Life Cycle Inventory Analysis (LCIA)

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1. INTRODUCTION

The development of industrial technology has enabled the transformation of the environment in different ways, changing the nature and extent of the environmental impacts of industrial activities. Resource depletion, air, water and land pollution, are examples of the environmental problems which have emerged as a result of intensified interventions into the environment. The chemical and process industries find themselves constantly under the scrutiny of various pressure groups demanding more environmentally acceptable processes, products and practices through the ideas of `waste minimization', `zero emission', `producer responsibility', etc. One of the potential dangers of this is that the companies exposed to environmental pressures may simply respond to satisfy a particular group. However, this short-term approach may lead to costly long term mistakes with little environmental improvement and no net business benefit. To avoid this, environmental issues must be assessed in a holistic way, along side financial, technical and other criteria (Azapagic, 1999).

A product's life cycle starts when raw materials are extracted from the earth, followed by manufacturing, transport and use, and ends with waste management including recycling and final disposal. At every stage of the life cycle there are emissions and consumption of resources. The environmental impacts from the entire life cycle of products and services need to be addressed. To do this, life cycle thinking is required.

Life Cycle Assessment (LCA) is a tool for the systematic evaluation of the environmental aspects of a product or service system through all stages of its life cycle. The assessment begins with the raw materials input, proceeds through the manufacturing processes, energy use, maintenance, and transportation. It considers use, reuse, and recycling, and concludes with waste management, the environmental impact of packaging, and ultimate disposal of the product (Azapagic, 1996). LCA provides an adequate instrument for environmental decision support. Life cycle assessment has proven to be a valuable tool to document the environmental considerations that need to be part of decision-making towards sustainability. A reliable LCA performance is crucial to achieve a life-cycle economy.

The Fig. 1 shows the interactions of various stages of LCA (Susan, 1995). The key elements of LCA are given below:

1. Identifies and quantifies the environmental loads involved; e.g. the energy and raw materials consumed, the emissions and wastes generated (Life Cycle Inventory Analysis).
2. Evaluates the potential environmental impacts of these loads (Life Cycle Impact Assessment).
3. Assesses the options available for reducing these environmental impacts (Interpretation of Life Cycle Inventory analysis and Impact Assessment).

In the present study mainly focus on Life Cycle Inventory analysis (LCIA)

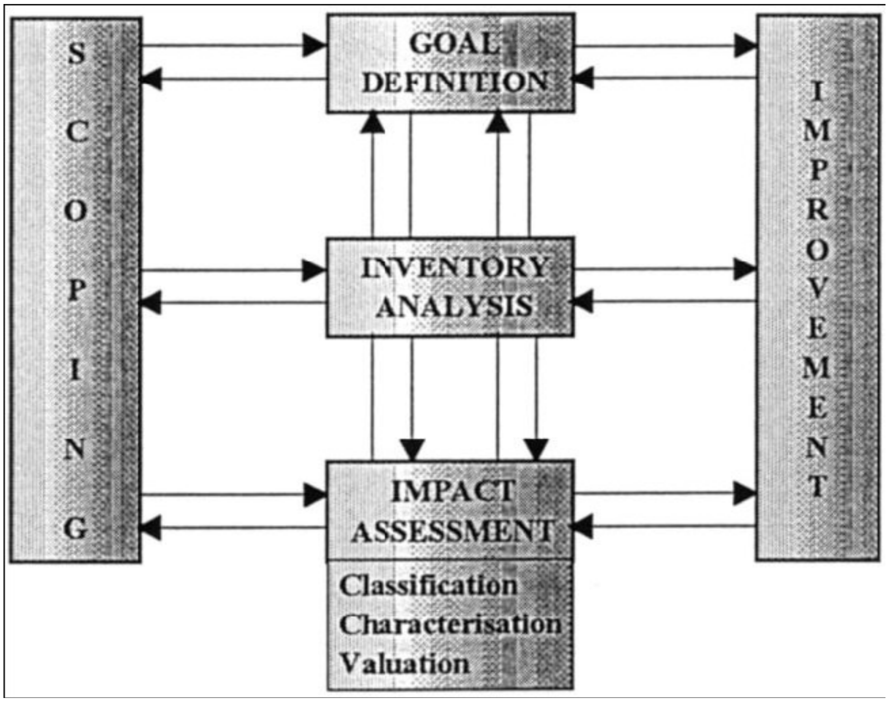


Fig. 1. Interaction between LCA stages

In the second, Inventory Analysis stage, material and energy balances are performed and the environmental burdens are quantified. The burdens are defined by resource consumption and emissions to air, water and solid waste. Aggregation of the burdens into a smaller number of impact categories (Classification) is done in the Inventory Analysis stage. In the present study mainly focus on Life Cycle Inventory analysis (LCIA).

2. LIFE CYCLE INVENTORY ANALYSIS (LCIA)

Life Cycle Inventory Analysis (LCIA) is a part of the Life Cycle Assessment (LCA), a thorough procedure accounting for the environmental loads during the product's life cycle (Babu and Ramkrishna, 2003). Inventory Analysis is a systematic, objective, stepwise procedure for quantifying energy and raw materials requirement, atmospheric emissions, water borne emissions, solid wastes, and other releases for the entire life cycle of a product, package process, material or activity (Manjare and Babu, 2005). LCIA is a process of data collection and calculations intended to quantify the inputs and outputs of a product system. These inputs and outputs may include resources used, as well as release to air, water, or land (SAIC, 2006).

An inventory may be conducted to aid in decision making by enabling companies or organizations to:

- Develop a baseline for a system's overall resource requirements for benchmarking efforts.
- Identify components of the process that are good targets for resource-reduction efforts
- Aid in the development of new products or processes that will reduce resource requirements or emissions.

- Compare alternative materials, products, processes, or activities within the organization.
- Compare internal inventory information to that of other manufacturers.

Managers using LCA to aid decision-making can improve the validity of the results and keep the analysis focused by precisely defining the scope of the "system" to be analyzed, considering practical constraints such as time and money. This step builds the foundation for the analysis that follows and should be understood and agreed upon by those responsible for commissioning the study. A system refers to a collection of operations that together perform some defined function. The system begins with all the raw materials taken from the environment and ends with the outputs released back to the environment as shown in Fig. 2 (Susan, 1995).

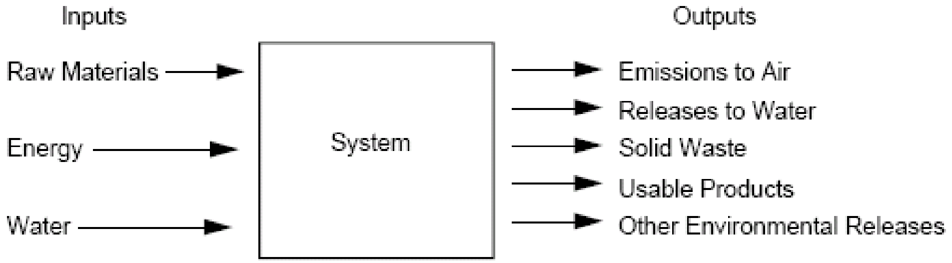
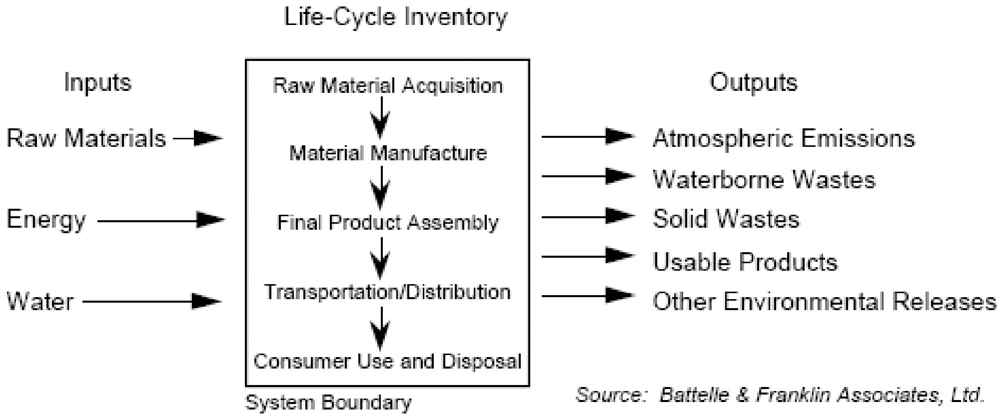


Fig.2. Input and output of a system.

Within most systems, three main groups of operations may be defined:

1. Operations for the production, use, transportation, and disposal of the product.
2. Operations for the production of ancillary materials such as packaging
3. The energy production needed to power the system.

A clearly defined scope will improve the results of subsequent steps when the total process is divided into subsystems. An example of typical subsystem categories is shown in Fig. 3 (Susan, 1995).



Source: Battelle & Franklin Associates, Ltd.

Fig. 3. Defining System Boundaries.

The linkages between subsystems make the process of collecting consistent measurements complex. For example, subsystems must be defined so that they are large enough to provide sufficient data for analysis but not so large that data is aggregated at a level that precludes detailed analysis. In addition, subsystems should be linked by a standard basis of comparison such as equivalent usage ratios.

A thorough understanding of how an inventory analysis is conducted, and the limitations and assumptions inherent in the various stages is critical to effective use of LCA in decision making. The following is a synopsis of the various subsystems analyzed in an inventory analysis.

2.1. Raw Materials Acquisition

Data are collected for this subsystem on all activities required to obtain raw materials, including transportation of the materials to the point of manufacture as shown in Fig. 4 (Susan, 1995).

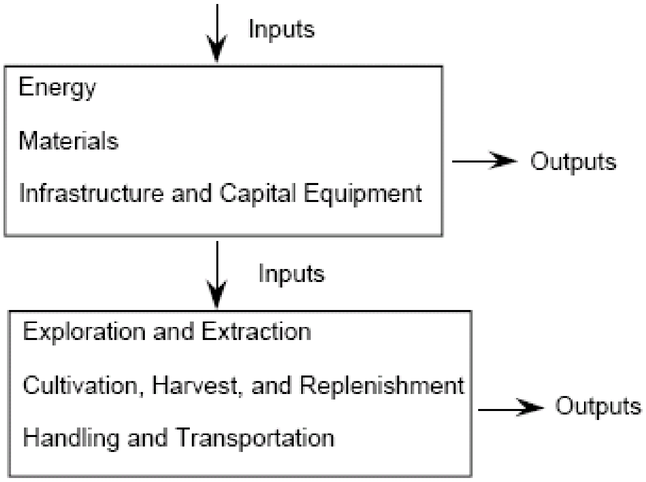


Fig. 4. Raw material acquisition subsystem.

Typically, raw materials are traced for the primary product and all primary, secondary and tertiary packaging. Managers should review the data to make sure equivalent comparisons are used. For example, a package containing recycled materials may need increased thickness to compensate for the decreased strength of recycled materials. In this case, managers must make a tradeoff between weight of materials that will someday become part of the waste stream and virgin material content. The inventory should also include all inputs of energy, materials, and equipment necessary for acquiring each raw material. Because this dramatically increases the complexity of the analysis, criteria must be determined to eliminate insignificant contributions. This may be done by establishing a threshold for inclusion. For example, any component contributing less than five percent of inputs might be ignored.

Ecosystems are impacted in many ways by the extraction or harvesting of raw materials, but only those effects that can be quantified, such as pesticide run-off from agriculture or soil loss from logging, should be included in the inventory. Effects that cannot be easily measured, such as loss of scenic or aesthetic value, may be covered in the more subjective impact assessment. At this point, attempts to quantify renewable or nonrenewable resources for inventory calculations are subjective, as quantifiable data is not publicly available. However, maintaining separate lists of renewable and nonrenewable materials may be helpful if an impact assessment is later performed.

Energy acquisition is actually part of the materials-acquisition subsystem, but because of the complexity of the subject, it warrants its own analysis. Data collected should include all energy requirements and emissions attributed to the acquisition, transportation, and processing of fuels. This means that if gasoline is used as a transportation fuel, not only should emissions related to combustion be included, but also energy consumption and emissions due to extraction and refining. In the U.S., energy is derived from a number of sources including coal, natural gas, petroleum, hydropower, nuclear power, and wood. Utilities use many different types of energy sources to produce electricity, so the energy analysis must include a determination of the fuel mix used to generate the electricity. Generally, the national average fuel mix may be used, but industry-specific information is preferred.

Some materials are made from energy resources and are therefore assigned an energy value. For example, plastics, made from petroleum and natural gas, release energy when burned. This energy value is credited against the system requirements for the primary product, resulting in a new energy requirement that is less than the total energy requirements for the system.

2.2. Manufacture and Fabrication

Data collected for this subsystem includes all energy, material, or water inputs and environmental releases that occur during the manufacturing processes required to convert each raw material input into intermediate materials ready for fabrication. This process may be repeated for several streams of resources as well as several intermediate cycles before final fabrication of the product as shown in Fig. 5 (Susan, 1995).

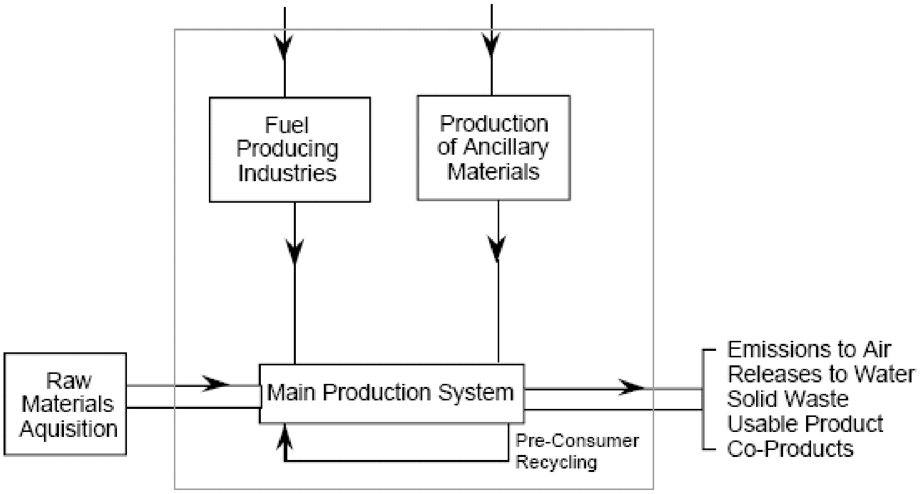


Fig. 5. Manufacturing and fabrication system.

Often co-products – outputs that are neither products nor inputs elsewhere in the system – are generated in the manufacturing process. Co-products are included in LCA until they are separated from the primary product being analyzed. Raw materials, energy, and emissions should be allocated between the primary product and the co-products by their proportionate weight or volume. If scrap within one subsystem is used as an input within the same subsystem, the raw material or intermediate material required from the outside is reduced and should be factored into the analysis. If industrial scrap is used in another subsystem, it is considered to be a co-product and should be allocated to the same consumption and emission rates required to produce the primary material. Some scrap is simply discarded and should be counted as solid waste.

Differences in technology throughout the industry require certain assumptions to be made at this stage. Comparisons between different-size facilities, differing ages of equipment, different capacity-utilization rates, and differing energy consumption per unit of production must be made explicit.

The data collected for final product fabrication assesses the consumption of inputs and the emissions required to convert all materials into the final product ready for consumer purchase. Calculations follow the same procedure as in converting raw material to intermediate materials and include the same limitations.

Data collected for fabrication of the final product includes the inputs and releases associated with filling and packaging operations. As this is a necessary step for virtually any product, this step focuses on differences between processes or materials being compared. If the filling procedure is identical for the two products being compared, this step can be ignored. Both primary and secondary packaging must be included in the calculations, taking care to keep packaging per unit consistent between alternatives.

2.3. Transportation/Distribution

An inventory of the related transportation activities of the product to warehouses and end-users may be simplified by using standards for the average distance transported and the typical mode of transportation used as shown in Fig. 6 (Susan, 1995).

