

"LIFE CYCLE ANALYSIS: A CRITIQUE"

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LIFE CYCLE ANALYSIS: A CRITIQUE

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Abstract

Life Cycle Analysis (LCA) is an increasingly important tool for environmental policy, and even for industry. Analysts are also increasingly interested in forecasting future materials/energy fluxes on regional and global scales, as a function of various economic growth and regulatory scenarios. A fundamental tenet of LCA is that every material product must eventually become a waste. To choose the "greener" of two products or policies it is necessary to take into account its environmental impacts from "cradle to grave". This includes not only indirect inputs to the production process, and associated wastes and emissions, but also the future (downstream) fate of a product.

The first stage in the analysis is quantitative comparisons of materials/energy flows and transformations. This can be an extremely valuable exercise, if done carefully. However, the data required to accomplish this first step is not normally available from published sources. Moreover, so-called "confidential" data is unverifiable (by definition) and may well be erroneous. In the absence of a formal

materials-balance accounting system, such errors may not be detected. A key thesis of this paper is that process data can, in many cases, be synthesized, using models based on the laws of thermodynamics and chemistry. While synthetic but possible data may not fully reflect the actual situation, it is far superior to "impossible" data.

Most of the recent literature on LCA focusses on the second stage of the analysis, namely the selection and evaluation of different, non-comparable environmental impacts ("chalk vs. cheese"). This problem is, indeed, very difficult — and may well be impossible to solve convincingly — even at the conceptual level. However, the only approach that can make progress is one that utilizes monetization to the limits of its applicability, rather than one that seeks to by-pass (or "re-invent") economics. Nevertheless, the evaluation problem is second in priority, for the simple reason that LCA has utility even if the evaluation technique is imperfect. On the other hand, LCA has no (or even negative) utility if the underlying physical data is wrong.

Background: Life-Cycle Analysis (LCA)

Life-cycle analysis, as the name implies, is an apparently straightforward methodology for assessing all the environmental impacts of a product (or service), from "cradle to grave", i.e. from the initial extraction and processing of raw materials to final disposal. The exact definition is the subject of some controversy, and has been the subject of several recent workshops and studies (e.g.

[1];[2];[3];[4]). The SETAC "Code of Practice" now divides LCA into three components. The first is taken to be the compilation of quantitative data on both direct and indirect materials/energy inputs and waste emissions, both in production and disposal of a product or service. This phase of the analysis is known as the "inventory". The second phase, impact assessment (sometimes called "eco-profile analysis" (e.g. [5]), includes classification of effects, characterization and valuation. The third phase is improvement assessment, which is analysis of implications for purposes of prioritization and assessment of policy alternatives.

An important precursor of LCA was "net energy analysis", a fairly hot topic during the 1970's. Studies of indirect energy consumption have a fairly long history. One of the first such studies was published in 1969 [6]. Several studies of energy requirements for packaging alternatives were carried out in the early 1970's (e.g. [7];[8];[9]). Other applications of interest included gasohol [10] and the proposed solar powered satellite [11]. Net energy analysis was developed as a formalized methodology over a period of years, with significant contributions published in the journal *Energy Policy* in 1974-75 and collected in book form by Thomas Thomas [12]. Input-output models were first used for energy analysis by Herendeen [13]; Herendeen & Bullard [14]; Ayres *et al* [15]; Bullard *et al* [16]. Virtually all of these studies were concerned with energy resource availability and energy efficiency. None of them considered energy-related waste emissions explicitly.

One of the first attempts to carry out a life cycle analysis taking into account waste emissions generated by direct and indirect production processes (as opposed to

a "net energy consumption") was sponsored by the U.S. National Science Foundation's program of Research on National Needs (RANN) in the early 1970's. The case selected for analysis was a comparison of glass, polyethylene (PE) and polyvinyl chloride (PVC) bottles [17-19]. This effort concentrated mostly on developing a model (the "materials-process-product model") to carry out what is now called the inventory phase of the analysis, although it also included elements of a policy assessment. Another early effort, also focussed on the resource and environmental impacts of packaging alternatives, was a report to the U.S. Environmental Protection Agency [20].

The first major example of a public controversy focussed on environmental impacts of products that was addressed using LCA seems to have been the unresolved competition between reusable cloth diapers and disposable paper diapers [21-22, 23]. In this case, disposables create 90 times more solid waste (but only 2% of the total of municipal waste, whereas reusable cloth diapers generate 10 times as much water pollution (including detergents) and consume 3 times as much energy [24].

Another classic example of a public controversy was the McDonalds' case involving a choice between groundwood (papier-maché) vs. polystyrene hamburger shells. This was ultimately decided by McDonald's in favor of the former, but apparently in response to a "green" campaign that had already prejudged the issue. It is not at all clear that, when manufacturing processes are considered, polystyrene causes more environmental harm than either virgin or recycled paper pulp. In a

similar case, it has been estimated recently that, though polystyrene foam cups occupy more space in landfills than paper cups, the latter requires 36 times more electricity and 580 times more wastewater to manufacture [25]. In addition, when paper is buried in a landfill it eventually decays anaerobically, generating methane.

The packaging industry has been the target of a disproportionate number of LCA's. Other examples include the competition between returnable and re-usable glass bottles, recyclable glass bottles, recyclable aluminum cans and various non-recyclable plastic containers (e.g. [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36]).

