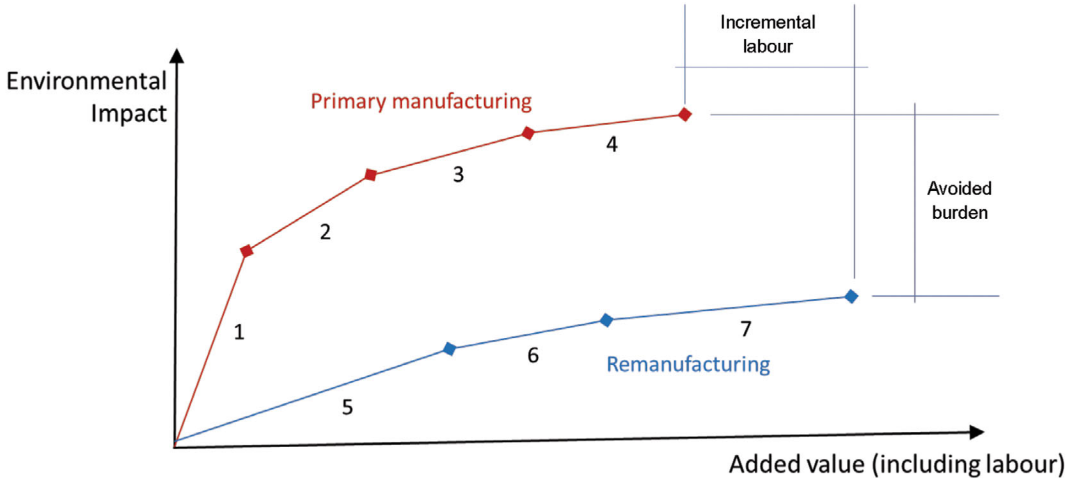


FIGURE 4 Relationship between environmental impact and labour for primary manufacturing versus remanufacturing. Re-worked from Clift and Wright.[42] 1: resource extraction; 2: processing and refining; 3: forming; 4: assembly; 5: collection; 6: dismantling; 7: re-assembly

resource.[8,12] Thus, compared to primary production, remanufacturing reduces inputs of non-renewable resources with large environmental impacts, notably energy and virgin materials, and substitutes a renewable resource: labour. The fact that current economics do not favour remanufacturing, so that specific legislation is needed to mandate remanufacturing and recycling of end-of-life products, is a failure of the economic system. The fiscal system offers a way to rectify the failure by shifting taxation away from renewables (such as labour) onto non-renewables (such as fossil energy) and emissions (such as greenhouse gases).[11,12,20]

The complementary approach—reducing $\dot{S}$ by reducing the stock $S$ required to meet a given societal demand for the function—represents the shift from circular economy to performance economy: an economic paradigm in which 'delivering services' and 'meeting needs' prevail over 'owning goods'. This shift is encouraged by regulations to extend product life (e.g., European Commission (EC)[5]) but requires a deeper shift in business models and practices.[11,12] The reconsideration of business models and political implications of stepping from a circular to a performance economy is a matter of current debate.[8,43,44] This shift will have important implications for innovation, and specifically, for chemical engineering, by opening up new and unexplored areas of business and technological development.

## 3.2 | Beyond end-of-life: Reprocessing and 'regenerative' chemistry

Reprocessing end-of-life products entails penalties, beyond the economic cost of remanufacturing, in terms of energy, material resources, and environmental impacts. Assessment of the costs and impacts requires detailed analysis of the transformations involved in reprocessing on a case-by-case basis. Nonetheless, some general conclusions can be drawn on the effectiveness and viability of reprocessing.

The well-known Sherwood diagram (Figure 5) relates the cost of extracting a material from a bulk source to its concentration in that source material. It was originally developed for materials obtained from primary sources like ores,[45] but it has been successfully extended to materials recovered by product reprocessing. Dahmus and Gutowski,[46] Johnson et al.[47] and House et al.[48] discuss the significance and limitations of the Sherwood plot in different contexts. For dilute mixtures, the energy penalty of separating and concentrating the valuable resource is very much greater than the minimum separation work corresponding to the change of Gibbs free energy, because of severe additional penalties due to vanishingly small second law efficiencies; as Lightfoot and Cockrem[49] pointed out, separation costs in dilute mixtures are more closely related to the 'processing of valueless constituents', rather than of valuable ones. Hence, the recovery cost $P_v$ from dilute mixtures per unit mass of valuable ($v$) material scales with the processing cost per unit mass of the mixture $P_m$ according to

$$P_v \simeq \frac{P_m}{C_v} \tag{8}$$

where $C_v$ is the mass fraction of the valuable resource in the mixture. Dahmus and Gutowski[46] estimate $P_m$ at approximately \$1/kg of initial mixture for separating organics, approximately \$0.01/kg for metal recovery and

