GPLS: A MODELING AND SIMULATION SYSTEM FOR PRODUCT LIFECYCLE DESIGN

Atsushi Aoyama, Yuji Naka, Akio Shimizu
Chemical Resources Laboratory, Tokyo Institute of Technology,
Nagatsuta Midori-Ku Yokohama 226-8503, Japan
Kazuhisa Hamada, Katsusyoshi Kameda, Takashi Kagiyama, Iwao Matsumoto, Yoshio Tsujikawa
Japan Chemical Innovation Institute, Jinpo Chiyoda-Ku Tokyo 101-0051, Japan

Abstract
Reduction of environmental impact and energy consumption becomes a crucial issue. LCA tools are used to assess environmental impacts of product lifecycle. A novel modeling and simulation system called GPLS has been developed for LCA. GPLS makes it possible to examine the effects of logistics, supply chain management, geographical distribution of processing facilities as well as new products and processes that cannot be examined by currently available LCA tools.

Keywords
PET resin, Lifecycle Assessment (LCA), Sustainability, Logistics, Simulation, Object oriented model

Introduction
Increasing human population and economic activity exceed the capacity of ecosystem. As a consequence, problems such as global warming, tropical-rain-forests reduction, acid rain and ozone layer depletion are occurring. In old days, process industries had to consider only customer demands: qualities, prices and variations of their products. They now have to consider the demands from society: reduction of environmental impact and energy consumption. An immediate attention has to be paid to develop products and processes to reduce environmental impacts. In order to assess the environmental impacts of new products or processes, an evaluation tool of entire product lifecycle is necessary. Such tools are called LCA (Lifecycle Assessment) tools. However, some people say that they are not satisfied with currently available LCA tools. Therefore, we set the aims of this paper as follows.

- To identify the requirements to LCA tools and examine whether currently available LCA tools satisfies those requirements or not
- To develop a new modeling scheme if currently available LCA tools do not satisfy the requirements.
- To develop a modeling and simulation system based on the proposed scheme

The rest of this paper is organized as follows. The next section introduces a PET bottle resin lifecycle example used to analyze and identify the requirements to LCA tools and the results of analysis are presented. In the following sections, a new modeling scheme to satisfy the requirements identified in the previous section is explained and the system configuration is described. Finally, a summary of the achievements concludes the paper.

Product Lifecycle Design

LCA for Product Lifecycle Design
Methods to reduce environmental impact are categorized into three kinds. The first is “Reduce”. “Reduce” means to reduce the amount of resources to be used. The second is “Reuse”. “Reuse” means to use the same product many times by recovering the used products from the market. Methods to promote “Reuse” include abolishing a regulation prohibiting reusing products and a reliable cleaning technology. The third is “Recycle”. Methods to promote recycle include a compromise in qualities to enable recycling (e.g. reduced transparency of plastic, to avoid using composite materials that are difficult to recycle). Lifecycle assessment (LCA) has been used to evaluate an environmental impact of existing products and manufacturing processes (Kobayashi, 2000). However, some people say that the functions of currently

available LCA tools are unsatisfactory. Therefore, we have decided to identify the requirements to LCA tools and examine whether currently available LCA tools satisfies those requirements or not.

PET Bottle Resin Lifecycle

A PET bottle resin lifecycle example has been employed to identify the requirement to LCA tools. The main reason is that we could collaborate with the PET bottle consortium of Japan that consists of companies doing business in a PET bottle resin lifecycle, such as resin manufacturers, bottle manufacturers, beverage makers, logistics companies and recycling companies. PET resin for beverage bottles has a unique feature with a high recovery rate (more than 50% and increasing) in relatively good condition in Japan. A current PET bottle resin recycle is a cascade system. PET resin recovered from discarded PET bottles is cut, separated from other kinds of plastics, metal, paper and cleaned, and used to manufacture fibers and sheets, not bottles. However, several bottle-to-bottle recycling technologies (e.g. chemical recycle, super clean combined with solid phase polymerisation) are going to be implemented in near future. It may have huge impacts on the businesses in PET bottle resin lifecycle. There exists a strong demand to evaluate the environmental impacts (e.g. global warming, ozone layer depletion) and the effects on current recycling systems of such new technologies.

Requirements for LCA tools

We identified the requirements to LCA based on the hearings from the members of the PET bottle consortium of Japan. The evaluation scenarios of PET bottle resin lifecycle can be classified into the four groups as listed below.

- Introduction of new products: a PET bottle with thinner PET resin layer
- Introduction of new processes: monomer recycle technology, super cleaning technology
- Introduction and modification of policies, regulations and management schemes: regulations on usage of recycled PET resin, bidding rules of collected used PET bottles
- Introduction and modification of logistics and supply chain management: supply chain management to equalize the seasonal change of the quantity of collected PET bottle resin, more collection ports for discarded PET bottles

Especially, the logistics issues are important because significant seasonal change of PET bottle production (high in summer and low in winter) exists and a temporal stock shortage can occur even though the material flow of PET bottle resin is balanced by annual average. In order to satisfy those requirements, a LCA tool has to facilitate both steady state and dynamic simulation, and ability to model management schemes, regulations and laws. Another requirement to LCA tool is flexibility because frequent revisions and changes in simulation scenario, models and evaluation criteria (e.g. various ecological indicators, costs, logistical feasibilities) are expected. A LCA tool has to satisfy the following functions as a software tool.

- Easy construction and maintenance of models
- Reusability of models
- Transparency of models and hypotheses

Two kinds of method are currently available to carry out LCA. The one is to use LCA tools. However, most of available LCA tools have the following drawbacks.