In none of the above cases has LCA or eco-profile analysis offered a clear-cut answer. In part this arises from the difficulty of comparing eco-profiles with completely different characteristics. How is the analyst to choose between a theoretically biodegradable product manufactured by a dirty process and a non-biodegradable product whose manufacturing process is relatively clean? The choice could well depend on the mode of disposal, which is very much a policy question itself. Thus, if municipal waste is disposed of in a traditional open landfill, paper will eventually be consumed by decay bacteria, whereas polystyrene will not. However, if solid waste is to be stored indefinitely in modern airtight and waterproof landfills, or if it is incinerated for energy recovery, polystyrene should probably be preferred to paper on the basis of a cleaner manufacturing process. Evidently, in many — perhaps most — cases LCA can only expose the tradeoffs. It can only

rarely point unambiguously at the "best" technological choice. I return to the question of valuation subsequently.

But LCA suffers from another problem that is less obvious, but not less serious. A detailed critique of the above-cited studies (among others) would require a substantial effort. However, all the studies of which I am aware suffer from a generic deficiency. There are two aspects to the problem. The first is the persistent use in most studies — especially those carried out by energy analysts — of non-comparable units of measurement. In particular, LCA manuals published by SETAC and other industry-sponsored organizations actually specify that energy data should be specified in energy units (such as joules), whereas other purchased material inputs and outputs are to be measured in mass terms. However waste emissions are specified in terms of mixed units such as BOD or COD (which cannot be exactly translated into mass) or in terms of mass with indeterminate composition (e.g. particulates, dust, suspended solids, dissolved solids, "industrial waste", "miscellaneous refuse" etc.)

The second aspect of the data deficiency problem is the near universal dependence on unpublished primary data from "confidential" (and consequently unverifiable) sources. Such data is often inconsistent (i.e. unbalanced) and therefore physically impossible. The combination of these issues leads us to consider the "data problem" in more detail.

Inconsistent, Unverifiable Data

To be absolutely clear, the data problem I want to address is *not* attributable to inherent uncertainties of measurement. To be sure, uncertainty is a fact of life in all matters pertaining to the physical world. All physical measurements are uncertain to some degree. In many cases, of course, the degree of uncertainty is itself a known quantity and statistical analysis is applicable. In other cases the uncertainty is, itself, uncertain (i.e. the distribution of errors is not well characterized). A competent analyst recognizes these facts, tries to put bounds on the range of uncertainty, and moves on.

The problem I am addressing here is much less sophisticated but much more urgent: it is the persistent use in LCA's of "data" that are internally inconsistent, that violate the laws of physics. Yet the data are commonly used such a way that their inconsistency — physical impossibility — is effectively obscured. Many LCA's do not even publish the underlying data. For instance, consider the following, taken from a series of three LCA's carried out recently by the European Center for Plastics in the Environment (PWMI), which is a unit of the Association of Plastics Manufacturers in Europe (APME):

"Information has been obtained from three operators of North Sea oil rigs. In each case the operator supplied information on the production of gas and oil, the quantities of different fuels and materials used as well as data on the

estimated air, water and solid waste emissions When the statistical data and the operators data are combined, the overall typical performance of North Sea production is summarized in Table 6 for gas feedstock and Table 7 for oil feedstock" [37]

or

"The distribution shown in Tables 12 and 13 is based on information supplied by the different operators but some of the returns did not provide complete data on the quantities of feedstock subsequently used as fuels. In general *it appears that there is a five percent real loss of feedstock materials in those processes leading up to the production of monomer, with a further one percent loss at polymerization; any excesses above these levels are used as fuels*" [38]

The tables referred to in the above quotes aggregate inputs to a whole chain of processes by a procedure that is only partially described. To ensure that no reader will be able to reproduce the chain of argument for himself, the aggregated inputs (fuels and feedstocks) are given in energy units (MJ), while emissions to air and water are presented in mass units. But the masses are allocated to such meaningless categories as "dust", "metals", "suspended solids", "dissolved solids", "dissolved organics", "miscellaneous refuse", "industrial waste", "mineral waste" and "non-toxic chemicals". But the actual physical composition is not given, either for inputs or outputs, so it is impossible to verify whether the data presented satisfy even a simple mass balance, never mind a detailed balance for such key elements as carbon, sulfur or chlorine.

The executive director of PWMI, the sponsor of the study, asserted without qualification that detailed materials balances were actually available for each process and had been used in the Boustead study [39]. Asked why — if available — mass balances were not presented in the report, he replied that the expert committee (of which Dr. Boustead, the consultant, is also the chairman) had "not recommended" it. Matthews asserted that the committee members were "the outstanding practitioners" in the field and denied absolutely that a desire for secrecy by the industrial sponsors of the study was in any way a factor. Nevertheless, the LCA reader — a legislator, regulator or member of some public interest group — is asked to take the consultant's unsupported word for the validity of the data presented. The consultant, in turn, accepts the unsupported word of the firms supplying the data, which are also the ultimate sponsors of the LCA.

Practitioners of LCA, of which Boustead is one of the best known, have consistently failed to insist on the use of common and comparable mass units. Rather, they have accepted (even encouraged) the use of incompatible and non-comparable units. For instance, LCA's typically attempt to separate energy carriers (measured in joules or some other energy unit) from "feedstocks", which would normally be measured in mass units. This is traditional among government and industry accountants and statisticians. But the distinction is arbitrary and dangerously misleading when applied to chemical processes where the process heat is produced by partial combustion of a feedstock yielding an intermediate (such as carbon monoxide) that participates chemically in the rest of the reaction. Major examples of

this include ammonia and methanol synthesis and carbothermic smelting of metals, but there are literally scores of other examples.

It is both unnecessary and extremely confusing to insist on counting feedstocks and fuels in separate categories in such cases. There is no real physical distinction between them. But if energy carriers and combustion wastes are not counted in mass terms, no materials balance is possible. Moreover, it is possible to claim that the yield of products from feedstocks is arbitrarily high (say 98% or 99%) with the disguised implication that process emissions are nearly zero. This is a strategy for pretending that there is no room (or need) for improvement. Moreover, by measuring fuels, feedstocks, and wastes in different units, there is no way to carry out a mass balance to compare outputs with inputs. For this reason, among others, the mass balance principle is rarely applied in practice at the commodity or industrial levels, even though it is a standard tool in process design (e.g. [40]).