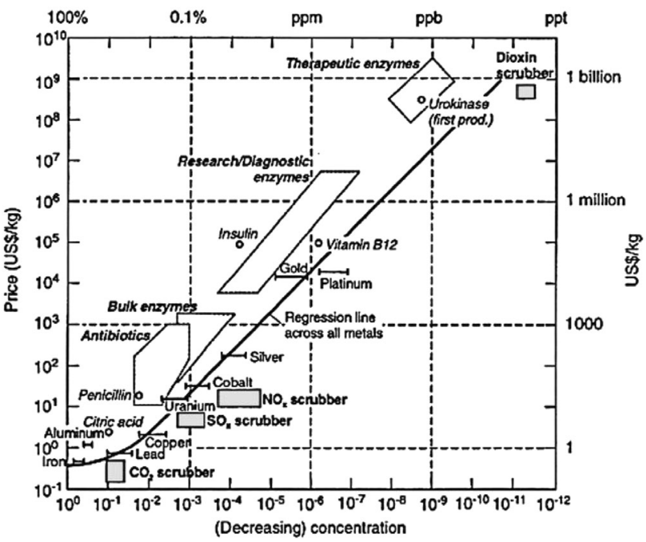


FIGURE 5 The Sherwood plot. Adapted from Grübler[45]

approximately \$0.001/kg for separating pollutants from mixed gas streams. The Sherwood plot is consistent with Equation (8) in the limiting case of dilute materials, as shown by the lines for organics, metals, and gas pollutants in Figure 5, which represent the best fits to available data. Departures from the correlations may be observed for elements produced or recovered as by-products of other elements, making the supply of by-products very inelastic to increases in demand and price.[50] Lithium is an example of such a substance because the economic incentive for recovery and recycling arises from other materials (see Section 2.3).

For end-of-life streams containing multiple materials, additional costs arise from separation of mixed materials into more homogeneous ones. Dahmus and Gutowski[46] developed a cost scaling scheme for product recycling, borrowing a methodology for binary sequential separation steps from information theory. The key parameter in the analysis is a material mixing index $H$ of the product, defined as:

$$H = -K \sum_{M} C_i \ln C_i \tag{9}$$

where $K$ is a constant (set as 1 by convention), $M$ is the number of distinct materials in the product, and $C_i$ the concentration of material $i$ in the product. Equation (9) presents a close analogy with the mixing Gibbs free energy of multicomponent mixtures but cannot be considered a thermodynamic constraint as it refers to heterogeneous multimaterial goods rather than homogeneous multicomponent ones. Based on a preliminary assessment of 20 products in the US market, a tentative 'apparent recycling boundary' and criterion for recycle of a 'complex' product to be feasible is given:

$$V = \sum_{M} m_i k_i > V_{\min} \cong 3 \cdot 10^{-4} e^{5.1 \cdot H} \tag{10}$$

where $V$, in US\$, is the total value of the different materials that can be recovered from the product, obtained as the sum of the mass of each, $m_i$, times its value in US\$ per unit mass, $k_i$. The strong dependence of the threshold value $V_{\min}$ for viable recycling on the mixing parameter, $H$, is notable, highlighting the recycling penalties resulting from using many different materials in a single manufactured product. Equations (10) and (8), represented by the Sherwood plot in Figure 5, are complementary: they express the cumulative reprocessing penalty associated with the 'mixedness' of complex multimaterial products and the dilute state of valuable materials.

In a linear economy, where end-of-life products are treated merely as waste for disposal, there are no barriers other than material cost to using many different materials in a manufactured product. However, once the sustainability of material use is addressed seriously, so that recycling end-of-life products becomes part of the business model, material recovery costs and the feasibility of recycling favour a more selective approach with fewer different materials. Johnson et al.[47] have investigated how and to what extent the 'ease of disassembly' of a product may encourage reduced complexity in order to facilitate reprocessing of disassembled end-of-life goods.

A final remark concerns the huge potential associated with the development of 'regenerative chemistry', the expanding branch of chemical technology aimed at regenerating end-of-life products and materials into primary chemicals. Chemical recycling of materials like waste plastics, $CO_2$-utilization, marginal biomass, and waste exploitation for the production of chemicals and fuels are examples of 'regenerative chemistry' that are approaching commercial maturity and deployment. The challenge of regenerative chemistry is most typically 'climbing' the Gibbs free energy gap along the reverse path from products back to reagents. For this to be done, energy, ideally from renewable sources, is needed, a feature that frequently links regenerative chemistry to solar chemistry. The need for 'closing the loop' along the regenerative chemistry paths opens up a further area needing new and creative solutions from chemical engineering thinking.