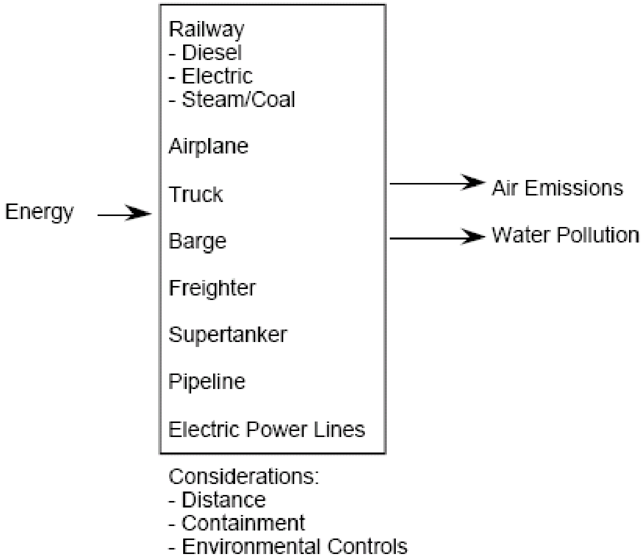


Fig. 6. Transportation/Distribution system.

Inventory of the distribution process includes warehousing, inventory control, and repackaging. Environmental controls such as refrigeration are components of both transportation and distribution. As in previous stages, clear boundaries must be established to define the extent to which issues such as building and maintaining transportation and distribution equipment will be factored into the inventory results.

2.4. Consumer Use/Disposal

Data collected for this subsystem cover consumer activities including use (product consumption, storage, preparation, or operation), maintenance (repair), and reuse is shown in Fig. 7.

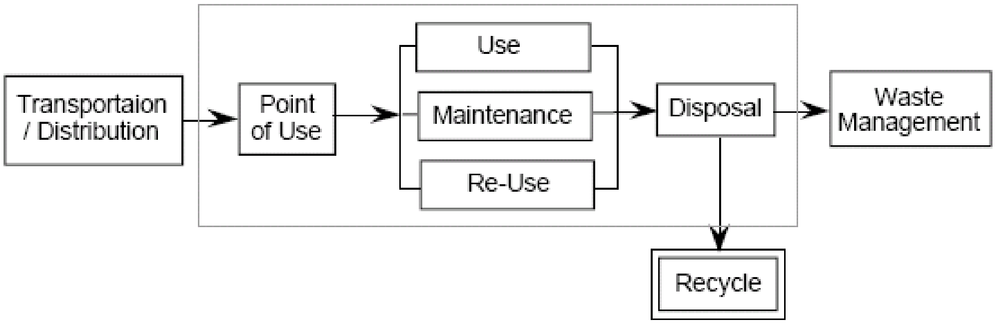


Fig. 7. Consumer use/disposal system.

Issues to consider when defining the scope of the subsystem include:

- Time of product use before it is discarded.
- Inputs used in the maintenance process.
- The typical frequency of repair.
- Potential product reuses options.

Managers should incorporate into the analysis any industry information on typical consumer usage patterns that may make the study's results more valid. For example, consumers may occasionally use two thinner paper cups to attain the strength of a single comparable polystyrene cup. Sources of data that may help this process include consumer surveys, published materials, and assumptions. Inventory reports must include documentation of assumptions including the timeliness of the data, potential biases, and other limitations.

Various disposal alternatives exist such as reuse, recycling, composting, incineration, and landfilling. Transportation and collection of post-consumer waste should also be included in the analysis. Inventories often use a national estimate of waste management methods, citing current averages for the percentage of waste disposed of by landfilling, recycling, and incineration methods.

2.5. Recycling

Recycling technology is expected to improve greatly in the future. Therefore, content levels and recycling rates should always be reported at current rates with documentation of study dates. Advances in technology will both increase rates and the number of products that are recyclable, altering both open and closed-loop recycling options as shown in Fig. 7 (Susan, 1995).

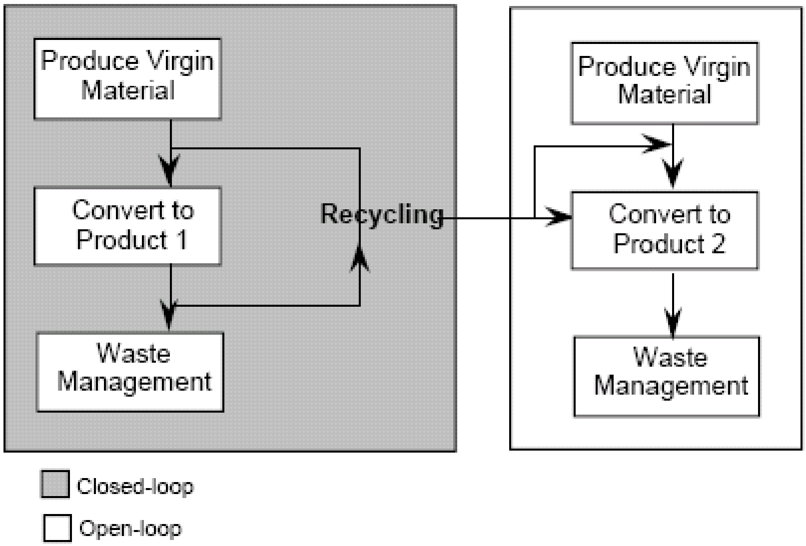


Fig. 8. Recycling subsystem

Open-loop recycling means that a product is recycled into a different product that is disposed of after use. In these cases, the resource requirements and environmental emissions related to the recycling and final disposal of the recycled material is divided equally between the two products produced.

Closed-loop recycling refers to materials that can be recycled into the same product repeatedly. This means that the more times the product is recycled, the less virgin material is required and the greater the number of cycles over which the resources and emissions can be allocated. The environmental effects of a closed-loop product will approach zero over the life of the product. For some products, a recycling infrastructure already exists, providing data on the collection, transportation, and processing of its materials. But for many products such information does not exist, leading to the use of data extrapolated from pilot programs or forecasts.

Wastes may be defined as materials that have no intrinsic or market value. Waste occurs in some form at every stage of the life cycle. Careful analysis of waste management issues is required as disposal options vary with the seasons, geography, and the technology used by a particular facility. Further complicating the inventory is the fact that many waste streams are combinations of materials derived from several subsystems, and that waste treatment facilities may produce a variety of releases including air, water, and solid wastes. For example, reported waterborne waste data should include an analysis of the water treatment system, the land associated with the treatment system, and atmospheric and solid wastes associated with the system. Information about emissions from solid waste is more difficult to find as there is no existing method to determine the emissions of a particular product once it has been mixed with municipal waste in a landfill or incinerator. If, however, a disposal process is being used for only one type of product (e.g., composting for yard waste or recycling for aluminum cans), accurate measures are available.

3. KEY STEPS IN LIFE CYCLE INVENTORY ANALYSIS

EPA's 1993 document, "Life-Cycle Assessment: Inventory Guidelines and Principles," and 1995 document, "Guidelines for Assessing the Quality of Life Cycle Inventory Analysis," provide the framework for performing an inventory analysis and assessing the quality of the data used and the results. The two documents define the following four steps of a life cycle inventory:

1. Develop a flow diagram of the processes being evaluated.
2. Develop a data collection plan.
3. Collect data.
4. Evaluate and report results.

3.1. Develop a Flow Diagram

A flow diagram is a tool to map the inputs and outputs to a process or system. The "system" or "system boundary" varies for every LCA project. The goal definition and scoping phase establishes initial boundaries that define what is to be included in a particular LCA; these are used as the system boundary for the flow diagram. Unit processes inside of the system boundary link together to form a complete life cycle picture of the required inputs and outputs (material and energy) to the system. Fig. 9 illustrates the components of a generic unit process within a flow diagram for a given system boundary (SAIC, 2006).

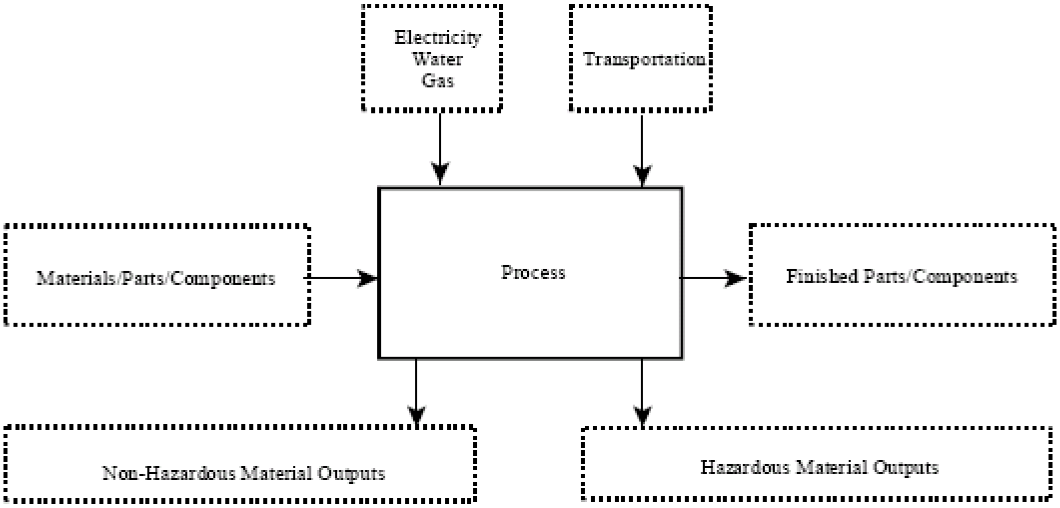


Fig. 9. Generic unit process.

The more complex the flow diagram, the greater the accuracy and utility of the results. Unfortunately, increased complexity also means more time and resources must be devoted to this step, as well as the data collecting and analyzing steps.

Flow diagrams are used to model all alternatives under consideration (e.g., both a baseline system and alternative systems). For a comparative study, it is important that both the baseline and alternatives use the same system boundary and are modeled to the same level of detail. If not, the accuracy of the results may be skewed.

For data-gathering purposes it is appropriate to view the system as a series of subsystems. A "subsystem" is defined as an individual step or process that is part of the defined production system. Some steps in the system may need to be grouped into a subsystem due to lack of specific data for the individual steps. For example, several steps may be required in the production of bar soap from tallow. However, these steps may all occur within the same facility, which may not be able to or need to break data down for each individual step. The facility could however, provide data for all the steps together, so the subsystem boundary would be drawn around the group of soap production steps and not around each individual one.

Each subsystem requires inputs of materials and energy; requires transportation of product produced; and has outputs of products, co-products, atmospheric emissions, waterborne wastes, solid wastes, and possibly other releases. For each subsystem, the inventory analyst should describe materials and energy sources used and the types of environmental releases. The actual activities that occur should also be described. Data should be gathered for the amounts and kinds of material inputs and the types and quantities of energy inputs. The environmental releases to air, water, and land should be quantified by type of pollutant. Data collected for an inventory should always be associated with a quality measure. Although formal data quality indicators (DQIs) such as accuracy, precision, representativeness, and completeness are strongly preferred, a description of how the data were generated can be useful in judging quality.

Co-products from the process should be identified and quantified. Co-products are process outputs that have value, i.e., those not treated as wastes. The value assigned to a co-product may be a market value (price) or may be imputed. In performing co-product allocation, some means must be found to objectively assign the resource use, energy consumption, and emissions among the co-products, because there is not a physical or chemical way to separate the activities that produce them. Generally, allocation should allow technically sound inventories to be prepared for products or materials using any particular output of a process independently and without overlap of the other outputs.

3.2. Develop an LCI Data Collection Plan

As part of the goal definition and scoping phase, the required accuracy of data was determined. When selecting sources for data to complete the life cycle inventory, an LCI data collection plan ensures that the quality and accuracy of data meet the expectations of the decision-makers. Key elements of a data collection plan include the following:

1. Defining data quality goals
2. Identifying data quality indicators
3. Identifying data sources and types
4. Developing a data collection worksheet and checklist.

3.2.1. Define Data Quality Goals

Data quality goals provide a framework for balancing available time and resources against the quality of the data required to make a decision regarding overall environmental or human health impact (EPA, 1986). Data quality goals are closely linked to overall study goals and serve two primary purposes:

1. Aid LCA practitioners in structuring an approach to data collection based on the data quality needed for the analysis.
2. Serve as data quality performance criteria.

No pre-defined list of data quality goals exists for all LCA projects. The number and nature of data quality goals necessary depends on the level of accuracy required to inform the decision-makers involved in the process.

3.2.2. Identify Data Quality Indicators

Data quality indicators are benchmarks to which the collected data can be measured to determine if data quality requirements have been met. Similar to data quality goals, there is no pre-defined list of data quality indicators for all LCIs. The selection of data quality indicators depends upon which ones are most appropriate and applicable to the specific data sources being evaluated. Examples of data quality indicators are precision, completeness, representativeness, consistency, and reproducibility.

3.2.3. Identify Data Sources and Types

For each life cycle stage, unit process, or type of environmental release, specify the necessary data source and/or type required to provide sufficient accuracy and quality to meet the study's goals. Defining the required data sources and types prior to data collection helps to reduce costs and the time required to collect the data. The required level of aggregated data should also be specified, for example, whether data are representative of one process or several processes.

A number of sources should be used in collecting data. Whenever possible, it is best to get well-characterized industry data for production processes. Manufacturing processes often become more efficient or change over time, so it is important to seek current data. Inventory data can be facility-specific or more general and still remain current.

Several categories of data are often used in inventories. Starting with the most disaggregated, these are:

Individual process and facility-specific: data from a particular operation within a given facility that are not combined in any way.

Composite: data from the same operation or activity combined across locations.

Aggregated: data combining more than one process operation.

Industry-average: data derived from a representative sample of locations and believed to statistically describe the typical operation across technologies.

Generic: data whose representativeness may be unknown but which are qualitatively descriptive of a process or technology.

3.2.4. Develop a Data Collection Spreadsheet

The next step is to develop a life cycle inventory spreadsheet that covers most of the decision areas in the performance of an inventory. A spreadsheet can be prepared to guide data collection and validation and to enable construction of a database to store collected data electronically. The following eight general decision areas should be addressed in the inventory spreadsheet:

1. Purpose of the inventory
2. System boundaries
3. Geographic scope
4. Types of data used
5. Data collection procedures
6. Data quality measures
7. Computational spreadsheet construction
8. Presentation of results.

The spreadsheet is a valuable tool for ensuring completeness, accuracy, and consistency. It is especially important for large projects when several people collect data from multiple sources. The spreadsheet should be tailored to meet the needs of a specific LCI. The overall system flow diagram, derived in the previous step, is important in constructing the computational spreadsheets because it numerically defines the relationships of the individual subsystems to each other in the production of the final product. These numerical relationships become the source of "proportionality factors," which are quantitative relationships that reflect the relative contributions of the subsystems to the total system.

It is important that each subsystem be incorporated in the spreadsheet with its related components and that each be linked together in such as way that inadvertent omissions and double-counting do not occur. The spreadsheet can be organized in several different ways to accomplish this purpose. These can include allocating certain fields or areas in the spreadsheet to certain types of calculations or using one type of spreadsheet software to actually link separate spreadsheets in hierarchical fashion. It is imperative, however, once a system of organization is used, that it be employed consistently. Haphazard organization of data sets and calculations generally leads to faulty inventory results.

Many decisions must be made in every life-cycle inventory analysis. Every inventory consists of a mix of factual data and assumptions. Assumptions allow the analyst to evaluate a system condition when factual data either cannot be obtained within the context of the study or do not exist. Each piece of information (e.g., the weight of paperboard used to package the soap, type of vehicle and distance for shipping the tallow, losses incurred when rendering tallow, or emissions resulting from the animals at the feedlot), fall into one or the other category and each plays a role in developing the overall system analysis. Because assumptions can substantially affect study results, a series of "what if" calculations or sensitivity analyses are often performed on the results to examine the effect of making changes in the system. A sensitivity analysis will temporarily modify one or more parameters and affect the calculation of the results.

Observing the change in the results will help determine how important the assumptions are with respect to the results. The computational spreadsheet is also used to perform these sensitivity analysis calculations.

Sometimes it is helpful to think ahead about how the results will be presented. This can direct some decisions on how the spreadsheet output is specified. The analyst must remember the defined purpose for performing the analysis and tailor the data output to those expressed needs.