It should be noted here that Boustead's assumption of only a 1% loss in polymerization (of ethylene and propylene) in the second quotation, above, is almost certainly far too optimistic. Stanford Research Institute's estimates of loss (the complement of yield) are 3% for HDPE, 4% for LDPE and 9% for polypropylene [41]. I do not know whether SRI is right or not, but Boustead's optimistic estimate is totally unsupported by any of the data he chooses to present. He apparently made the assumption rather casually, assuming it would not be important — an assumption traceable to his fixation on energy consumption rather than process emissions. Similarly, his estimate of 5% loss in all processes leading up to the monomer

(mainly naphtha cracking) must be equally questionable. This example is hardly a minor one, inasmuch as the major emissions — especially of volatile organic compounds (VOC's) — from chemical processes are precisely equal to these losses. In underestimating process losses by factors of 3 to 9, Boustead is probably underestimating emissions by similar factors. In effect, he has assumed away the major source of emissions.

A related data problem is that chemical process descriptions, as published in standard encyclopedias ([42], [43], are also almost always unbalanced. In all of the standard sources of process information, waste streams are simply neglected. This is also true of the process data in Stanford Research Institute's Process Economics Program (PEP), which is proprietary but widely used in the chemical industry.

The following simple example illustrates this point. Ethyl chloride (C_2H_5Cl) is a chemical used in the manufacture of tetraethyl lead. One (obsolete) manufacturing process was to react ethylene (C_2H_2) directly with anhydrous hydrochloric acid (HCl) in the presence of an aluminum chloride catalyst. According to the published process description, the reaction requires 488 kg of ethylene and 625 kg of hydrogen chloride to yield 1 metric ton (1000 kg) of ethyl chloride [44]. The process inputs add up to 1113 kg. It seems that 113 kg of mass has disappeared from the output side of the process. This is an obvious violation of the first law of thermodynamics, namely the conservation of mass. Thus, the sum total of mass inputs to the process is typically greater than the sum total of process outputs. The neglected outputs are, of course, wastes.

Understandably, chemists in the past have been relatively uninterested in the detailed composition of process waste streams. Moreover, chemical engineering reference books tend to simplify process descriptions, since authors do not have access to proprietary company data on yields, catalysts and process conditions (temperatures, pressures, reaction times). But past disinterest in process waste streams on the part of the chemists and chemical process designers is no excuse for total neglect of this problem in LCA where the whole point of the exercise is to account for process wastes and environmental pollutants.

Worse, the casual neglect of elementary mass balance considerations permits errors of all kinds — even typographical and transcription errors — to go undetected. *Table 1* above is an example of an impossible process taken from the so-called IDEAS data base, created by the International Institute for Applied Systems Analysis (IIASA) for LCA [45]. The IDEAS database remains unpublished because, initially, IIASA was hoping to license the entire system, data included, to LCA practitioners. Unfortunately, anyone who used it might have encountered some surprises.

In this case, by-product ammonia and tar are overstated by large factors; two orders of magnitude in the case of by-product ammonia and at least one order in the case of tar. The authors of the study (in response to a critique by the author) made a formal attempt to balance the total material inputs against the total material outputs. However, instead of searching for the error, they forced a "mass balance" by arbitrarily including "process air" on the input side and neglecting the corresponding

output of nitrogen. There is no such thing as "process NH₃" in a coking plant. The original problem is almost certainly attributable to a transcription error, compounded by incompetence. However, it does not matter how the error was created. The point is that the mass balance was not used to detect the error, but rather to disguise it.

IIASA is not the only respected organization generating LCA's from impossible data. Here is another example, from an official report published by the Swiss government. Consider *Table 2*, taken from one of the most recent and detailed studies of packaging materials [46]. It is trivial to verify that mass balance conditions are not satisfied. For instance, in the case of PVC the total of "used materials" input per kg is 1930.82 gm per kg of product, while products and by-products add up to 2174.47 gm. not including emissions. The inconsistency is not immediately obvious, since the input list is itself incomplete (atmospheric oxygen is omitted, for example, as are fuels) and the output list (not shown) omits major mass flows like carbon dioxide and water vapor. Nevertheless it is easy to see that the missing mass on the output side is greater than the missing mass on the input side. However, it is impossible to cross-check the calculations or reconcile the obvious discrepancy. Unfortunately, the example illustrated is by no means an isolated case.

To emphasize that the use of unbalanced (i.e. impossible) data is not a rare and exceptional problem, consider *Figure 1* taken from the same LCA cited above [47]. In this case a number of processes leading into primary aluminum smelting are aggregated into a much smaller number. The process inputs seem to consist of 27.5 kg of bauxite, 2.4 kg of an output of electrolysis of rock salt (actually sodium

hydroxide, NaOH) and 0.5 kg of some output of calcination of limestone (lime, CaO). While the diagram is quite confusing, it appears that 30.4 kg of inputs flow into process K (aluminum fluoride manufacturing), producing 18 kg of product, leaving 12.4 kg of inputs unaccounted for. This, in itself, is an impossibility.