## 3.3 | Material substitution in a changing economy

The last and obvious path to manage 'unsustainable' depletion of limited resources in a growing system is substitution with alternative, less scarce, materials that can be used in more sustainable ways. The growing attention to

**TABLE 2** Substitution of selected abiotic materials, after US Geological Survey[35]

| Abiotic material | Substitution |
|---|---|
| Aluminium | Composites can substitute for aluminium in aircraft fuselages and wings. Glass, paper, plastics, and steel can substitute for aluminium in packaging. Composites, magnesium, steel, and titanium can substitute for aluminium in ground transportation uses. Composites, steel, vinyl, and wood can substitute for aluminium in construction. Copper can replace aluminium in electrical and heat-exchange applications. |
| Copper | Aluminium substitutes for copper in automobile radiators, cooling and refrigeration tube, electrical equipment, and power cable. Titanium and steel are used in heat exchangers. Optical fibre substitutes for copper in telecommunications applications, and plastics substitute for copper in drainpipe, plumbing fixtures, and water pipe. |
| Lithium | Substitution for lithium compounds is possible in batteries, ceramics, greases, and manufactured glass. Examples are calcium, magnesium, mercury, and zinc as anode material in primary batteries; calcium and aluminium soaps as substitutes for lithium stearates in greases; and sodic and potassic fluxes in ceramics and glass manufacture. |

substitution is witnessed by specific studies[6,51] and dedicated sections in major directories of commodities (e.g., US Geological Survey,[35] British Geological Survey[52]). As an example, Table 2 reports a non-selective list of possible substitutions for the elements introduced in Section 2 as case studies of stock growth, namely, Al, Cu, and Li.[35]

Distinguishing between stocks and flows, as in Section 2, provides a basis for systematic assessment of substitutability. For example, flows of aluminium through the economy are dominated by uses with short service lives, notably as beverage containers where the alternative materials are plastic or glass.[28] Aluminium is favoured for this use because it is light, reducing the cost of long-distance transport. However, distribution systems for beverages are changing—another aspect of a socio-economic transition[8] exemplified by the rise of local craft breweries[53] whose business model relies on local sales, often to customers refilling glass containers, rather than long-distance transport.[54] Even large companies are starting to use containers that can be refilled by individual consumers.[55] Thus, substitution to reduce demand for aluminium in packaging is driven, in part, by changes in business practice, which complements the push from material scarcity.

By contrast with the flows associated with packaging, the growing stock of aluminium is dominated by long-life building components such as windows and door frames.[28] Here, durability, rather than weight, is the main criterion. Of the alternative materials suggested in Table 2, wood is currently subject to supply problems. This explains the current emphasis on polyvinyl chloride and other plastics for use in building components. The long product life overrides the current concern over pollution arising from plastics for packaging and other short-life applications.[56]

The surge in demand for lithium has arisen for use in LIBs, primarily for transport. Substitutes for established short-life dissipative uses are readily available (see Table 2). The motivation to find substitutes for lithium in batteries arises from uncertainty over production capacity and stability of supply, rather than the size of the total global resource,[27] exacerbated by the barriers to development of systems for recovering and recycling lithium[31] (see Section 3.2). Alternative battery technologies, such as the relatively inexpensive Zn–air battery, are available but LIBs are preferred for their higher energy density. In the absence of effective lithium recycling, transport batteries whose performance has degraded are commonly downcycled into stationary applications such as back-up storage.[31] The most likely substitution is therefore in stationary applications, in place of the downcycled LIBs as recycling systems for lithium develop.

A notable consequence of the search for sustainable primary resources as substitutes for abiotic materials is the growth of the bio-based economy. The underlying vision is that using biological resources and processes can lead to less unsustainable growth in bio-based products, energy, and services. However, this general aspiration must be qualified by recognizing that land itself is a scarce resource, so that material and energy crops must be reconciled with food and feed production (e.g., Brandão et al.[57]). Therefore, development of biorefineries and bioproducts in pursuit of sustainability requires an approach to process engineering that incorporates broader system thinking using life cycle assessment (e.g., Sadhukhan et al.[58]).

## 4 | CONCLUSIONS

Chemical engineering as a discipline and as a way of thinking can play its full role in the transition to a more sustainable economy if the skills of the chemical engineer are deployed in new ways, going beyond developing new technologies. The emerging field of industrial ecology embodies chemical engineering but applies it to flows through the economy rather than inside pipes. Systems for the production, use, remanufacture, and recycling of durable goods are an area where relatively simple process analysis can yield new and valuable insights and stimulate creative solutions. Modelling the system in terms of the material flows needed to build up, operate, and maintain the stock relates demand for virgin material to the proportion of end-of-life products recovered and recycled and to a dimensionless growth rate of stock representing the fractional growth of stock during the lifetime of a single item. The analysis shows how demand for scarce materials develops as their industrial ecologies mature and reveals the importance of extending product life and intensifying the use of stock. Remanufacturing goods is preferable to recycling of individual elements. The penalties of recycling increase rapidly with the decreasing concentration of valuable materials and the increasing number of materials in the mixture. Therefore, promoting closed-loop use of materials involves rethinking product design to reduce the number of different materials used. Material substitution can reduce demand for scarce materials, but vision and foresight are essential to look beyond current applications and consider how materials will be used in the future economy.