3.3. Collect Data

Data collection efforts involve a combination of research, site-visits and direct contact with experts, which generates large quantities of data. As an alternative, it may be more cost effective to buy a commercially available LCA software package. Prior to purchasing an LCA software package the decision-makers or LCA practitioner should insure that it will provide the level of data analysis required.

A second method to reduce data collection time and resources is to obtain non-site specific inventory data. Several organizations have developed databases specifically for LCA that contain some of the basic data commonly needed in constructing a life cycle inventory. Some of the databases are sold in conjunction with LCI data collection software; others are stand-alone resources. Many companies with proprietary software also offer consulting services for LCA design. The use of commercial software risks losing transparency in the data. Often there is no record of assumptions or computational methods that were used. This may not be appropriate if the results are to be used in the public domain. Revisiting the goal statement is needed in order to determine if such data are appropriate.

All industrial processes have multiple input streams and many generate multiple output streams. Usually only one of the outputs is of interest for the life cycle assessment study being conducted, so the analyst needs to determine how much of the energy and material requirements and the environmental releases associated with the process should be attributed, or allocated, to the production of each co-product. For example, steam turbine systems may sell both electricity and low-pressure steam as useful products. When co-products are present, the practitioner must determine how much of the burdens associated with operating and supplying the multi-output process should be allocated to each co-product. The practitioner must also decide how to allocate environmental burdens across co-products when one is a waste stream that can be sold for other uses.

The guidance provided by the International Standards Organization (ISO) recognizes the variety of approaches that can be used to treat the allocation issue and, therefore, requires a step-wise approach. The following stepwise procedure shall be applied.

Step 1: Wherever possible, allocation should be avoided by:

- Dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes.

- Expanding the product system to include the additional functions related to the co-products, taking into account the requirements of (function, functional unit, and reference flow).

Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way which reflects the underlying physical relationships between them, i.e., they shall reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system. The resulting allocation will not necessarily be in proportion to any simple measurement such as mass or molar flows of co-products.

Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way which reflects other relationships between them. For example, input and output data might be allocated between co-products in proportion to the economic value of the products. The flow diagram(s) developed in Step-1 provides the road map for data to be collected.

Step 2 specifies the required data sources, types, quality, accuracy, and collection methods. Step 3 consists of finding and filling in the flow diagram and worksheets with numerical data. This may not be a simple task. Some data may be difficult or impossible to obtain, and the available data may be difficult to convert to the functional unit needed. Therefore, the system boundaries or data quality goals of the study may have to be refined based on data availability. This iterative process is common for most LCAs.

3.3.1. Inputs in the Product Life-Cycle Inventory Analysis

The decision on which raw/intermediate material requirements to include in a life-cycle inventory is complex, but several options are available:

- Incorporate all requirements, no matter how minor, on the assumption that it is not possible *a priori* to decide to exclude anything.
- Within the defined scope of the study, exclude inputs of less than a predetermined and clearly stated threshold.
- Within the defined scope of the study, exclude inputs determined likely to be negligible, relative to the intended use of the information, on the basis of a sensitivity analysis.
- Within the defined scope, consistently exclude certain classes or types of inputs, such as capital equipment replacement.

The advantage of the first option is that no assumptions are made in defining and drawing the system boundary. The analyst does not have to explain or defend what has been included or excluded. The disadvantage is that application of this approach could be an endless exercise. The number of inputs could be very large and could include some systems only distantly related to the product system of interest. Besides the computational complexity, interpretation of the results with respect to the single desired product, package, or activity could be difficult.

The second option, if implemented with full explanation of what the threshold is and why it was selected, would have the advantages of consistency and lower cost and time investments. Two sub-options can be identified, depending on the nature of the threshold. One sub-option is to specify a percentage contribution below which the material will be excluded, for example, one percent of the input to a given subsystem or to the entire system. The one percent rule historically has been useful in limiting the extent of the analysis in inventories where the environmental consequences of quantitatively minor materials are not considered. The disadvantage of the one percent rule is that the possible presence of an environmentally damaging activity associated with these materials could be overlooked. Also, when used with mixed percentages (e.g., percent of system energy, percent of subsystem input), the result may be confusing or inconsistent. The scoping analysis should provide a rationale for choosing to apply such a rule.

The second sub-option is to set a threshold based on the number of steps that the raw/intermediate material is removed from the main process sequence. Caustic manufacture from brine electrolysis is part of the main process sequence and would clearly be included. Sodium carbonate is an input material for the production of caustic is therefore a secondary input. Applying a "one-step back" decision rule would include the steps associated with sodium carbonate production. Ammonium chloride is an input material for the production of sodium carbonate using the Solvay process. Relative to caustic, ammonium chloride is a tertiary input and would be excluded if a "one-step back" decision rule were applied. As in the first option, the "one-step back" decision rule has the advantages of clarity and consistent application. For some inputs that are analyzable in exact mathematical terms, the "one-step back" rule may be justifiable. If the inputs to a given process bear a fixed relationship to the next-tier process, one step is all that may be necessary to obtain a sufficiently accurate value (Boustead and Hancock 1979).

The third option, drawing boundaries based on sensitivity analysis, adds the advantage of being systematic rather than arbitrary in assigning the threshold. The disadvantages of a sensitivity analysis-based approach are that the analyst needs to be very clear in describing how the analysis was used and, unless a large existing database is available to supply preliminary values that can be used in the sensitivity analysis, the required analysis effort may not be limited by a very large amount.

The final option, excluding certain classes or types of input, also has been found through experience to apply to many systems. The advantage of this option is that many complex subsystems can often be excluded. The disadvantages are the same as those for the first option, namely, that a highly significant activity may be eliminated. Capital equipment is the most commonly excluded input type. The analyst should perform a preliminary analysis to characterize the basic activities in each class or type of input to ensure that a significant contribution is not left out.

3.3.1.1. Energy

Energy represents a combination of energy requirements for the subsystem. Three categories of energy are quantifiable: process, transportation, and energy of material resources (inherent energy).

Process energy is the energy required to operate and run the subsystem process(es), including such items as reactors, heat exchangers, stirrers, pumps, blowers, and boilers. Transportation energy is the energy required to power various modes of transportation such as trucks, rail carriers, barges, ocean vessels, and pipelines. Conveyors, forklifts, and other equipment that could be considered with transportation or process are labeled according to their role in the subsystem. For example, power supplied to a conveyor used to carry material from one point in the subsystem would be labeled process energy. On the other hand, the power supplied to a conveyor used to transport material from one subsystem to a different subsystem would be considered transportation energy.

Two alternatives exist for incorporating energy inputs in a subsystem module. One is to report the actual energy forms of the inputs, e.g., kilowatt-hours (kWh) of electricity or cubic feet of natural gas. The other is to include the specific quantities of fuels used to generate the produced energy forms in the module.

The advantage of the first approach is that the specific energy mix is available for each subsystem. For example, a company may want to evaluate the desirability of installing a natural gas-fired boiler to produce steam compared to using its electrically heated boiler powered by a combination of purchased and on-site generated electricity. A specific fuel mix could be applied to compute the energy and fuel resource use. The second approach, incorporating specific fuel quantities, allows a subsystem comparison of primary energy fuels.

Within each subsystem, the energy input data should be given as specific quantities of fuel and then converted into energy equivalents according to the conversion factors.

3.3.1.2. Energy Sources

Energy is obtained from a variety of sources, including coal, nuclear power, hydropower, natural gas, petroleum, wind, solar energy, solid waste, and wood biomass. Fuels are interchangeable, to a high degree, based on their energy content. For example, an electric utility decides which fuel or other energy source to use based on the cost per energy unit. Utilities can and do use multiple forms of energy sources, making possible an economic decision based on the energy cost per kilowatt-hour of electricity generated. Manufacturing companies also choose among energy sources on the same basis. However, reasons other than cost, such as scarcity or emissions to the environment, also affect the energy source decision. For example, during periods of petroleum shortages, finding products that use predominantly non-petroleum energy sources may be desirable. For that reason, the inventory should characterize energy requirements according to basic sources of energy. Thus, it would consider not only electricity, but also the basic sources (such as coal, nuclear power, hydropower, natural gas, and petroleum) that produce the electricity.

3.3.1.3. Water

Water volume requirements should be included in a life-cycle inventory analysis. In some locations, water is plentiful. Along the coasts, seawater is usable for cooling or other manufacturing purposes. However, in other places water is in short supply and must be allocated for specific uses. Some areas have abundant water in some years and limited supplies in other years. Some industrial applications reuse water with little new or makeup water required. In other applications, however, tremendous amounts of new water inputs are required.

How should water be incorporated in an inventory?

The goal of the inventory is to measure, per unit of product, the gallons of water required that represent water unavailable for beneficial uses (such as navigation, aquatic habitat, and drinking water). Water withdrawn from a stream, used in a process, treated, and replaced in essentially the same quality and in the same location should not be included in the water-use inventory data. Ideally, water withdrawn from groundwater and subsequently discharged to a surface water body should be included, because the groundwater is not replaced to maintain its beneficial purposes. Data to make this distinction may be difficult to obtain in a generic study where site-specific information is not available.

In practice, the water quantity to be estimated is net consumptive usage. Consumptive usage as a life-cycle inventory input is the fraction of total water withdrawal from surface or groundwater sources that either is incorporated into the product, co-products (if any), or wastes, or is evaporated. As in the general case of renewable versus nonrenewable resources, valuation of the degree to which the water is or is not replenishable is best left to the impact assessment.

3.3.2. Outputs of the Product Life-Cycle Inventory Analysis

A traditional inventory qualifies three categories of environmental releases or emissions: atmospheric emissions, waterborne waste, and solid waste. Products and co-products also are quantified. Most inventories consider environmental releases to be actual discharges (after control devices) of pollutants or other materials from a process or operation under evaluation. Inventory practice historically has included only regulated emissions for each process because of data availability limitations. It is recommended that analysts collect and report all available data in the detailed tabulation of subsystem outputs. In a study not intended for product comparisons, all of these pollutants should be included in the summary presentations.

A comparative study offers two options. The first is to include in the summary presentation only data available for alternatives under consideration. The advantage of this option is that it gives a comparable presentation of the loadings from all the alternatives. The disadvantage is that potentially consequential information, which is available only for some of the alternatives, may not be used. The second option is to report all data whether uniformly available or not. In using this option, the analyst should caution the user not to draw any conclusions about relative effects for pollutants where comparable data are not available. “Comparable” is used here to mean the same pollutant.

For example, in a summary of data on a bleached paper versus plastic packaging alternatives, data on dioxin emissions may be available only for the paper product. The second option is recommended for internal studies and for external studies where proper context can be provided.

3.3.2.1. Atmospheric Emissions

Atmospheric emissions are reported in units of weight and include all substance classified as pollutants per unit weight of product output. These emissions generally have included only those substances required by regulatory agencies to be monitored but should be expanded where feasible. The amounts reported represent actual discharges into the atmosphere after passing through existing emission control devices. Some emissions, such as fugitive emissions from valves or storage areas, may not pass through control devices before release to the environment. Atmospheric emissions from the production and combustion of fuel for process or transportation energy (fuel-related emissions), as well as the process emissions, are included in the life-cycle inventory.

Typical atmospheric emissions are particulates, nitrogen oxides, volatile organic compounds (VOCs), sulfur oxides, carbon monoxide, aldehydes, ammonia, and lead. This list is neither all-inclusive nor is it a standard listing of which emissions should be included in the life-cycle inventory. Recommended practice is to obtain and report emissions data in the most speciated form possible. Some air emissions, such as particulates and VOCs, are composites of multiple materials whose specific makeup can vary from process to process. All emissions for which there are obtainable data should be included in the inventory. Therefore, the specific emissions reported for any system, subsystem, or process will vary depending on the range of regulated and non-regulated chemicals.

Certain materials, such as carbon dioxide and water vapor losses due to evaporation (neither of which is a regulated atmospheric emission for most processes), have not been included in most inventory studies in the past. Regulations for carbon dioxide are changing as the debate surrounding the greenhouse effect and global climate change continues and the models used for its prediction are modified. Inclusion of these emerging emissions of concern is recommended.

3.3.2.2. Waterborne Wastes

Waterborne wastes are reported in units of weight and include all substances generally regarded as pollutants per unit of product output. These wastes typically have included only those items required by regulatory agencies, but the list should be expanded as data are available. The effluent values include those amounts still present in the waste stream after wastewater treatment, and represent actual discharges into receiving waters. For some releases, such as spills directly into receiving waters, treatment devices do not play a role in what is reported. For some materials, such as brine water extracted with crude oil and reinjected into the formation, current U.S. regulations do not define such materials as waterborne wastes, although they may be considered in solid waste regulations under the Resource Conservation and Recovery Act (RCRA). Other liquid wastes may also be deep well injected and should be included. In general, the broader definition of emissions in a life-cycle inventory, in contrast to regulations, would favor inclusion of such streams. It can be argued, from a systems analysis standpoint, that materials such as brine should count as releases from the subsystem because they cross the subsystem boundary. If wastes and spills that occur are discharged to the ocean or some other body of water, these values are always reported as wastes.

As with atmospheric wastes, waterborne wastes from the production and combustion of fuels (fuel-related emissions), as well as process emissions, are included in the life-cycle inventory.

Some of the most commonly reported waterborne wastes are biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solids, dissolved solids, oil and grease, sulfides, iron, chromium, tin, metal ions, cyanide, fluorides, phenol, phosphates, and ammonia. Again, this listing of emissions is not meant to be a standard for what should be included in an inventory. Some waterborne wastes, such as BOD and COD, consist of multiple materials whose composition can vary from process to process. Actual waterborne wastes will vary for each system depending on the range of regulated and non-regulated chemicals.

3.3.2.3. Solid Waste

Solid waste includes all solid material that is disposed from all sources within the system. Solid wastes typically are reported by weight. A distinction is made between industrial solid wastes and post-consumer solid wastes, as they are generally disposed of in different ways and, in some cases, at different facilities. *Industrial solid waste* refers to the solid waste generated during the production of a product and its *Post-consumer solid waste* refers to the product/packaging once it has met its intended use and is discarded into the municipal solid waste stream.

Process solid waste is the waste generated in the actual process, such as trim or waste materials that are not recycled, as well as sludges and solids from emissions control devices. *Fuel-related waste* is solid waste produced from the production and combustion of fuels for transportation and operating the process. Fuel combustion residues, mineral extraction wastes, and solids from utility air control devices are examples of fuel-related wastes.

3.3.2.4. Products

The products are defined by the subsystem and/or system under evaluation. In other words, each subsystem will have a resulting product, with respect to the entire system. This subsystem product may be considered either a raw material or intermediate material with respect to another system, or the finished product of the system. All other material outputs (not released as wastes or emissions) are considered co-products. Classifying a material as a product in a life-cycle study depends, in part, on the extent of the system being examined, i.e., the position from which the material is viewed or the analyst's point of view.

3.3.2.5. Transportation

The life-cycle inventory includes the energy requirements and emissions generated by the transportation requirements among subsystems for both distribution and disposal of wastes. Transportation data are reported in miles or kilometers shipped. This distance is then converted into units of ton-miles or ton-kilometers, which is an expression involving the weight of the shipment and the distance shipped. Materials typically are transported by rail, truck, barge, pipeline, and ocean transport. The efficiency of each mode of transport is used to convert the units of ton-miles into fuel units (e.g., gallons of diesel fuel). The fuel units are then converted to energy units, and calculations are made to determine the emissions generated from the combustion of the fuels.

3.3.2.6. Co-Product Allocation

Most industrial processes are physical and/or chemical processes. The fundamentals of life-cycle inventory are based on modeling a system in such a way that calculated values reasonably represent actual (measurable) occurrences. Some processes generate multiple output streams in addition to waste streams. In attributional LCAs, only certain of these output streams are of interest with respect to the primary product being evaluated. The term co-product is used to define all output streams other than the primary product that are not waste streams and that are not used as raw materials elsewhere in the system examined in the inventory. Co-products are of interest only to the point where they no longer affect the primary product, i.e. the product that is part of the life cycle system being studied. Subsequent refining of co-products is beyond the scope of the analysis, as is transport of co-products to facilities for further refining. A basis for co-product allocation needs to be selected with careful attention paid to the specific items calculated. Each industrial system must be handled on a case-by-case basis since no allocation basis exists that is always applicable. In effect, the boundary for the analysis is drawn between the primary product and co-products, with all materials and environmental loadings attributed to co-products being outside the scope of the analysis. The first step is to investigate any complex process in detail and attempt to identify unit sub-processes that produce the product of interest. If sufficient detail can be found, no co-product allocation will be necessary.