There is worse. *Figure 1* apparently aggregates the production of the two different materials, aluminum fluoride and synthetic cryolite (sodium -aluminum-fluoride) under the single label "aluminum fluoride". Taking them together, it shows 18 kg of this material being used per metric ton of aluminum. Although the diagram does not show it, the fluorine is lost in the electrolysis because it is released when aluminum is electro-deposited on the anode, and the only reason for adding aluminum fluoride to the electrolytic bath is to replace this loss. The sodium in the synthetic cryolite obviously comes from an input stream of sodium hydroxide, as correctly indicated by *Figure 1*. The aluminum in both chemicals is ultimately derived from bauxite, though there is actually an intermediate stage (refined alumina). However *Figure 1* completely omits any source of the element fluorine. In the real process fluorine would be derived either from hydrofluoric acid or another precursor such as fluosilicic acid. This omission is not accidental. That is, it is not a simple mistake in drawing the diagram. A detailed account of inputs and outputs to the aluminum fluoride manufacturing process is found in the Appendix of the document, again lacking any source of, or reference to, fluorine. The omission is hardly unimportant: Fluorine in air emissions is the single most dangerous pollutant in the aluminum reduction process.

It is likely — virtually certain — that the inconsistent data came from an unpublished, "confidential" or "proprietary" industry source. The omission of fluorine was probably sheer carelessness, compounded by ignorance on the part of whoever was collecting the data. But the practice of disguising the source of such data obscures a more fundamental problem: namely the fact that process descriptions available from published sources are nearly always *unbalanced* i.e. inconsistent and thus physically impossible. Fluorine compounds cannot be produced by a process without a fluorine input. Such a diagram, or the accompanying table — presented without backup calculations or references — cannot be trusted. Nor can any LCA based on it. Nor can the document in which it is found. Nor, to be blunt, can one trust any LCA produced by a similar procedure.

It cannot be argued that the above examples are rare exceptions, or that the authors did the best possible job in the circumstances. The damage is self-inflicted. It arises from an inappropriate preoccupation with energy and a blind unreasonable trust in unverifiable data from "confidential" sources. Moreover, it is perfectly possible to do better. If data are missing, there are often ways of filling in the missing data, at least approximately, *without assuming physical impossibilities*. I discuss this topic next.

Materials/Energy Balance Principle

The laws of physics tell us that mass flows into and out of each process, in steady state, *must* balance. This must be true for both large units and small ones, for each nation, for each region, for each industry and each factory. It must also be true for each unit process, and the balance must apply to each chemical element.

The first law of thermodynamics — conservation of mass-energy — is applicable to every process and every process network. It is therefore applicable to every firm and every industry that is in a steady state. This means, in words, that, for every process or process-chain, the mass of inputs (including any unpriced materials from the environment) must exactly equal the mass of outputs, including wastes. For continuous process, this balance condition must hold for any arbitrary time period.¹ The materials balance condition is much more powerful than it appears at first glance, since chemical elements do not transmute under normal terrestrial conditions. Taking this into account, the balance condition holds independently for each chemical element. Moreover, in many processes, non-reactive chemical components, such as process water and atmospheric nitrogen, can also be independently balanced. Thus half a dozen, or more, independent materials balance constraints may have to be satisfied for each steady-state process.

¹ The case of batch processes or continuous processes with time variability, requires more careful consideration. In general, however, the accounting rule holds: stock changes equal inputs minus outputs. When stock changes are zero, or can be neglected, inputs equal outputs.

A point of some importance here is that, even if the balances are partly based on theory and not always on direct measurement, the additional conditions imposed by the balancing requirement leave far less room for uncertainty than an unbalanced process would do. In short, systematic use of materials balance conditions can increase the accuracy of empirical data by reducing error-bounds. Alternatively, the materials balance conditions can be used to "fill in" missing data.

Recall the process for manufacturing ethyl chloride described briefly in the last section. According to the published process description, the reaction requires 488 kg of ethylene and 625 kg of hydrogen chloride to yield 1 metric ton (1000 kg) of ethyl chloride [50]. The process inputs add up to 1113 kg. It seems that 113 kg of mass has disappeared from the output side of the process. More precisely, there 113 kg of waste products need to be accounted for. What might these waste products be?

But we can narrow things down by comparing inputs and outputs one element at a time. Inputs of carbon, hydrogen and chlorine, in that order, were 417 kg, 87 kg and 607 kg. Subtracting outputs accounted for in the ethyl chloride product, we have unaccounted for outputs of 45 kg C, 58 kg Cl and 9 kg H. Presumably, the waste (or by-product) stream consists of a number of other compounds of these three elements. In actual fact, according to the same source, the major component of this waste stream should be ethylene dichloride ($C_2H_4Cl_2$). However, if all the excess chlorine ended up in ethylene dichloride the mass of ethylene dichloride would be 81 kg, leaving a bit over 24 kg of C and a bit under 6 kg of H. This comes close — but not quite close enough — to the specification for ethylene. In other words, to make

everything come out even, i.e. to get all the reactive elements recombined, a more complex solution is necessary.

One can test various other hypotheses, one by one. Suppose all the leftover chlorine (58 kg) is used up in making ethylene dichloride. Based on the chemical formula given above, it is easy to verify that this would use up a little less than 12 kg of C and 1 kg of H, leaving just over 33 kg of C and 8 kg of H. This combination of masses would work if all the carbon remained in the form of unreacted ethylene (38.5 kg) leaving 2.5 kg of hydrogen gas, Or, suppose all the chlorine were left in the form of unreacted hydrogen chloride? In this case 58 kg of chlorine would use up about 1.7 kg of H, leaving 45 kg of C and 7.3 kg of H. But, even if the carbon and hydrogen combined as methane (CH_4) the available hydrogen could only combine with 22 kg of carbon, leaving 23 kg uncombined (as carbon black?).

Neither of the above hypotheses seems likely, but that is not the point. Notice that all of these possible outcomes can be tested using materials balance information and simple chemical combinations alone, without even knowing the reaction conditions. No deep knowledge of chemistry — the probabilities and rates of reaction — was involved.