## NOMENCLATURE

| | |
|---|---|
| $C_i$ | concentration of material $i$ in mixture ($kg_i/kg_{tot}$) |
| $C_v$ | mass fraction of the valuable resource in the mixture |
| $f$ | fractional contribution of secondary material in new products |
| $F(\tau)$ | fraction of products entering system whose service life will be $\tau$ or greater |
| $H$ | material mixing parameter |
| $K$ | constant by convention equal to 1 |
| $k_i$ | value per unit mass of material $i$ in the product (US$/kg) |
| $M$ | number of distinct valuable materials |
| $m_i$ | mass of material $i$ in the product (kg) |
| $p$ | flow of material in products passing into use phase (kg/year) |
| $\dot{p}$ | rate of growth of flow of material in products passing into use phase (kg/year$^2$) |
| $P_m$ | processing cost per unit mass of mixture (US$/kg) |
| $P_v$ | recovery cost (US$/kg) |
| $q$ | material in goods leaving the use phase (kg/year) |
| $R$ | recycle ratio |
| $S$ | stock of material in goods in use (kg/year) |
| $\dot{S}$ | rate of growth of stock (kg/year) |
| $t$ | time (year) |
| $T$ | product service life (year) |
| $v$ | input of virgin material to product system (kg/year) |
| $V$ | single product recycled material value (US$) |
| $w$ | flow of downcycled or lost material (kg/year) |

### Greek letters

| | |
|---|---|
| $\alpha$ | dimensionless growth rate of stock |
| $\tau$ | product service life (year) |

## AUTHOR CONTRIBUTIONS

**Piero Salatino:** Conceptualization; data curation; methodology; writing – original draft; writing – review and editing. **Roberto Chirone:** Conceptualization; data curation; methodology; writing – original draft; writing – review and editing. **Roland Clift:** Conceptualization; data curation; methodology; writing – original draft; writing – review and editing.

## ACKNOWLEDGEMENT

Open Access Funding provided by Universita degli Studi di Napoli Federico II within the CRUI-CARE Agreement.

## PEER REVIEW

The peer review history for this article is available at https://publons.com/publon/10.1002/cjce.24625.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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**How to cite this article:** P. Salatino, R. Chirone, R. Clift, *Can. J. Chem. Eng.* **2023**, *101*(1), 283. https://doi.org/10.1002/cjce.24625

## APPENDIX A

### A.1 | ANALYSIS OF FLOWS INTO AND OUT OF STOCK

The material balance around the stock-in-use block yields:

$$p(t) = q(t) + \dot{S} \tag{A1}$$

We introduce a function $F(\tau)$ to describe the cumulative distribution of service lives in the products entering the system, defined as the fraction whose service life will be $\tau$ or greater. A product with life $\tau$ leaving the system at time $t$ entered at time $(t - \tau)$. Therefore, the stock $S(t)$ and the rate $q(t)$ of products leaving the system are related to the product input rate $p(t)$ by:

$$q(t) = \int_0^{+\infty} p(t-\tau) \cdot \frac{dF}{d\tau} d\tau \tag{A2}$$

$$S(t) = \int_0^{+\infty} p(t-\tau) \cdot [1 - F(\tau)] d\tau \tag{A3}$$

For the sake of simplicity, we consider the case where all products have the same service life $T$; hence $F = H(\tau - T)$ is the Heaviside step function. Accordingly:

$$q(t) = p(t-T) \tag{A4}$$

$$S(t) = \int_0^{+\infty} p(t-\tau) \cdot [1 - H(\tau - T)] d\tau = \int_0^{T} p(t-\tau) d\tau \tag{A5}$$

Upon linearization of the equations around $t$:

$$p(t-\tau) = p(t) - \dot{p}\tau \tag{A6}$$

$$q(t) = p(t-T) = p(t) - \dot{p}T \tag{A7}$$

$$\dot{S} = \dot{p}T \Longrightarrow \dot{p} = \frac{\dot{S}}{T} \tag{A8}$$

$$S(t) = \int_0^{T} p(t-\tau) d\tau = \int_0^{T} [p(t) - \dot{p}\tau] d\tau = p(t)T - \dot{p}\frac{T^2}{2} = p(t)T - \dot{S}\frac{T}{2} \tag{A9}$$

From Equations (A7) to (A9):

$$p(t) = \frac{S(t)}{T} + \frac{\dot{S}}{2} \tag{A10}$$

$$q(t) = \frac{S(t)}{T} - \frac{\dot{S}}{2} \tag{A11}$$