If a process produces several different chemical products, care must be taken in the analysis. It will be necessary to write balanced chemical equations and trace the chemical stoichiometry from the raw materials into the products. A simple mass allocation method frequently gives reasonable results, but not always. In calculating energy, heat of reaction may be the appropriate basis for allocating energy to the various co-products.

For environmental emissions from a multiple-product process, allocation to different co-products may not be possible. It has been suggested that the selling price of the co-products could be used as a basis for this allocation. Because the selling prices of the various co-products can vary greatly with time and with independent competitive markets for each co-product, a market-based approach would have to accommodate such variations, by using an average value ranged over several years, or similar method.

One important role of an inventory is to provide information upon which impact assessment and improvement analysis can be based. In cases where there is no clear methodological solution, the inventory should include reasonable alternative calculations or apply sensitivity analysis to determine the effect of allocation on the final results. It remains at some later time to make the judgments as to which of several reasonable alternatives is the correct one. In any event, it should be made clear what assumptions were made and what procedures were used.

3.3.2.7. Industrial Scrap

One co-product stream of particular interest is *industrial scrap*. This term is used to specifically identify process wastes of value (trim scraps and off-spec materials) that are produced as an integral part of a manufacturing process. Further, the wastes have been collected and used as input materials for additional manufacturing processes. The last criterion is that these scrap materials have never been used as originally intended when manufactured. For example, a common polyurethane foam product is seat cushions for automobiles. The trim from cutting the cushions is never incorporated into seat cushions. Likewise, off-spec seat cushions sold as industrial scrap are never used as seat cushions, but are used as input material for another process.

A careful distinction must be made between industrial scrap and post-consumer waste for proper allocation in the inventory. If the industrial scrap is to be collected and used as a material input to a production system or process, it is credited in the life-cycle inventory as a co-product at the point where it was produced. Unfortunately, systems that use material more efficiently, i.e., that produce lesser amounts of salable co-products, assume a higher percentage of the upstream energy and releases using the criterion.

When the consumption of a co-product falls within the boundaries of the analysis, it must no longer be considered as a co-product, but as a primary product carrying with it all the energy requirements and environmental releases involved with producing it, beginning with raw materials acquisition.

3.3.2.8. Data Time Period

The time period that data represents should be long enough to smooth out any deviations or variations in the normal operations of a facility. These variations might include plant shutdowns for routine maintenance, startup activities, and fluctuation in levels of production. Often data are available for a fiscal year of production, which is usually a sufficient time period to cover such variations.

3.3.2.9. Specific Data versus Composite Data

When the purpose of the inventory is to find ways to improve internal operations, it is best to use data specific to the system that is being examined. These types of data are usually the most accurate and also the most helpful in analyzing potential improvements to the environmental profile of a system. However, private data typically are guarded by a confidentiality agreement, and must be protected from public use by some means. Composite, industry-average data are preferable when the inventory results are to be used for broad application across the industry, particularly in studies performed for public use.

Although composite data may be less specific to a particular company, they are generally more representative of an industry as a whole. Such composite data can also be made publicly available, are more widely usable, and are more general in nature. Composite data can be generated from facility-specific data in a systematic fashion and validated using a peer review process. Variability, representativeness, and other data quality indicators can still be specified for composite data.

3.3.2.10. Geographic Specificity

Natural resource and environmental consequences occur at specific sites, but there are broader implications. It is important to define the scope of interest (regional vs. national vs. international) in an inventory. A local community may be more interested in direct consequences to itself than in global concerns.

3.3.2.11. Data Categories

Environmental emission databases usually cover only those items or pollutants required by regulatory agencies to be reported. For example, as previously mentioned, the question of whether to report only regulated emissions or all emissions is complicated by the difficulty in obtaining data for unregulated emissions. In some cases, emissions that are suspected health hazards may not be required to be reported by a regulatory agency because the process of adding them to the list is slow. A specific example of an unregulated emission is carbon dioxide, which is a greenhouse gas suspected as a primary agent in global warming. There is no current requirement for reporting carbon dioxide emissions, and it is difficult to obtain measured data on the amounts released from various processes. Thus, results for emissions reported in a life-cycle inventory may not be viewed as comprehensive, but they can cover a wide range of pollutants. As a rule, it is recommended that data be obtained on as broad a range as possible. Calculated or qualitative information, although less desirable and less consistent with the quantitative nature of an inventory, may still be useful.

3.3.2.12. Routine/Fugitive/Accidental Releases

Whenever possible, routine, fugitive, and accidental emissions data should be considered in developing data for a subsystem. If data on fugitive and accidental emissions are not available, and quantitative estimates cannot be obtained, this deficiency should be noted in the report on the inventory results. Often estimates can be made for accidental emissions based on historical data pertaining to frequency and concentrations of accidental emissions experienced at a facility.

3.3.2.13. Special Case Boundary Issues

In all studies, boundary conditions limiting the scope must be established. The areas of capital equipment, personnel issues, and improper waste disposal typically are not included in inventory studies, because they have been shown to have little effect on the results. Earlier studies did consider them in the analysis; later studies have verified their minimal contribution to the total system profile. Thus, exclusion of contributions from capital equipment manufacture, for example, is not excluded *a priori*. The decision to include or not to include them should be clearly noted by the analyst.

3.3.3. Economic Input-Output Approach to LCIA

Economic Input/Output offers an alternative way to create life cycle inventory. The input/output model divides an entire economy into distinct sectors and represents them in table, or matrix, form so that each sector is represented by one row and one column. The matrix represents sales from one sector to another. The economic input-output model is linear so that the effects of purchasing $1,000 from one sector will be ten times greater than the effects of purchasing $100 from that sector.

In order to create life cycle inventory, the economic output for each sector is first calculated, then the environmental outputs are calculated by multiplying the economic output at each stage by the environmental impact per dollar of output. The advantage of the economic input/output approach is that it quickly covers an entire economy, including all the material and energy inputs, thereby simplifying the inventory creation process. Its main disadvantage is that the data are created at high aggregate levels for an entire industry, such as steel mills, rather than particular products, such as the type of steel used to make automobiles.

"Hybrid" models which combine the economic input/output model with process models have also been proposed in order to utilize the advantages offered by both approaches (Hendrickson *et al.*, 2006).

3.4. Evaluate and Document the LCI Results

When writing a report to present the final results of the life-cycle inventory, it is important to thoroughly describe the methodology used in the analysis. The report should explicitly define the systems analyzed and the boundaries that were set. All assumptions made in performing the inventory should be clearly explained. The basis for comparison among systems should be given, and any equivalent usage ratios that were used should be explained.

Life-cycle inventory studies generate a great deal of information, often of a disparate nature. The analyst needs to select a presentation format and content that are consistent with the purpose of the study and that do not arbitrarily simplify the information solely for the sake of presenting it. In thinking about presentation of the results, it is useful to identify the various perspectives embodied in life-cycle inventory information. These dimensions include, but may not be limited to, the following:

- Overall product system
- Relative contribution of stages to the overall system
- Relative contribution of product components to the overall system
- Data categories within and across stages, e.g., resource use, energy consumption, and environmental releases
- Data parameter groups within a category, e.g., air emissions, waterborne wastes, and solid waste types
- Data parameters within a group, e.g., sulfur oxides, carbon dioxide, chlorine, etc.
- Geographic regionalization if relevant to the study, e.g., national versus global
- Temporal changes.

The life-cycle analyst must select among these dimensions and develop a presentation format that increases comprehension of the findings without oversimplifying them. Two main types of format for presenting results are tabular and graphical.

Sometimes it is useful to report total energy results while also breaking out the contributions to the total from process energy and energy of material resources. Solid wastes can be separated into post-consumer solid waste and industrial solid waste. Individual atmospheric and water pollutants should be reported separately. Atmospheric emissions, waterborne wastes, and industrial solid wastes can also be categorized by process emissions/wastes and fuel-related emissions/wastes. Such itemized presentations can assist in identifying and subsequently controlling certain energy consumption and environmental releases.

The results from the inventory can be presented most comprehensibly in tabular form. The choice of how the tables should be created varies, based on the purpose and scope of the study. If the inventory has been performed to help decide which type of package to use for a particular product, showing the overall system results will be the most useful way to present the data. On the other hand, when an analysis is performed to determine how a package can be changed to reduce its releases to the environment, it is important to present not only the overall results, but also the contributions made by each component of the packaging system. For example, in analyzing a liquid delivery system that uses plastic bottles, it may be necessary to show how the bottle, the cap, the label, the corrugated shipping box, and the stretch wrap around the boxes all contribute to the total results. The user can thus concentrate improvement efforts on the components that make a substantial contribution when evaluating proposed changes.

Graphical presentation of information helps to augment tabular data and can aid in interpretation. Both bar charts (either individual bars or stacked bars) and pie charts are valuable in helping the reader visualize and assimilate the information from the perspective of “gaining ownership or participation in life-cycle assessment” (Werner 1991). However, the analyst should not aggregate or sum dissimilar data when creating or simplifying a graph.

For internal industrial use by product manufacturers, pie charts showing a breakout by raw materials, process, and use/disposal have been found useful in identifying waste reduction opportunities.

For external studies, the data must be presented in a format that meets one fundamental criterion - clarity. Ensuring clarity requires that the analyst ask and answer questions about what each graph is intended to convey. It may be necessary to present a larger number of graphs and incorporate fewer data in each one. Each reader should understand the desired response after viewing the information.

Once the data has been collected and organized into one format or another, the accuracy of the results must be verified. The accuracy must be sufficient to support the purposes for performing the LCA as defined in the goal and scope.

4. Interpretation of Data

Life cycle interpretation is a systematic technique to identify, quantify, check, and evaluate information from the results of the LCI and the LCIA, and communicate them effectively. Life cycle interpretation is the last phase of the LCA process.

International Standard Organization (ISO) has defined the following two objectives of life cycle interpretation:

1. Analyze results, reach conclusions, explain limitations, and provide recommendations based on the findings of the preceding phases of the LCA, and to report the results of the life cycle interpretation in a transparent manner.
2. Provide a readily understandable, complete, and consistent presentation of the results of an LCA study, in accordance with the goal and scope of the study.

The first step of the life cycle interpretation phase involves reviewing information from the first three phases of the LCA process in order to identify the data elements that contribute most to the results of both the LCI and LCIA for each product, process, or service, otherwise known as "significant issues."

The results of this effort are used to evaluate the completeness, sensitivity, and consistency of the life cycle inventory analysis. The identification of significant issues guides the evaluation step. Because of the extensive amount of data collected, it is only feasible within reasonable time and resources to assess the data elements that contribute significantly to the outcome of the results.

Before determining which parts of the LCI and LCIA have the greatest influence on the results for each alternative, the previous phases of the LCA should be reviewed in a comprehensive manner (e.g., study goals, ground rules, impact category weights, results, external involvement, etc.). Review the information collected and the presentations of results developed to determine if the goal and scope of the LCA study have been met. If they have, the significance of the results can then be determined. Determining significant issues of a product system may be simple or complex. For assistance in identifying environmental issues and determining their significance, the following approaches are recommended:

Contribution Analysis - the contribution of the life cycle stages or groups of processes are compared to the total result and examined for relevance.

Dominance Analysis - statistical tools or other techniques, such as quantitative or qualitative ranking, are used to identify significant contributions to be examined for relevance.

Anomaly Assessment - based on previous experience, unusual or surprising deviations from expected or normal results are observed and examined for relevance.

Significant issues can include:

1. Inventory parameters like energy use, emissions, waste, etc.
2. Impact category indicators like resource use, emissions, waste, etc.
3. Essential contributions for life cycle stages to LCI or LCIA results such as individual unit processes or groups of processes (e.g., transportation, energy production).

The evaluation step of the interpretation phase establishes the confidence in and reliability of the results of the LCA. This is accomplished by completing the following tasks to ensure that products/processes are fairly compared:
Completeness Check - examining the completeness of the study.
Sensitivity Check - assessing the sensitivity of the significant data elements that influence the results most greatly.
Consistency Check - evaluating the consistency used to set system boundaries, collect data, make assumptions, and allocate data to impact categories for each alternative.

The objective of this step is to interpret the results of the life cycle impact assessment (not the life cycle inventory analysis) to determine which product/process has the overall least impact to human health and the environment, and/or to one or more specific areas of concern as defined by the goal and scope of the study.

5. CASE STUDY – 1: ENVIRONMENTAL IMPACT MINIMIZATION ISSUES IN BATCH / SEMI-CONTINUOUS PLANTS (Stefanis et al., 1997)

A key characteristic of batch plants is their inherent operational flexibility in utilizing available resources (equipment, utilities, production time). This feature introduces an extra complexity in the design of such plants, since design considerations are interlinked with operational/scheduling aspects. This, in turn, implies that waste generation in batch plants depends on both design and scheduling decisions over a time horizon, related to product sequencing, task scheduling, need for cleaning as well as type and sizes of equipment. Another key issue for consistent environmental impact assessment is the need to translate waste generation over time to some measure of environmental damage as well as to account for input wastes (to the process) and their interactions with output waste generation. Consider for instance the simplified process in Fig. 10, which is part of a cottage cheese production chain (Crooks, 1992).

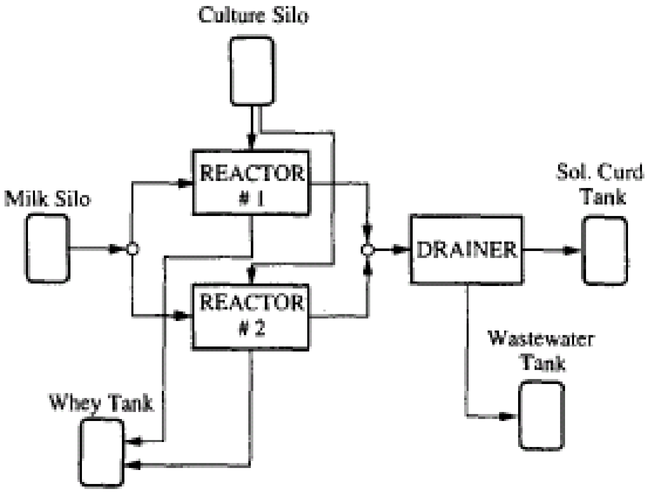


Fig. 10. Batch plant for motivating example.

Milk is mixed with culture in two vat processors to produce curd cheese, an intermediate cheese state, and whey by-product. The curd yield depends on fat, casein and moisture content of the input milk (Lucey and Kelly, 1994). The curd is then drained to produce the required amount of cheese. Pollution is due to the organic matter in the drainer effluent, which slowly oxidizes under bacterial and chemical action creating oxygen demand. The Biological Oxygen Demand (BOD) of that waste water stream is increased due to the skim milk intake loss (approximately equal to 4-5% weight) and strongly depends on the input milk fat content, as confirmed by statistical analysis of experimental values (Purnell and Flagg, 1984). A single campaign operating policy is assumed with a cyclic four-hour schedule repeated over a production time of 5508 h/y in order to generate 275.4 tons curd. Task information such as duration, type of input (I) and output (O) states from each task and their corresponding mass fractions and unit characteristics are given in Tables 1 and 2. For example, O Solcurd implies that Solidified Curd is an output from the task Drain, it is produced 30 min after the task starts and its mass fraction at the exit of the task is 0.9. Input milk costs £0.16 /kg, whereas the curd product is sold at £0.655/kg.

Table-1. Task information for motivating example.

TASK	Duration (min)	In-out state	In-out time (min)	In-out fraction
Vat Proc	240	I culture	0	0.12
		I milk	0	0.88
		O Whey	240	x(F*)
		O Curd	240	1- x(F)
Drain	30	I curd	0	1.0
		O Solcurd	30	0.9
		O Waste Water	30	0.1

* % wt of milk fat

Table-2. Unit characteristics for motivating example

Units	Capacity (kg)		Costs	
	Minimum	Maximum	Fixed (k£)	Variable (k£)
Vat 1	50	1100	75	0.45
Vat 2	50	1800	81	0.5
Drainer	5	225	45	0.3
Milk Silo	-	14,100	15	0.1
Culture Silo	-	10,000	15	0.1
Whey Tank	-	10,000	15	0.1
Waste link	-	10,000	15	0.1
Sol. Curd Tank	-	10,000	15	0.1

Table-3. Batch plant design alternatives.