Of course, there are many theoretically possible combinations of chemicals in the waste stream that would satisfy the materials balance conditions. But the number of possibilities is much smaller than the number of impossibilities. The latter, at least, can be eliminated from further consideration. In fact, one can do much better

by introducing additional data and constraints. The materials balance condition is not the only one that is applicable. The energy conservation condition is another. The energy conservation condition states that the so-called "free energy" (or "available work") used in any endothermic process steps must either be supplied from exothermic processes or by external heat or electricity inputs. Indeed the second law of thermodynamics also implies a constraint that can be expressed as an "entropy conservation" condition: it states that the entropy of process outputs minus the entropy of process inputs must equal the entropy generated by the process itself.

These additional constraints are quite complex to apply in practice.

Nevertheless, knowing the thermodynamic properties of the various reactants in a process it is possible to predict their probabilities and rates of reaction as a function of various external conditions (temperature, pressure, electric field). Using this kind of information, far more detailed predictions of complex chemical reaction paths are possible today. In fact, much of this knowledge has been programmed into software packages available even for desk-top computers (e.g. Aspen Plus[®]). In short, it is now feasible to estimate the *molecular* composition of waste streams from the composition of process inputs and approximate knowledge of reaction conditions, notably temperatures, pressures and catalysts.

The logic of materials balance also applies at higher levels of aggregation. There are numerous situations where enough data is available from conventional administrative or accounting sources to permit the missing items to be calculated with high precision. For example, *Figure 2* shows a schematic materials balance for

a chemical product. There are 16 distinct mass flows, labelled A through Q. Mass flows A through F represent quantities for which economic statistics are normally available. These are, respectively, domestic (or local) production, by-products of other domestic production processes, net transfers from stock, net imports, dissipative uses and conversion uses. The last two add up to total domestic consumption; however the allocation between them requires some market data that may not be published. The 10 streams G through Q, represent other pathways for the chemical, as shown on the schematic. There are five steady-state materials balance conditions that can be used to reduce the number of unknowns. These are as follows:

$$1) G = A + B + C + D - E - F \text{ (steady-state supply)}$$

$$2) F = L + M$$

$$3) G = H + I$$

$$4) E = J + K$$

$$5) O = P + Q$$

This set of equations leaves just 5 unknowns to be determined by means of process data, especially including treatment processes. As noted, flux G, namely aggregate wastes from the domestic (or local) production process, can be computed most accurately by using accounting data. This is available (in principle) to a plant manager who wants to know, though is not likely to be available to outsiders. However, G can also be estimated from process simulation models — like Aspen

Plus® — that are generally available to chemical engineers, as mentioned above.

Thus, there are external means of verification.

Next, flux H represents wastes from the domestic production process that are treated on site by impoundment or conversion to a harmless form. This can be determined from the throughput of the treatment process (which must be known to the plant manager, and should also be available to the regulatory agency). An outsider with some knowledge of the process technology would also be able to make use of simulation models for verification purposes. Untreated emissions (flux I) would thus be the difference between G and H. (Direct measurement is a much less reliable means of determination in many cases because of the inherent difficulties involved in detecting small quantities of substances in inhomogeneous, non-isotropic streams of mixed wastes).

Similarly, the amount of the chemical actually converted into other downstream products, L, can be estimated quite accurately by the on-site process engineer — or by computerized process models available to outsiders — from knowledge of the downstream conversion process yield. The unconverted fraction of inputs must then be treated (flux M) or discharged (flux N). Again, M can be estimated most accurately from the throughput of the treatment or disposal process in use in connection with the conversion process (if any), leaving N as the difference. The same logic applies to dissipative uses. In some cases, at least, it is possible to treat an effluent stream from a dissipative uses, such as solvents, used motor oil or detergents. The stream J accounts for such cases, while K is the

untreated remainder. Finally, the same logic applies to the indirect flux O, of which some (P) may be treated, leaving an untreated remainder Q.

Again, direct measurement of emissions is potentially helpful as a means of verifying treatment efficiency process data, but that it cannot be relied upon as the exclusive means of determining aggregate waste flows, especially from dispersed consumption streams. The foregoing scheme can be applied to the estimation of aggregate waste streams at various levels, from the process or product, to the plant, the industry, or the nation.

Evaluation: Déjà Vu?

As noted previously, most of the discussion of LCA methodology currently concerns evaluation methodology rather than data. To give credit where it is due, it is generally recognized that different environmental impacts ("chalk and cheese") cannot be legitimately compared. As the PWMI concedes, "unless the comparison is 'like with like' the judgment cannot be valid" [51]. Yet, having said this, many studies proceed to reduce all dimensions of the problem to but a single measure. Most commonly, this measure is energy use or "energy efficiency". For instance, virtually all of the studies commissioned or cited by PWMI compare plastic products with others exclusively in terms of energy efficiency. One of the most cited studies is that by Hocking [52], comparing polystyrene with paper cups.

The current generation of LCA practitioners appears to have forgotten some important history. During the mid-1970's, when there was a considerable amount of public concern about energy availability and potential scarcity, many of the same people strongly advocated "net energy analysis" (NEA) as a kind of quick and dirty alternative to economic benefit cost analysis (BCA). The proposals ranged from the relatively modest notion that NEA would be a useful *supplement* to BCA to the much more extreme idea that NEA would be a superior alternative to BCA. It should be sufficient to point out that there is no reasonable objection to the former. However, the latter notion amounts to espousing an energy theory of value.

The idea that energy would be a better measure of value than money is not new. It has been proposed many times in the past by non-economists of various stripes. Frederick Soddy, the 1921 Nobel laureate in chemistry, wrote several books on the subject and actually started a political party in the 1930's, based on the energy theory of value. Howard Odum, an ecologist, is the best known of the more recent proponents of the idea [53]. The most sophisticated argument in favor of net energy analysis as a substitute for economic valuation (at the macro-level only) makes one major point: NEA accurately measures the use and depletion of resources that are used in the economy to do useful work, whereas monetary figures are distorted by other factors [54], [55], [56].

However, the above argument for energy analysis — whatever its merits — does not justify the use of net energy as a proxy for environmental damage. Internal

inconsistencies in the energy theory of value have been pointed out by economists, since Soddy's time. While markets are often imperfect, it has been proven long ago that, in cases where markets do work well, they allocate resources in a Pareto-optimal manner. To the extent that net energy analysis would imply a different allocation, it would lead to suboptimal results (e.g. [57]). The literature on this issue is extensive, and need not be reviewed here in detail.

The notion of substituting some single measure of environmental impact (other than monetary value) nevertheless continues to be extremely seductive to ecologists, physicists, geographers and various other non-economists. Apart from "net energy", the most popular idea seems to be a "scoring model" of some sort, in which "eco-points" are awarded (or subtracted) for each kind of environmental impact. Other candidates have been put forward with varying degrees of enthusiasm. One of the most pertinent comments that can be made about such schemes is that they are numerous and generally inconsistent with each other [58]. Again, any of these alternatives can be thought of as either a supplement or as a substitute for monetary valuation. Again, there can be no serious objection to the former. In fact, in this spirit, all of the proposed measures can be used together. (But, of course, none of them would then be unique).

However, none of the suggested measures is a plausible substitute for monetary valuation, at least in the realm where economic analysis is applicable, namely where there are (or can be) efficient markets for the exchange of mutually substitutable goods and services, or even of rights and/or privileges of access to services. There

are some economists who appear to believe that this realm of actual or potential monetary valuation encompasses virtually everything. Others are willing to concede that there are limits to monetization, viz. where environmental services — or access to them — cannot be contained, quantified or exchanged and environmental disservices cannot be compensated by equivalent economic services. (I am one of the minority that belongs to the second camp).

It must be said, however, that even in the realm where markets are inherently non-functional, economists would not welcome a "scoring model" or any non-monetary theory of value (e.g. [59]). What they would generally accept, however, is a multi-objective decision-theoretic approach, following in the footsteps of Keeney & Raiffa [60], as developed further by others (e.g. [61]). The modern version is generally known as "risk-benefit analysis" in contrast to "cost benefit analysis". This framework has been adapted to the LCA case recently by Field and Ehrenfeld [62].

Summary of Conclusions

In summary, the methods and models underlying both many published LCA's and many scenario-building efforts are inadequate to their stated purposes. The problems of LCA's are (1) failure to publish underlying process data attributable to credible sources, (2) failure to impose materials balance conditions on inventory data (often because of unnecessary and confusing attempts to distinguish energy carriers

from feedstocks) and (3) unjustified attempts to substitute implicit energy (or other) inappropriate theories of value for market-based valuation.

To cure (or, at least, abate) the data-related problems it is suggested that LCA "codes of practice" should insist on the use of common mass units and mass balances for all inputs and outputs displayed in the inventory phase of the analysis. Material inputs and waste emissions should be characterized explicitly in terms of elemental composition, at least, and chemical composition wherever feasible.

Process data should be published in material-balanced form, even in cases where firms claim proprietary secrecy. In fact, standardized process design models exist and are used by most of the world's large chemical firms. A standard set of conditions could be prescribed, for instance by the ISO, for presentation of printouts from these models. (The major element of secrecy is the process yield and details of the reactor operating conditions and catalyst. "Possible" versions of the process, satisfying all necessary physical constraints, could be presented without any breach of confidence. In fact, this approach has been used successfully for many years by SRI in its Chemical Economics Program).

More data on metal and chemical production and consumption should be published. The old Census rule that data is suppressed when it might reveal proprietary information (i.e. when three or fewer firms are producing the material) is obsolete. First of all, competition is now worldwide, so that U.S. based firms are in a world market. Second, there is no good reason for governments to protect proprietary information on behalf of oligopolies. In any event, such interests can be

protected in other ways, by averaging² over all establishments using the process, extending (if necessary) beyond national boundaries. This should be done at the national level when more than three firms use the same process. However, the averaging could also be extended to the EEC region as a whole in cases where *any* of the member countries have three or fewer competing firms using a given process.

Only with the help of a formal tool like LCA is it possible to make rational judgments on the relative environmental load of competing end-use products or competing processes for producing a given product. The case for (or against) recycling in specific cases also depends on such analysis. This is not to suggest, however, that the desired tool actually exists, except in very primitive form.

There is currently an effort to standardize the methodology by industry-sponsored organizations, such as the Society for Environmental Toxicology and Chemistry (SETAC) and the International Standards Organization (ISO). These efforts may be premature. Regrettably, the formalized LCA methodology that has been widely promulgated by industry groups (such as SETAC) is deeply flawed. It is based on the false notion that environmental impacts are largely attributable to energy consumption. Because of this fatal bias, the protocol for data presentation adopted by virtually all current practitioners (mostly former analysts by background) are inherently incapable of verification by the only means available: a mass-balance accounting system. In consequence, the practitioners depend largely — if not entirely — on the validity of process and emissions data obtained from "confidential"

² The average should, of course, be weighted by the level of output of each producer.

industry sources. Such sources cannot be relied upon. In far too many cases, detailed examination reveals glaring internal inconsistencies. No methodology based on unverifiable (and often erroneous) data can ever be accepted as an objective basis for comparing products or policies. The danger is that LCA itself will be discredited.