	Case 1	Case 2
	Units capacity (kg)	
Vat 1	1100	1100
Vat 2	787	1476
Drainer	130	128
Milk Silo	1661	2267
Culture Silo	227	310
Whey Tank	1665	2353
Waste Tank	23	23
Sol. Curd Tank	200	200
Milk Fat Content (% wt) Total Annual Cost (k£) BOD of Effluent (kg/cycle)	1.4 548.75 8.29	0.05 681.82 7.01

Table 3 and Fig. 11 depict two design alternatives (and their schedules) corresponding to the solution of the following cases:
Case 1: minimization of total annualised cost (TAC in £/y)
Case 2: minimization of *BOD* in the waste water stream (kg).

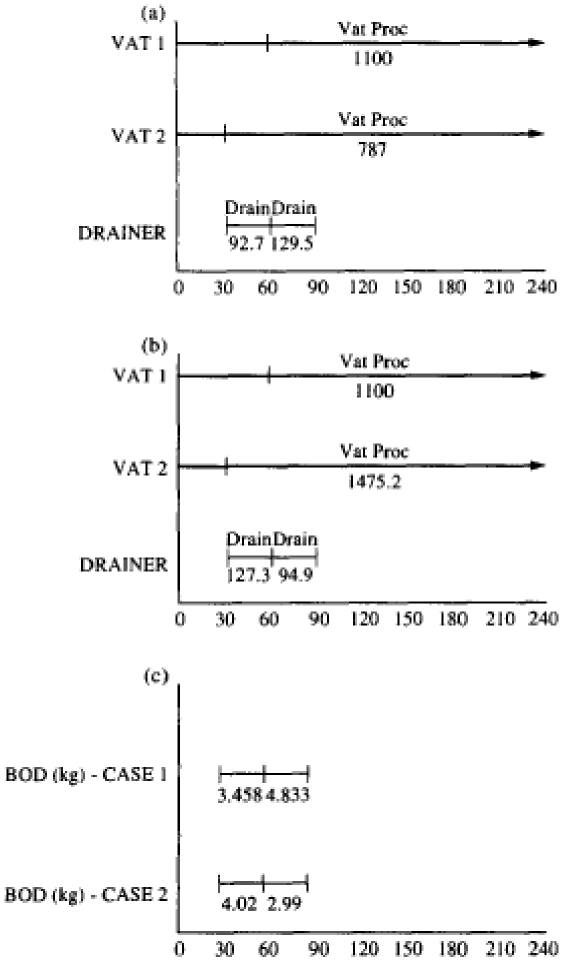


Fig. 11. Optimal schedules and waste generation of motivating example.

A careful examination of these results reveals a number of interesting features:
Waste emissions are due to the operation of the drainer, which is operational only 25% of the batch cycle time (see Fig. 11c); thus, unlike continuous plants in which waste output can be quantified on an hourly basis, in batch plants the horizon time, the mode of operation and the specific scheduling pattern over time, all should be simultaneously taken into account in properly quantifying waste output (in some aggregated over time form).

On a waste mass discharge basis, the two designs are almost equivalent: i.e. 23 kg of wastewater per cycle of operation. However, their environmental damage, translated into an effluent *BOD,* is distinctly different (with 20% less *BOD* for Case 2, see Table-3).

Milk fat content is much lower in Case 2 compared to Case 1 (Table-3). This is achieved, however, at the expense of increased requirements in raw material (milk requirements in Case 2 are 2267 kg compared to 1661 kg in Case 1), since curd yield increases when milk fat content increases. Additional raw material consumption results in general in an increase of the input waste to the cottage cheese process, i.e. the waste associated with the production of milk. Clearly, such trade-offs are important and must be taken into consideration if a consistent environmental impact assessment is desired. Trade-offs also exist (as expected) between cost and environmental impact: Case 1 compares favorably to Case 2 on economic grounds (25% less expensive) but poorly with respect to environmental impact (20% more *BOD).* Furthermore, results indicate that waste generation increases substantially for high fat input milk (3% wt. milk fat content results approximately in 15% waste increase).

5.1. A methodology for environmental impact minimization of batch plants

As mentioned before, waste generation in batch a plant is a function of time and critically depends on detailed scheduling/operational and design decisions. In this work we consider the following problem.
Given:

- A set of desired products (fixed amounts)
- A set of raw material alternatives
- Technology of raw material extraction processes
- Regarding the batch process of interest; for example,
  - Campaign mode
  - Design alternatives
  - Task information (processing times, input – output details)
- Cost data
  - Equipment cost
  - Raw material, product and utility prices
- environmental data (from databases)
  - Maximum Acceptable Concentration Limits (in air, water)
  - Long Term Effect Potentials (such as Global Warming, Ozone Depletion and other)

The objective is to obtain the cost optimal, structural designs and operating policies of a multipurpose batch process so as to minimize the adverse environmental effects on a conventional or global basis.

The following methodology is thus proposed involving three main steps:

1. Definition of batch plant system boundary
2. Aggregated (over time) environmental impact assessment
3. Incorporation of environmental impact criteria in batch plant design/scheduling.

5.1.1. Definition of batch plant system bound(w)

The conventional system boundary of a batch plant can be expanded to include all processes associated with raw materials extraction, energy generation and capital manufacture. A global batch plant system boundary is defined by backtracking from the conventional batch process all the way back to the natural state of pure raw materials which are available at no environmental penalty. By defining such an expanded batch plant system boundary, input wastes to the batch plant can be accounted together with output emissions in a global waste vector.

5.1.2. Aggregated environmental impact assessment

Having defined a global system boundary for the batch plant, an assessment of the aggregated site-wide waste vector must be performed. This involves the following (see Fig. 12):

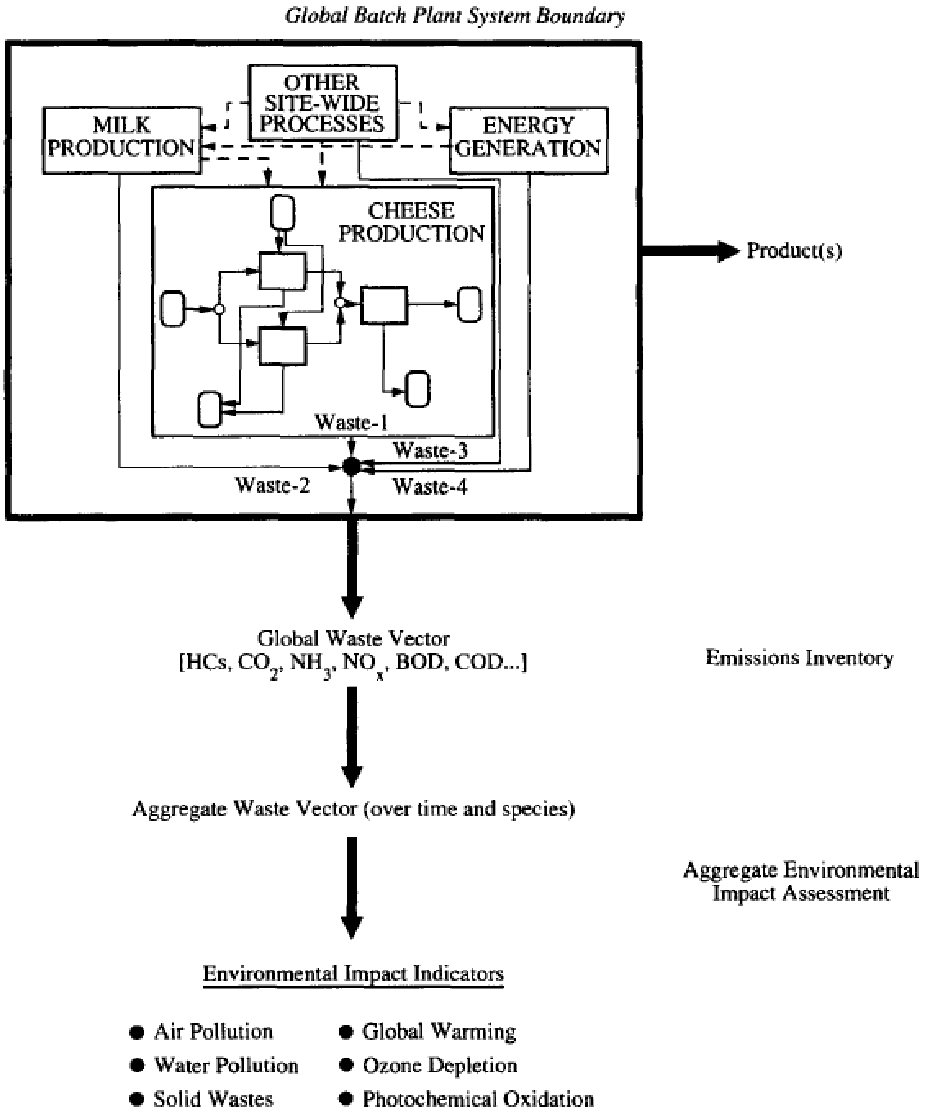


Fig. 12. Aggregated environmental impact assessment in batch plants. (Basis: one cycle of operation.)

(a) Defining a suitable time period as a basis for a consistent evaluation of the environmental impact. If a campaign mode of batch operation is assumed, then the cycle time *T* is used; otherwise, the horizon time H can be used instead.

(b) Defining an emissions inventory comprising all wastes generated in any stage of the batch processing network within the global boundary of the batch plant of interest.

(c) Grouping systematically these wastes in terms of the environmental damage caused (air pollution, water pollution, global warming etc.). Assuming that there are no post-release interactions among pollutants, an Environmental Impact Vector *E1* per time interval is defined to account for the fact that tasks generating waste do not operate continuously over time. Therefore. for each unit to task allocation, the indices which measure air pollution *(CTAM,* kg air), water pollution *(CTWM,* kg water), solid wastes (*SMD*, kg solids), global warming *(GWI* kg CO2), photochemical oxidation (*POI*, kg ethylene) and stratospheric ozone depletion *(SODI*, kg CFC11) are expressed for each waste *w* emitted at time interval *t*, as shown in Table 4. Note that these metrics depend on the current legislation limits and the mass of pollutant disposed (expressed as a proportion of the unit batch size).

Table-4. Time dependent environmental impact indicator

$CTAM_{wt}$ (kg air) (Habersatter, 1991)	Mass of emissions *w* at interval *t* (kg *w*)/standard limit value (kg w/kg air)
$CTWM_{wt}$ (kg water) (Habersatter, 1991)	Mass of pollutant *w* at interval *t* (kg *w*)/standard limit value (kg w/kg water)
SMD_{wt} (kg solids) GWI_{wt} (kg CO_2) (Lashof and Ahuja, 1990)	Mass of solid disposed at interval *t* (kg *w*/h) Mass of pollutant *w* at interval *t* (kg *w*) x GWP (kg CO_2/kg *w*)
POI_{wt} (kg ethylene) (UK Ecol. Board, 1993)	Mass of pollutant *w* at interval *t* (kg *w*) x POCP (kg C_2H_4/kg *w*)
$SODI_{wt}$ (kg CFC11) (UK Ozone Grp., 1998)	Mass of pollutant *w* at interval *t* (kg *w*) x SODP (kg CFC11/kg *w*)

(d) Aggregating over time. For example, for cyclic operation the cycle time T^2 is used as a basis for the quantification of Global Environmental Impact (GEI).

$$GEI = \sum_{t=1}^{T} \sum_{w=1}^{w} EI_{wt} = \sum_{t=1}^{T} \sum_{w=1}^{W}$$

$$[CTAM_{wt} CTWM_{wt} SMD_{wt} GWI_{wt} POI_{wt} SODI_{wt}]^{T}_{process}$$

The environmental impact vector defined above, can be employed on a site wide as well as on a process basis; it can also be used in conjunction with typical metrics such as *BOD, COD* etc. Note also that the assumption of the linear pollutant contribution can be relaxed by considering the fate of each pollutant in the environment by accounting for pollutant interactions and pollutant media partitioning (Stefanis et al., 1996).

5.1.3. Incorporation of environmental impact criteria in the design and scheduling of batch plants

In order to consider environmental criteria as distinct objectives together with cost in the design and scheduling problem of batch plants, a multi-objective optimization formulation is considered to generate the family of designs and the corresponding operating policies that refer to the pareto curve of solutions trading-off cost versus pollution metrics. Using the e-constraint method (Hwang and Masud, 1979), this can be effectively transformed into a scalar parametric optimization problem with the other objectives added as inequality constraints, as follows:

(P) min Annualized Cost
s.t.
Batch Plant Design Model
Scheduling Constraints
$GEI \leq \varepsilon$

Varying the parameter vector ε results in the generation of the trade-off curve of solutions (pareto curves, see Fig. 13) which can help analyze the environmental implications at both the process and site-wide level and obtain compromise solutions. Note also that batch process synthesis aspects are not directly included in problem (P) – such considerations would require detailed macro-level information regarding choice of reaction, solvents, recipes, etc.

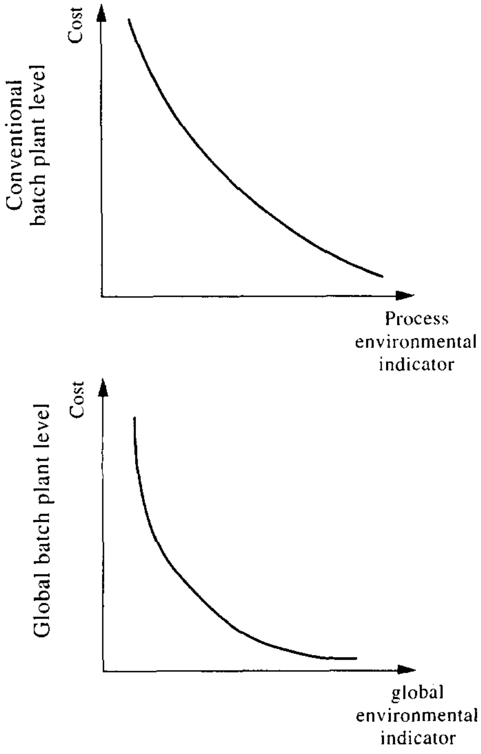


Fig. 13. Pareto curves in MEIM.

6. CASE STUDY – 2: LIFE CYCLE INVENTORY ANALYSIS OF HARD COAL BASED ELECTRICITY GENERATION (Laura et al., 2005)

In the present LCI, a product system of the hard coal electricity is presented which covers all the life cycle stages - starting from the extraction of resources up to the delivery of electric power to the grid. Since the OSELCA project is focused on the future, not on the average Finnish situation, the Finnish Meri-Pori power plant, representing the best available power plant technology, was chosen as a case study power plant. Although the Meri-Pori obtains its fuel from many different countries, inventory data on the coal mining was collected using the average interventions of coal mining in Poland, as Poland is one of the largest suppliers of hard coal to Finland. In this report LCI results are analysed briefly. The current inventory analysis concentrates on the quantitatively measured emissions.