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**Table 1: Materials Balance for Basic Coking Process
from IIASA's IDEAS Database**

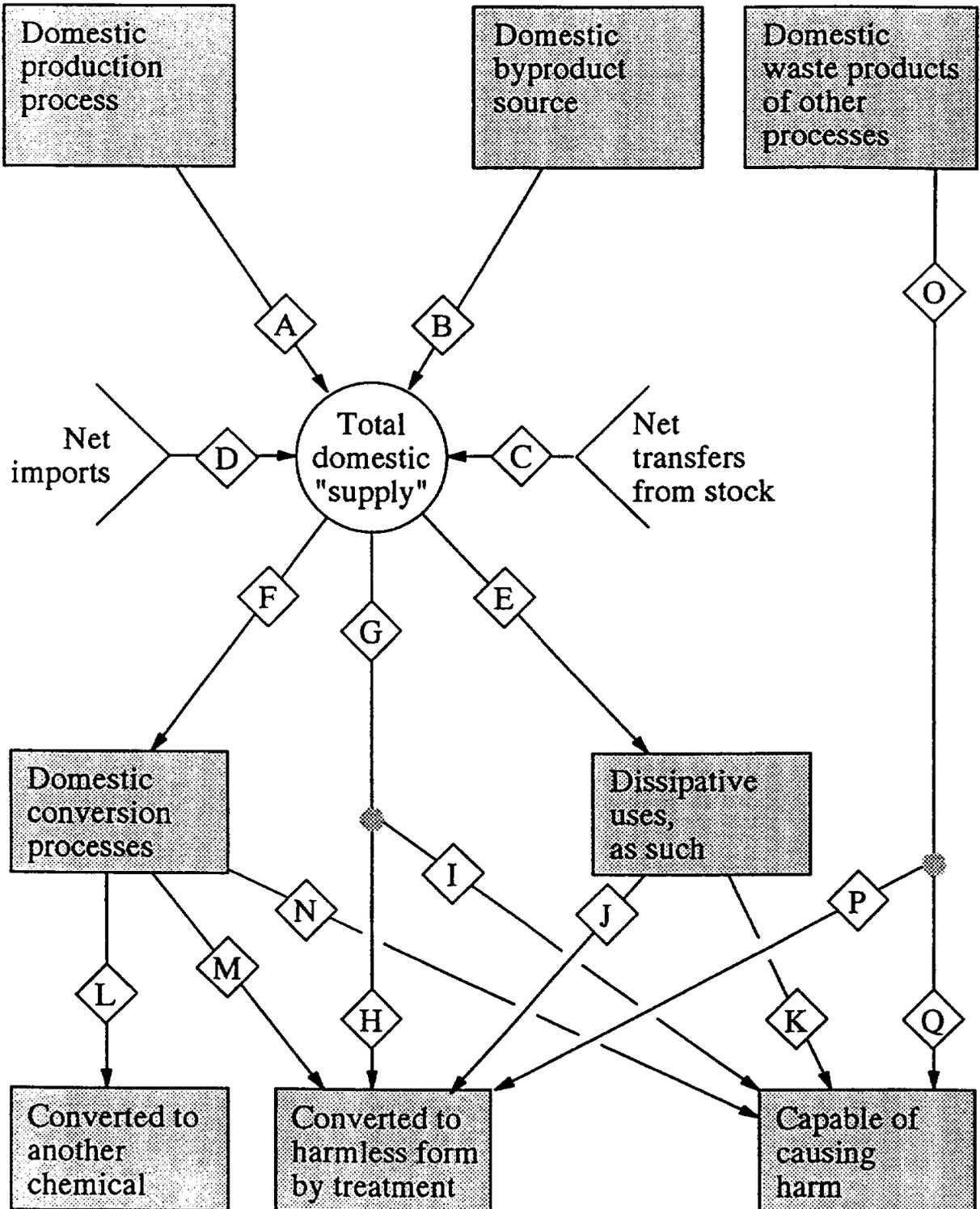
UTILITY INPUTS			
	Electricity		0.0426 Kwh
	Heat		4.393 GJ
Quantities below in mass units per 1 mass unit of output (Coke)			
INPUTS		OUTPUTS	
Water, process	12.48	Water, process	12.333
Air, process	1.60	Water, waste	0.05
		Steam (output)	0.35
		Carbon dioxide (CO ₂)	0.0175
		Sulfur dioxide (SO ₂)	0.00150
		Carbon monoxide (CO)	0.00120
		NO _x	0.000700
		BOD ₅	0.000640
		VOC	0.000300
	<hr/>		<hr/>
Subtotal	14.08		12.75
Coal, coking	1.41	Coke (unit output)	1.00
		Ammonia, process (NH ₃)	0.682
		Tar	0.530
		Offgas, coking	0.250
		Coke breeze	0.163
		Oil, light crude	0.133
		TSP	0.00100
		TSS	0.000170
		Cyanides	0.000056
		Oil & grease	0.000010
		Cadmium (Cd)	0.00000002
	<hr/>		<hr/>
Subtotal	1.41		2.76
TOTAL	15.49		15.51

Table 2: Ecobalances of Plastics

Balance per kg plastics	Unit	HD-PE	LD-PE	PET	PP	PS	HI-PS	PVC
<i>Used materials</i>								
Petroleum	[g]	1964.21	1966.42	4014.37	1964.21	3493.89	3406.56	906.35
Hydrogen	[g]	1.88	1.88	23.52	1.88	6.48	6.20	0.87
Oxygen	[g]			527.00				
Rock salt	[g]							1016.43
NaOH	[g]			0.45				
By-products	[g]			-1303.85		-321.32	-301.55	-716.28
By-products with calor.value	[g]	-945.46	-9.50	-2103.20	-946.96	-2189.44	-2116.51	-458.19
Adjuvants, additives	[g]	9.00	3.78	0.06	1.30	35.05	35.11	7.17
Miscellaneous	[g]	5.00		20.07				
<i>Energy carriers (excl. transp. + electr. prod.)</i>								
Fuel gas	[dm3]	255.35	255.63	189.00	227.00	108.00	114.00	192.56
Residues with calorific value	[g]	418.49	418.96	652.00	381.43	407.00	406.00	193.11
Steam	[kg]	-3.29	-3.96	0.32	-1.45	2.11	2.23	0.89
<i>Energy balance</i>								
Energy from material input	[MJ]	44.36	43.74	35.10	43.66	40.93	41.37	17.24
Process energy	[MJ]	19.00	16.94	38.74	21.98	29.88	30.44	20.14
Auxiliary plants	[MJ]	0.17	0.19	0.60	0.35	0.21	0.24	0.67
Precombustion	[MJ]	-0.96	-1.15	0.15	-0.40	0.64	0.68	0.33
<i>Total production</i>								
Thermal energy	[MJ]	62.57	59.72	74.59	65.59	71.66	72.73	38.37
Electric energy	[kWh]	0.53	0.88	1.04	0.57	0.38	0.41	1.34
E eq as per UCPTTE 88	[MJ]	67.6	68.1	84.5	71.0	75.3	76.6	51.1
<i>Disposal</i>								
Credit WIP	[MJ]	-20.78	-20.78	-15.07	-21.12	-19.15	-19.20	-8.64
Transportation	[MJ]	0.04	0.04	0.04	0.04	0.04	0.04	0.04
<i>Total production & Disposal</i>								
	[MJ]	41.83	38.98	59.56	44.52	52.55	53.57	29.77
	[kWh]	0.53	0.88	1.04	0.57	0.38	0.41	1.34
E eq as per UCTPE 88	[MJ]	46.9	47.3	69.5	50.0	56.2	57.5	42.5

Source: [48]

Figure 1: "Material flow chart of aluminium production"
 (Production of aluminium after the Bayer-process)



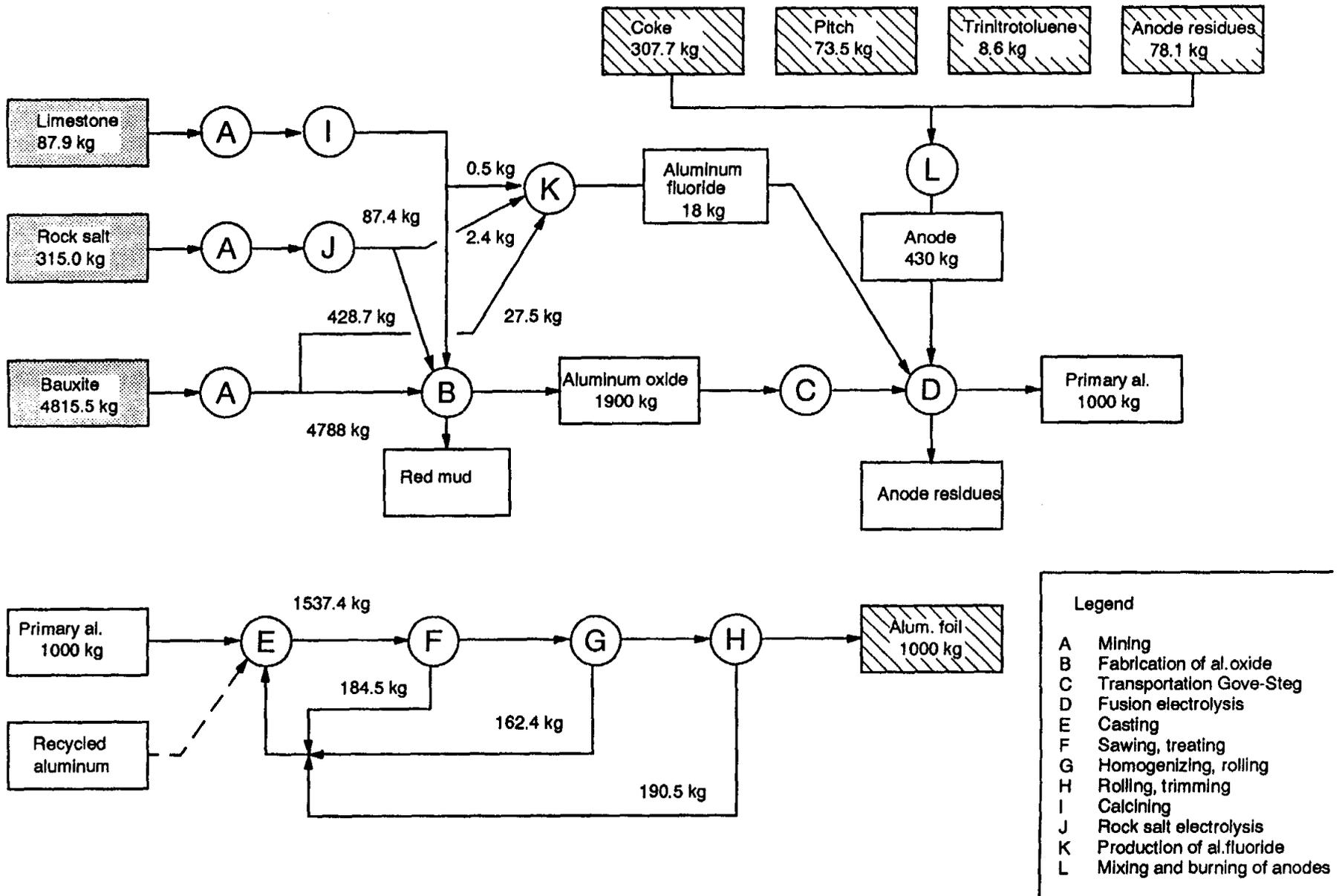


Figure 2: "Materials balance for a chemical product"