Division of the product system into different life cycle stages facilitates the interpretation of the LCI results. It enables one to evaluate and compare the relative contributions of the interventions between the stages. How the life cycle stages are defined depends on the purpose of the study. In this inventory, the LCI data was compiled according to the following six life cycle stages (see Fig. 14):

1. Hard coal mining and processing
2. Raw materials to coal mines and the power plant
3. External electricity and heat generation in Poland (coal mining and its raw materials) and in Finland (power plant and its raw materials)
4. Hard coal power plant
5. Transportation
6. Recovered wastes, treated as by-products

All these life cycle stages are shown on the flowchart with different colors. The software calculates the inventory results per the functional unit (1MWh electricity) by the modules, the life cycle stages or for the system as a whole. In the flowchart the mining modules are marked with grey color. They include mining and processing of the hard coal, also manufacturing and burning of fuels used in the mine. The raw material modules are marked with light green. They cover the production of raw materials for both mining and power plant. The external electricity and heat generation in Poland is marked with dark green and in Finland with turquoise. The power plant module is colored with purple. This module includes also the final product - i.e. 1 MWh of electricity at grid – including average transmission losses in Finland. The transportation modules are painted blue and shown as short diagonal lines, which cross the arrows. Transportation was not taken into account for all the raw materials or by-products. Indirect (from the production of fuels) and direct emissions together constitute summarized input and output factors, used in the transportation modules. Credited by-product modules (i.e. avoided emissions) are marked with dark lilac color. These contain waste materials from the mine or the power plant that were utilized in other production processes to replace virgin raw materials. In the following section the modules of the product system and their data sources are described in detail from the viewpoint of the two main processes – hard coal mining in Poland and electricity generation from hard coal in Finland - with all their material and energy inputs. The Polish and Finnish electricity generation models, used for manufacturing of raw materials. The LCI results are, however, presented according to the life cycle stages.

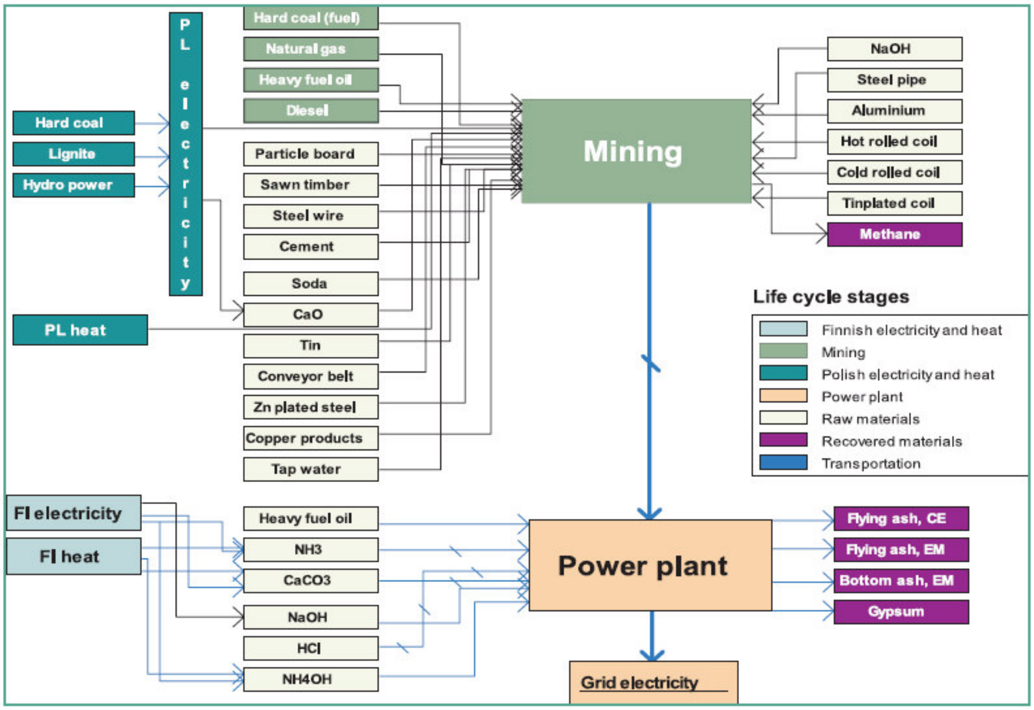


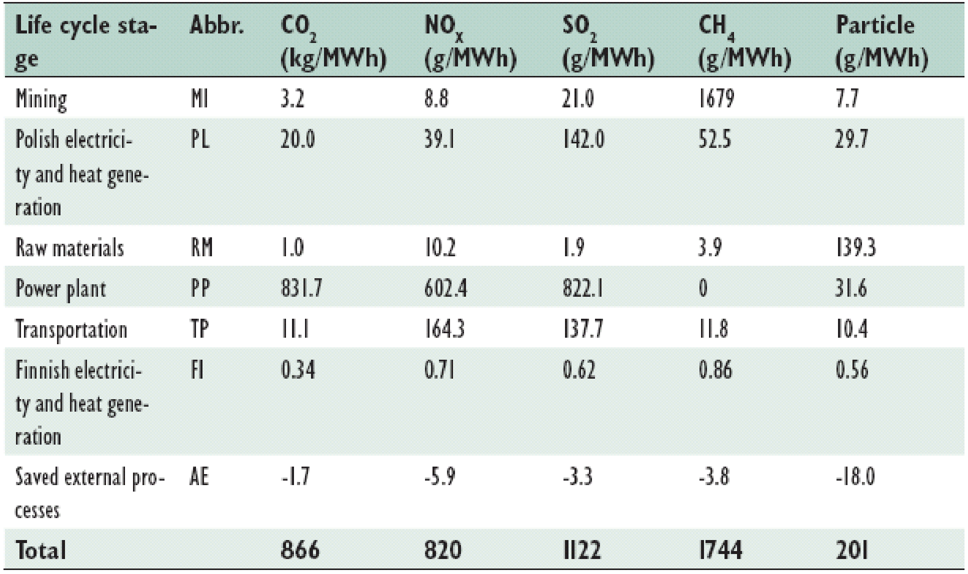
Fig. 14. Flow chart of the hard coal electricity product system.

In this inventory, electricity generation with hard coal was assessed. For this, environmental inputs and outputs throughout the product life cycle, i.e. from hard coal mining to the electrical power network, were gathered. Whereas the hard coal production took place in Poland and mining data was assumed to be average Polish mining technology, the electricity generation was assumed to take place in Finland, at the Meri-Pori power plant. In the following sections, summary of the inventory results is presented.

6.1. Inputs and outputs per 1 MWh electricity produced

Summary results of the main emissions to air from the system are shown in Table 5. The heavy metal emissions to the atmosphere occur mainly at the power plant (Fig. 15). It produces 57-95% of total heavy metal emissions except for Hg, the share of which was 11%. Also Polish electricity generation (mainly used in the mining operations) is a large contributor to the heavy metal emissions. It produces most (~63%) of the Hg emissions and over 5-25% of the other metal emissions. Transportation of hard coal within Poland by electric trains also produces about 17% of the Hg emissions.

Table-5. Some emissions to air from the product system.



Life cycle stage	Abbr.	CO_2 (kg/MWh)	NO_x (g/MWh)	SO_2 (g/MWh)	CH_4 (g/MWh)	Particle (g/MWh)
Mining	MI	3.2	8.8	21.0	1679	7.7
Polish electricity and heat generation	PL	20.0	39.1	142.0	52.5	29.7
Raw materials	RM	1.0	10.2	1.9	3.9	139.3
Power plant	PP	831.7	602.4	822.1	0	31.6
Transportation	TP	11.1	164.3	137.7	11.8	10.4
Finnish electricity and heat generation	FI	0.34	0.71	0.62	0.86	0.56
Saved external processes	AE	-1.7	-5.9	-3.3	-3.8	-18.0
Total		**866**	**820**	**1122**	**1744**	**201**

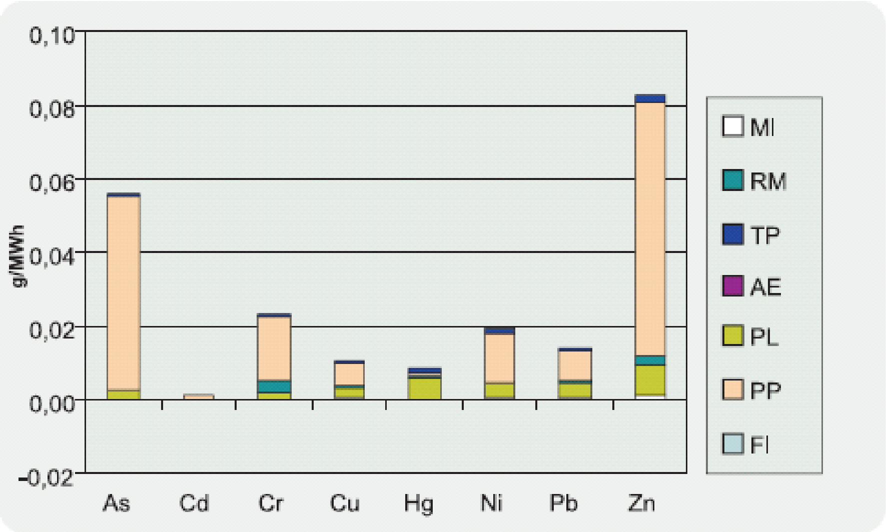


Fig. 15. Atmospheric emissions of some heavy metals (g/MWh). The abbreviations of the life cycle stages are explained in Table-14.

6.2. Inputs and outputs according to the life cycle stages

The life cycle stages of the studied product system are following: mining, external electricity and heat generation in Poland, production of raw materials for both mining and power plant, power plant processes, transportation, external electricity and heat generation in Finland, and saved external processes. Approximately 95% of all the CO_2 emissions of the whole system originate from the power plant (Figure 16). The power plant also causes most of the NO_X and SO_2 emissions (Figs. 17 and 18). In addition, transportation of the hard coal from the mines to the power plant induces a great deal of

NO_X emissions - 30% of the total emissions. It should be noted that CO_2, NO_X and SO_2 emissions are not measured at the mines. Therefore emissions from burning fuels at the mine area were included to the flow chart from the *Ecoinvent* database. Their contribution to the total emissions is minimal, however. As could be expected, CH_4 originates mainly from the mines (Fig. 19). The contribution of the other life cycle stages to the CH_4 emissions is insignificant.

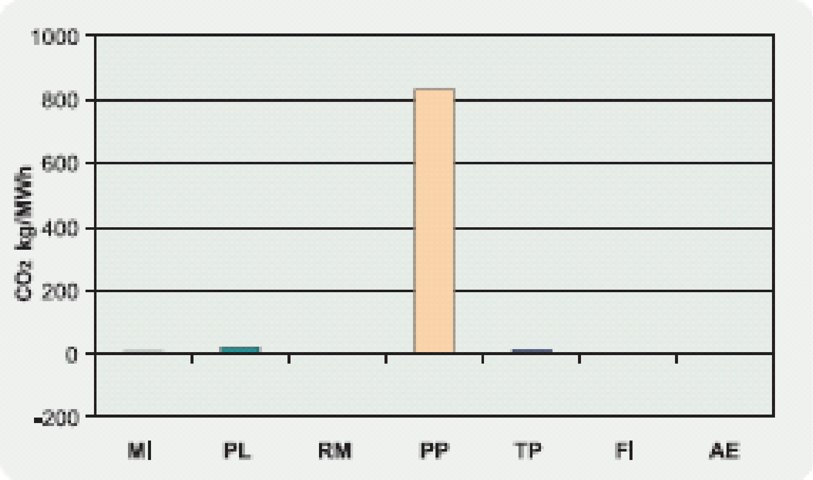


Fig. 16. CO_2 emissions according to the life cycle stages

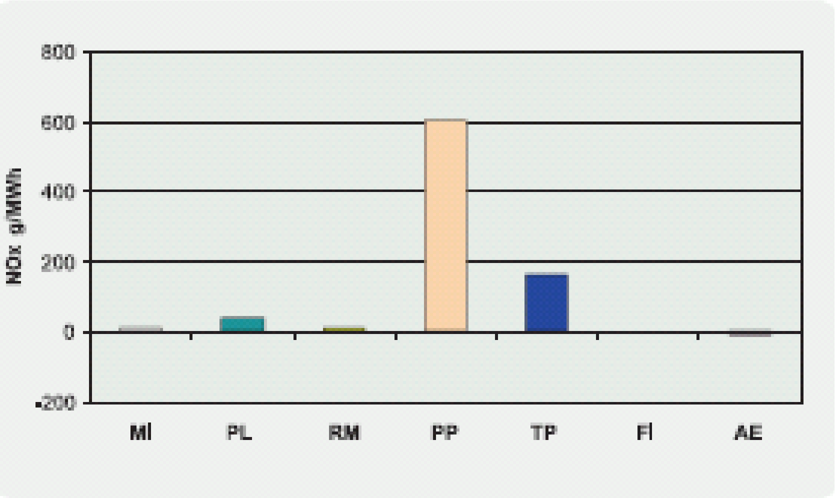


Fig. 17. NO_X emissions according to the life cycle stages

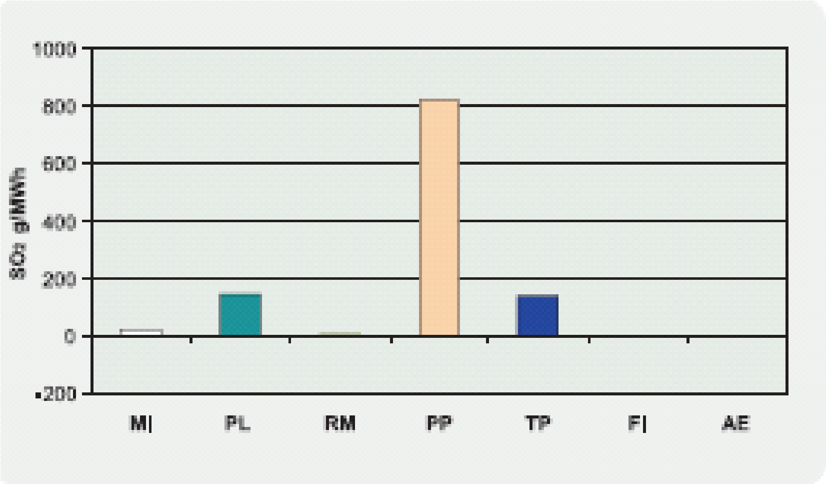


Fig. 18. SO_2 emissions according to the life cycle stages

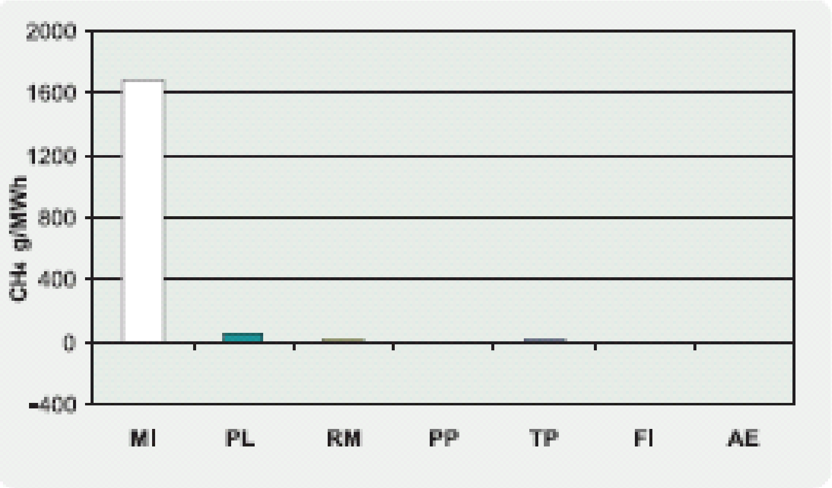


Fig. 19. CH_4 emissions according to the life cycle stages
(Abbreviations: MI = Mining, PL = Polish electricity and heat generation, RM = Raw materials, PP = Power plant, TP =Transportation, FI = Finnish electricity and heat generation and AE = Saved external processes)

In this product system, most of the particle emissions originate from the production of limestone, which is used to reduce SO_2 emissions from the power plant (Fig. 20). On the other hand, replacement of cement through fly ash recycling produces an approximately 4% reduction in particle emissions through saved limestone.

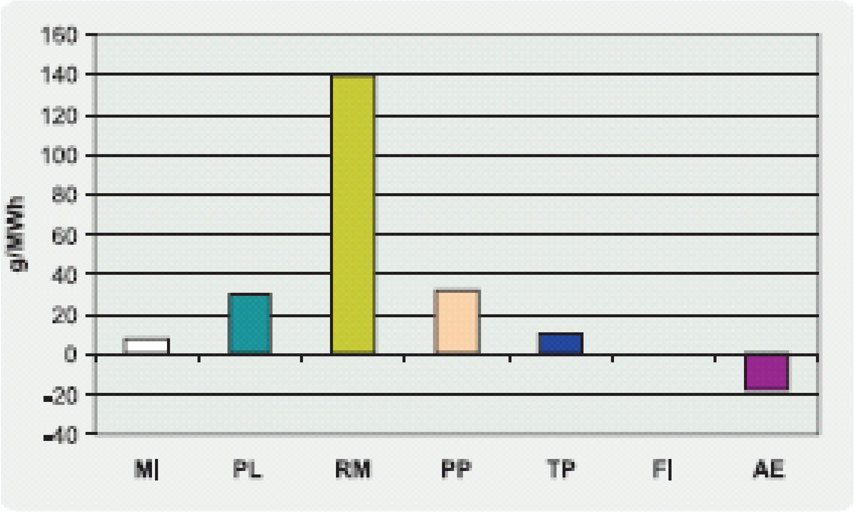
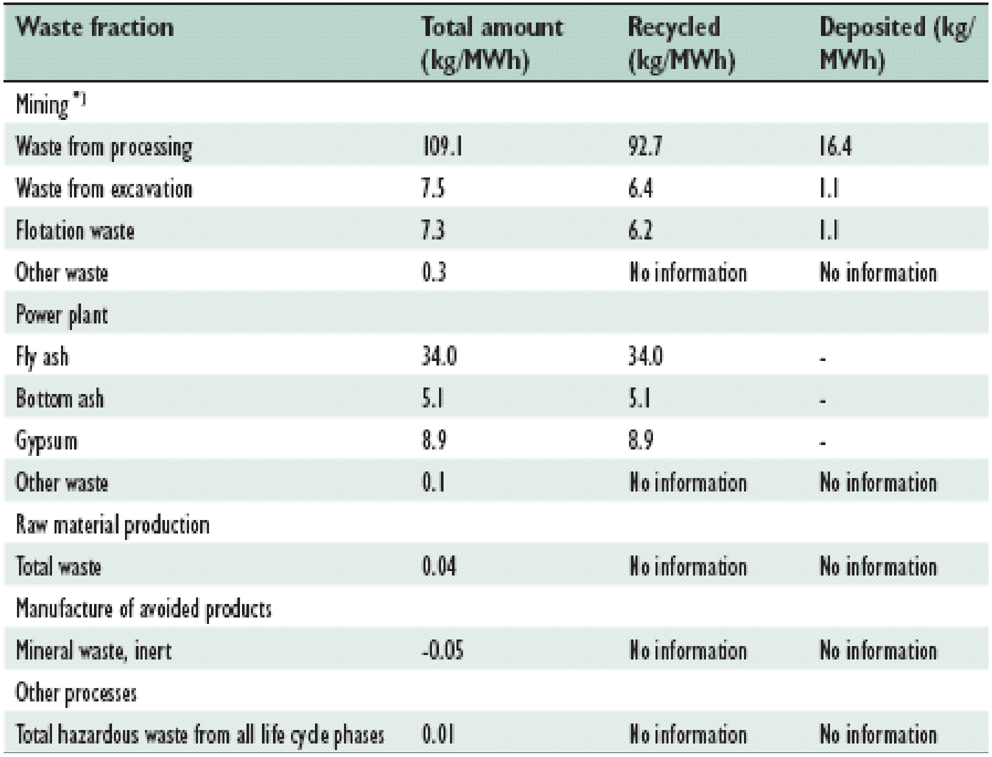


Fig. 20. Particle emissions according to the life cycle stages

6.3. Waste generation and land use

The largest waste fraction of the system, 109.1 kg/MWh, is created during processing of hard coal. Mining (excavation) generates about 7.5 kg waste/MWh. Also fly ash and gypsum produced at the power plant are large waste fractions. Waste generation during the raw material production is minimal compared to mining and power plant. Additionally, the amount of avoided waste from the saved external processes is larger than the amount of waste generated by raw material production (Table-6).

Table-6. Waste generation according to the life cycle stages.



Waste fraction	Total amount (kg/MWh)	Recycled (kg/MWh)	Deposited (kg/MWh)
Mining *)			
Waste from processing	109.1	92.7	16.4
Waste from excavation	7.5	6.4	1.1
Flotation waste	7.3	6.2	1.1
Other waste	0.3	No information	No information
Power plant			
Fly ash	34.0	34.0	-
Bottom ash	5.1	5.1	-
Gypsum	8.9	8.9	-
Other waste	0.1	No information	No information
Raw material production			
Total waste	0.04	No information	No information
Manufacture of avoided products			
Mineral waste, inert	-0.05	No information	No information
Other processes			
Total hazardous waste from all life cycle phases	0.01	No information	No information

Land use directly related to hard coal mining and energy conversion is presented in Table-7. It will be dealt with more extensively in the impact assessment, especially land use of mining activities. According to the present data, land use for mining appears to be surprisingly small compared to the land use by the power plant. Possible differences in calculation procedures and boundaries will be checked at a later stage of the project. It should be noted that, the power plant waste disposal area is an area that has been reserved for the power plant but so far it has not been necessary to dispose any waste there.

Table-7. Land usage for the mining and power plant operations.

Operation area	Land use (m2/MWh)
Mine area	0.10
Processing plants	0.01
Tailings disposal areas	0.17
Power plant area	0.17
Coal field	0.04
Power plant waste disposal area	0.26

6.4. Sensitivity Analysis

The sensitivity of the system to changes in four different factors, namely hard coal transportation distance (Case 1), power plant technology (Case 2), external electricity and heat generation (Case 3) and use of fly ash in concrete manufacturing (Case 4) was analysed (Fig. 21). In each case, the variable in question was varied while everything else was held constant. In the following the four cases will be discussed.

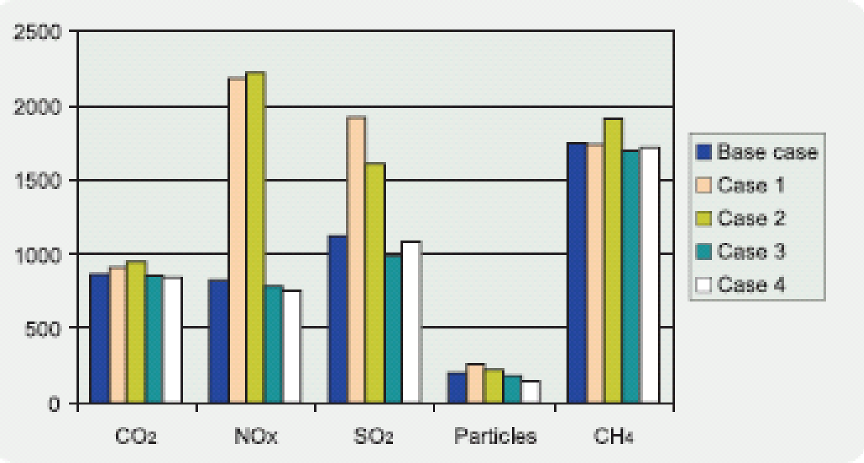


Fig. 21. The sensitivity of the main emissions to air to the four different factors studied

6.5. Hard coal transportation distance

In this inventory, the hard coal is assumedly transported from Poland. However, the Meri-Pori power plant could also use hard coal transported from regions further away - such as from South America or South-East Asia. The impact of the much longer transportation distance on emissions to air was investigated (Fig. 21, Case 1). Instead of transportation from Poland to Meri-Pori by electric train and ferry, hard coal was assumedly transported with ocean freight ferries from Colombia or Indonesia to Meri-Pori. Emissions are calculated by Koskela (2002). Transportation distance was estimated to be 10,000 km (average distance from Colombia or Indonesia to Finland). Train transportation was omitted. Increasing transportation distance would lead to almost tripling of the NO_X emissions (see Fig. 21). SO_2 emissions would rise by ca 70% and particle emissions by ca 30%. Thus, it can be concluded that hard coal transportation distance significantly influences NO_X, SO_2 and particle emissions of the whole system.

6.6. Power plant technology

Meri-Pori power plant represents the *Best Available Technology (BAT)* for the power plant and its emissions are therefore relatively low. In order to see how an older power plant would perform, inventory results were calculated for another power plant with less advanced emission reduction technology – for Tahkoluoto power plant, which is situated right next to Meri-Pori plant (Fig. 21, Case 2). Data on Tahkoluoto power plant were taken from Vahti database. As no information was available over the raw material consumption of Tahkoluoto (except for the hard coal and heavy fuel oil), it was assumed to be the same as that of Meri-Pori. This assumption is probably not realistic but as the role of the power plant raw materials for the whole inventory was proved to be insignificant, this assumption was considered justified. Fig. 21 shows the results of the comparison. For all substances, Tahkoluoto's emissions were higher than those of Meri-Pori. For NO_X and SO_2 the difference was 170% and 45%, respectively, which reflects Meri-Pori's advanced emission reduction systems. It is notable that if hard coal also was transported to Tahkoluoto from overseas (Case 1), the increase in NO_X, SO_2 and particle emissions would almost double.

6.7 External electricity and heat generation

Over 90% of the Polish electricity is generated from hard or brown coal. More than 50% of the Finnish electricity is generated from nuclear power, hydropower and natural gas, so it is therefore not so emission-intensive. In order to study the impact of Polish electricity and heat generation on the total emissions of the production system, the results were recalculated with the assumption that all external electricity and heat were generated in Finland. As seen from the Fig. 21 (Case 3), the change in total emissions would be insignificant in this product system - CO_2, NO_X and CH_4 emissions would decrease by 2-4%. However, particle and SO_2 emissions would decrease by 10 and 11% respectively.

6.8 Use of fly ash in cement manufacturing

Cement production is energy intensive and highly polluting. The fly ash from hard coal power plants can be utilised in concrete manufacturing to replace cement. Current utilization rate of the Meri-Pori plant's flying ash in cement manufacturing is 5% while the rest is used for earth construction works. Considerable emission reductions could be achieved by increasing the recycling rate. Fig. 21 (Case 4) shows emission reductions, resulting from increasing the recycling rate up to 80% (the rest would still be utilized in earth construction). The increased recycling rate would have the greatest impact on total particle emissions, which would be reduced by approximately 30%. For the other emissions the reduction would range from 1.5 (CH_4) to 8% (NO_X).

7. CASE STUDY – 3: COMPARISON OF END-OF-LIFE TYRE TREATMENT TECHNOLOGIES: LIFE CYCLE INVENTORY ANALYSIS (Silvestravičiūtė and Karaliūnaitė, 2006)

7.1. Introduction of the problem

The disposal of used tyres is an environmental problem nowadays. The challenge of scrap tyre management arises mainly from the technical and commercial issues relating to tyres both as a product and as a waste. Tyres are made from a mixture of materials including synthetic and natural rubber, textiles, steel, carbon black, aromatic extender oils and various chemical additives, which are "vulcanised" at a high temperature during the manufacturing process. The result is a particularly stable product that requires a great deal of energy to break it down. For instance, tyres are more difficult to combust than conventional fuels (even though the energy content is higher than that of most coals and similar to that of natural gas), and therefore tyres require higher temperatures and/or longer residence times to promote a complete breakdown of the hydrocarbon content into carbon dioxide and water. A significant amount of energy is also needed to mechanically reduce the size of tyres, in order to produce materials that are suitable to be recycled into engineering, commercial or industrial products. So while tyres represent a feedstock with a high energy content, which contain potentially valuable constituents such as carbon black, organic oils and steel, extracting these materials in a cost-effective manner is extremely difficult (Archer, 2004).

Scrap vehicle tyres make a significant contribution to the generation of waste. The rate of scrap tyre generation in EU countries is approximately 7 kg per capita (~9 kg per capita in the USA) (Reschner, 2003; Staniškis, 2004). It is estimated that 2.8 million tonnes of used tyres per year are generated in the EU member states 2.5 million tonnes in North America and 1 million tonnes in Japan. Lithuanian production of waste tyres should be up to17 000 tonnes per year considering, that the annually generated amount of end-of-life tyres is a difference between the import and export of tyres. In 1999-2000 in EU three Directives were enacted regarding post-consumer tyres. The EU Landfill Directive (Council, 1999) banned the landfilling of whole tyres from 2003 and will ban the landfilling of shredded tyres in 2006. Moreover, the indirect impact of the European End The Waste Incineration Directive was adopted with the aim of preventing or limiting emissions from incineration and co-incineration of waste (Directive, 2000). The Directive sets more stringent emission standards for a number of pollutants including dust, HCl, HF, NOx, dioxins and heavy metals. Since thermal recovery in cement kilns and power plants is one important route for disposal of scrap tyres, the Waste Incineration Directive may compel some current users of tyre-derived fuel to refurbish their emission control systems. It is estimated that all the above-mentioned legal restrictions will incur an additional amount of over 1 million tonnes of scrap tyres requiring appropriate treatment in the EU. At the moment, the most significant methods and technologies developed for waste tyre recovery and/or disposal are:

- Reusing in the original form
- Retreading of worn tyres
- Shredding operations to get a powdered or scrapped form

- Thermal treatments to perform material and/or energy recovery
- Utilisation in building applications; other treatments
- Landfilling, heaping and abandonment

7.2. Object of the study

The treatment of scrap tyres is associated with diverse potential environmental impacts. From a very general point of view, a significant effect is caused due to the material flow within an industrial society. The protection of natural resources is likely to be the main ecological justification for recovery of used tyres. The main objective of the study was to evaluate and compare five different end-of-life tyre treatment technologies and their environmental impacts.

Five different technologies for recovery of used tyres were analysed in this study:
1. Co-incineration in cement kiln.
2. Thermolysis.
3. Mechanical recycling (conventional).
4. Baro-destructive recycling.
5. Mechanical recycling (ultrasound).

7.3. Methodology

The environmental impact assessment methodology and data were chosen as the main source of initial inventory data, because only one of the analyzed technologies is already in operation in Lithuania; the other technologies are still in the implementation process, but EIA has been conducted for all of them.

7.3.1. Functional unit and system boundaries

One of the most important elements in a LCA study is a clear description of the system's function and, derived from it, the functional unit for the study. In comparative studies, it is essential that the systems are compared on the basis of the same function. In the present study, the *functional unit* was considered to be the recovery of 1 tonne of end-oflife tyres. Another important issue is the definition of system boundaries. A life cycle process diagram of tyres is presented in Fig. 22. The definition of the tyre recovery system boundaries has been based on the assumption that production, use and collection stages in tyre life cycle are equivalent, therefore these processes were not included in the study. However, evaluation of five different technologies of scrap tyre recovery necessitated collection of quite a number of different data and information. Several more assumptions had to be made in relation to the analysed technologies:

- It's very difficult to distinguish air emissions caused by the combustion of a tyre from the ones caused by the cement production process. At this stage of the research, air emissions of tyre combustion in the cement kiln were separated from the process air emission flow and were estimated according to the emission rate from the combustion of a tyre alone. This decision was based on the choice of the worst case; • in case of co-incineration in the cement kiln, energy consumption for lifting the tyres into the feeder was not evaluated, as these data were not available.
- There has been made an assumption that the calorific value of thermolysis gas is equal to the calorific value of natural gas in calculations of

energy balance.

- The definition of products is based on an assumption that all materials generated during the recovery process are considered as products if they have any practical application.
- All calculations were based on the assumption that used tyres were of average quality and composition and that the analyzed technologies were of an average to advanced level for tyre waste treatment.

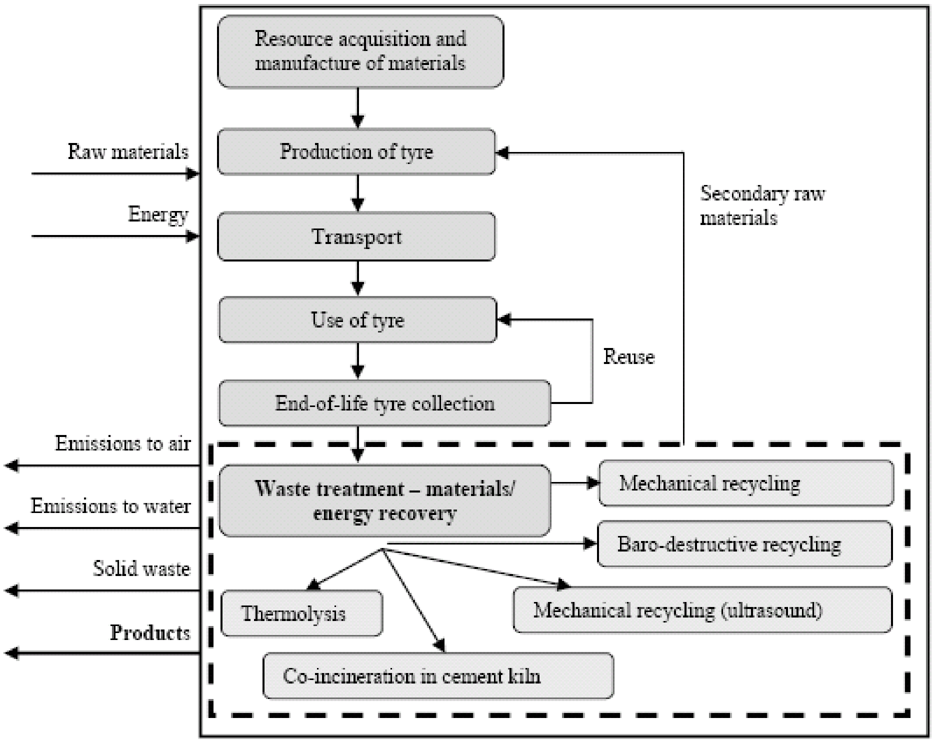


Fig. 22. Tyre life cycle diagram and boundaries of life cycle analysis.

7.3.2. Life cycle inventory analysis

The first step in life cycle assessment is an inventory analysis, which includes and quantifies material and energy use and emissions to the environment (EN ISO, 1998). This article is aimed to present only the results of this LCA phase. Primary data on the inputs and outputs were taken from EIA carried out in advance to estimate the local impact of the recovery systems chosen for this study. The data used in IAE were calculated according to appropriate methodologies adopted in Lithuania or modeled according to the method of analogy, i.e. estimated on the basis of analogous technologies used in other countries. Data gaps were filled with information from supplementary technical documents and other literature sources

7.4. Results and Discussion

Environmental impact assessment was conducted for all analyzed technologies, and the proposed economic activities by virtue of their nature and environmental impacts can be executed in the chosen sites in Lithuania. The life cycle inventory analysis of end-of-life tyre recovery was performed according to the LCA methodology (EN ISO, 1998). The general view of the main input and output data is outlined in Fig. 23. All inventory data are expressed per functional unit.

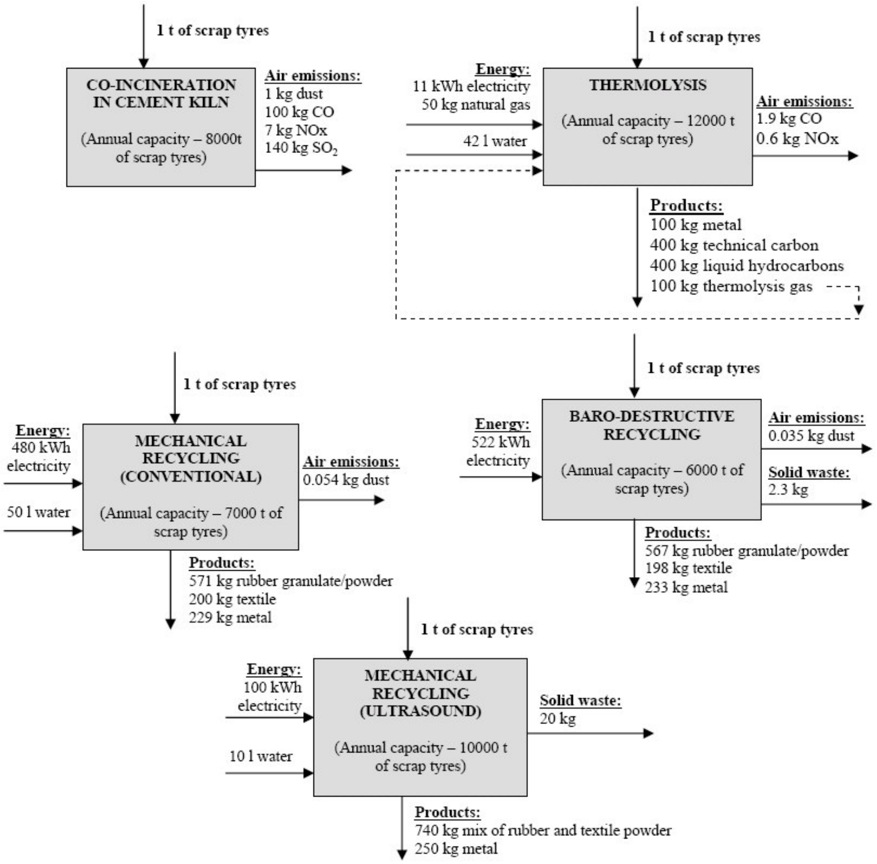


Fig. 23. Inventory analysis – the main input and output data

Mechanical recycling, thermolysis and coincineration of waste tyres in a cement kiln produce different products: energy, gas and liquid fuels, rubber, metal, textile and technical carbon. A comparison of the material outputs was made on the basis of mass yield (Fig. 24). Energy output of coincineration of tyres is presented in Fig. 25. As it cannot be expressed in mass parameters, it is compared with energy output that can be gained during the combustion of thermolysis products – gas and liquid fuels. Comparison of energy consumption and production of all analysed technologies (Fig. 26) shows that the highest demand of electric power is needed by the baro-destructive method of recycling of used tyres, while the highest amount of heat energy is generated during direct tyre co-incineration. Water is used in three analysed technologies: for steam production in the thermolysis process, for tyre watering in conventional mechanical recycling, and for dust removal in the scrubber in the ultrasound recycling process.

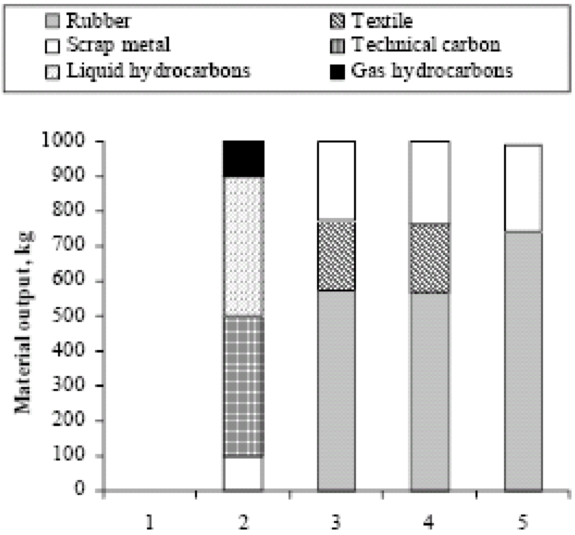


Fig. 24. Material outputs per functional unit (from recovery of 1 tonne of tyres): 1 – co-incineration in cement kiln; 2 – thermolysis; 3 – mechanical recycling; 4 – baro-destructive recycling; 5 – mechanical recycling

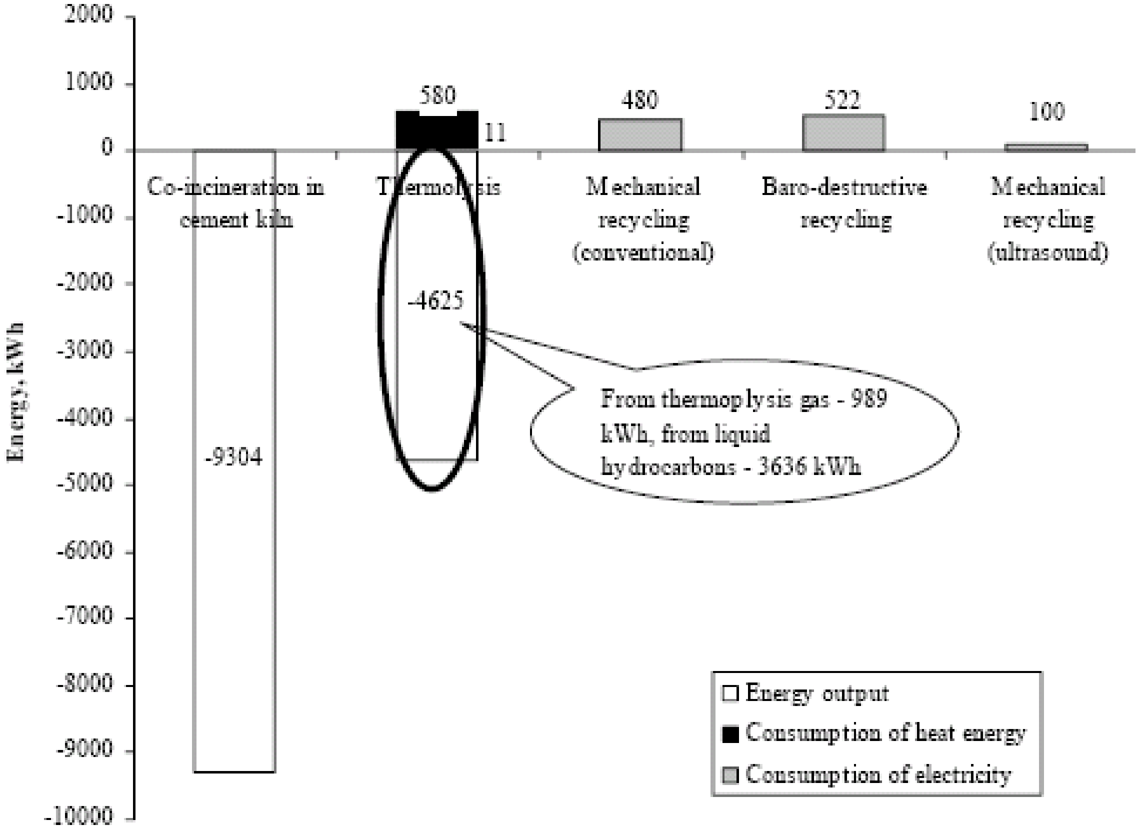


Fig. 25. Comparison of energy consumption and production per functional unit (recovery of 1 tonne of tyres)

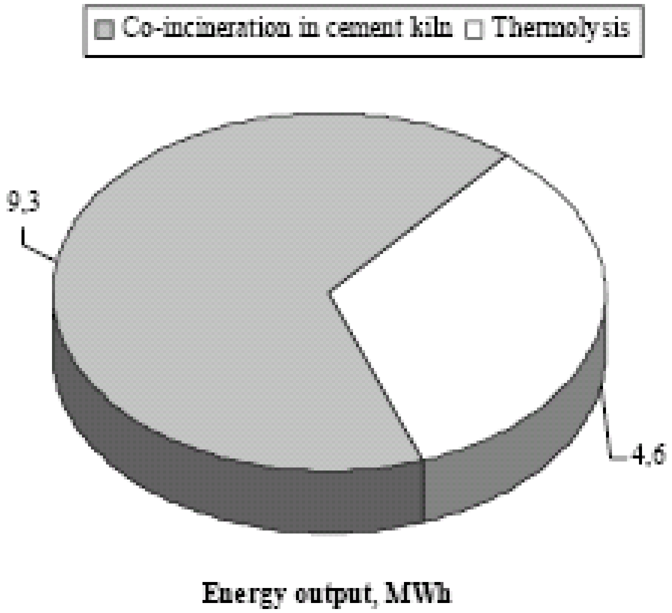


Fig. 26. Energy output from co-incineration of 1 tonne of scrap tyres in cement kiln and potential energy output from thermolysis of combustible products from 1 ton of tyres

Water consumption is relatively low in all technological processes (Fig. 27), although water re-circulation is applied only in thermolysis. It should be mentioned that no industrial wastewater is discharged in either of the cases. Pseudo-latex pulp from scrubber of ultrasound technology is landfilled as well as dust from fabric filters of the barodestructive method (Fig. 28). The dust collected in the electrostatic precipitator in a cement plant as well as in fabric filters of conventional mechanical recycling is returned back into the processes.

Co-incineration of tyres in cement kiln generates the biggest amount of direct air emissions compared with the other analysed technologies of crap tyre treatment. However, air emissions from the cement kiln co-incinerating scrap tyres insignificantly differ from emissions generated by the combustion of main fuel (pulverised coal):

- NOx emissions decrease approximately by 5–10%;
- SO2 emissions may increase up to 10%;
- Possible peaks of CO emissions (at the moment of whole tyre feeding into the kiln);
- Dust emissions may increase by 15–20%.

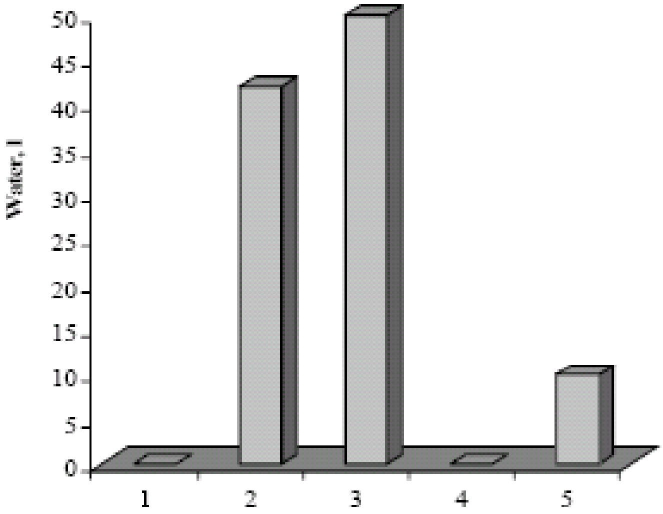


Fig. 27. Water consumption per functional unit (recovery of 1 tonne of tyres)

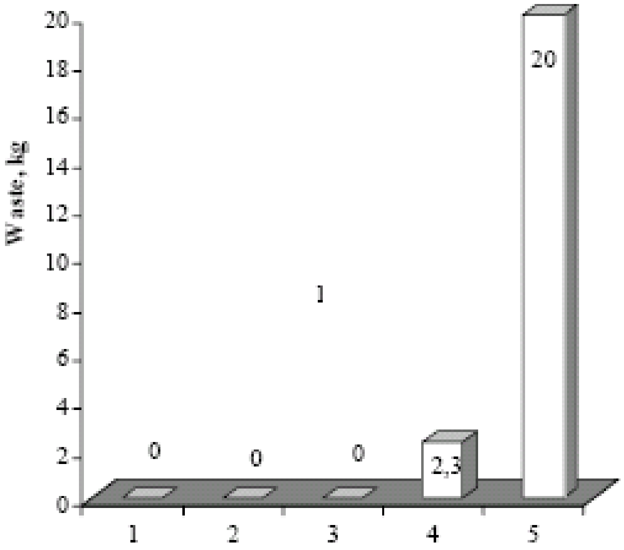


Fig. 28. Waste generation per functional unit (recovery of 1 tonne of tyres)

8. Conclusions

The following conclusion are drawn from the present study.

- Life Cycle Inventory Analysis is found to be the foundation for the Life Cycle Assessment.
- Inventory analysis required the thorough understanding of subsystems.
- Flow diagrams are used to model and compare all alternatives under consideration.
- Data collection step is very important step in LCIA to determine how much of the energy and material requirements and the environmental releases associated with the process.
- The economic input output approach is quickly covers an entire economy, including all the material and energy inputs.
- The results from the inventory can be presented most comprehensibly in tabular form or graphical form.
- The identification of significant issues is possible by interpreting the inventory results.
- A process systems methodology for incorporating environmental concerns in the optimal scheduling and design of batch processes has been presented in case study-1.
- The proposed methodology identifies waste generation sources within a batch plant and after establishing relationships to link output to input waste generation transforms it into an aggregated over time and species environmental impact vector.
- The heavy metal emissions to the atmosphere occur mainly at the power plant.
- It produces 57-95% of total heavy metal emissions except for Hg, the share of which was 11%.
- Approximately 95% of all the CO2 emissions of the whole system originate from the power plant.
- Transportation of the hard coal from the mines to the power plant induces a great deal of NOX emissions - 30% of the total emissions.
- The baro-destructive method of used tyre recycling requires the highest amount of electric power (522 kWh per 1 tonne of scrap tyres to be recovered).
- While the highest amount of heat energy is generated during direct tyre co-incineration in a cement kiln (energy recovery of 1 tonne of scrap tyres equals to 9304 kWh).

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