- Not possible to evaluate regulatory or management policies
- Limited ability to evaluate new recycling processes and product designs
- No consideration of dynamic behavior of product lifecycles
- No consideration of logistics or SCM in product lifecycles

The other is to use a custom made LCA program to meet the specific requirements. However it has following drawbacks.

- Program development needs resources and time
- Models and preconditions are hard to be understood by other people
- Reusability of developed models is limited

We have decided to develop a modelling and simulation system called GPLS (Green Production and Logistics Simulator) to meet the above-mentioned requirements.

GPLS Model

The GPLS model structure is designed based on the basic concepts described below. The first concept is modular modelling. Based on this concept, a product lifecycle is modeled as Unit Processes (UPs) and their links. A PET bottle resin lifecycle is configured from Resin Manufacture UP, Bottle Manufacture UP, Consumer UP, Local Government UP, Transport UP and Recycler UP and their links. Combined UP (CUP) is defined on the boundaries of the model and gives boundary conditions. In a PET bottle resin lifecycle, manufacturing of PTA, EG, production of beverage, cap, label, and landfill are defined as CUPs.

Although modular modeling simplifies the model management and increases reusability of models, its effect is limited. As we analyzed each UP more closely, we found that UP can be constructed from only three kinds of elemental UPs: Transportation UP, Logistic UP and Manufacturing UP. Transportation UP models a transportation of material from one place to the other without quality change. Logistic UP models merging and branching of material flows, and accumulation of stocks. Manufacturing UP models the transformation of material quality.

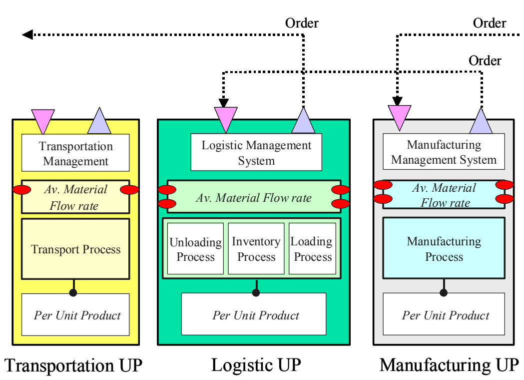


Figure 1 Transportation UP, Logistics UP and Manufacturing UP

UPs representing individual companies, factories or smaller regions may be combined to configure UPs representing industrial sectors or regions (e.g. industrial sector, province and prefecture). Those higher-level UPs in turn can be combined to configure the UP representing an entire PET bottle resin lifecycle of a whole country. Elemental UP has an internal structure based on the concept of Multi-Dimensional Formalism (MDF) that enables an explicit representation of structural, behavioral, and managerial perspectives. The core of this formalism is based on the more general multi-dimensional object-oriented model (MDOOM) (Batres et al. 1996) that provides a conceptual and generic framework. What distinguishes the MDF from other modeling paradigms is that the management model is separated from the behavior model. Consequently, it is possible to develop a management scheme independently of the behavior model. This is the basis of simulation environments in which different product lifecycles and management schemes can be explored with little burden of model reconfiguration. Figure 2 shows a structure of typical UP. The structure model of this example has two pairs of input-output ports, one pair for the product and the other for the byproduct. The structure model also holds attributive parameters of plant name, location and operation rate. The behavior model of UP has internal state variables and functions to specify the relationship between inputs (e.g. resource flow rates, resource quality), outputs (e.g. product flow rates, product quality) and internal states (e.g. amount of stocks, environmental impacts and energy consumption per unit). The management model has input and output information ports used to exchange data with other UP's management model to execute supply chain management for example. The management can change the attributive parameters of corresponding structure model. The structure model parameters in turn work as constraints on the corresponding behavior model.

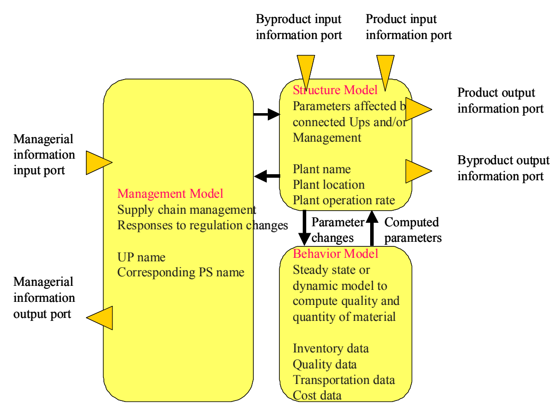


Figure 2 Structure of Elemental UP

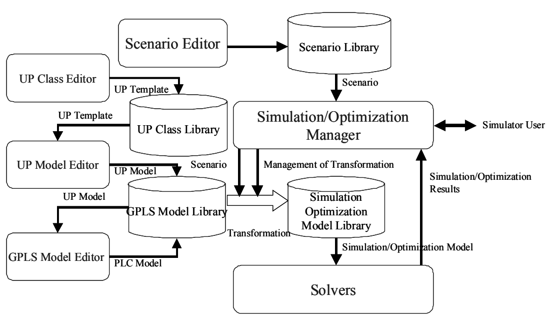
GPLS System

System Configuration

This section describes the system configuration of GPLS. GPLS system consists of four editors (UP class editor, UP model editor, GPLS model editor, Scenario editor), two program modules (Simulation/Optimization manager, Solver) and four data libraries (UP class library, GPLS model library, Simulation/Optimization model library, Scenario library). UP class editor aids the user to define new UP classes or modify existing UP classes by specifying the characteristics of component models and managerial and material information exchange ports.

Defined UP class is stored in the UP class library. UP model editor aids the user to create a specific UP by instantiating UP class. UP model editor checks the user inputs, and extracts and clears inconsistencies in parameters. GPLS model editor aids the user to create a product lifecycle model by linking UPs. Both UPs and product lifecycle model are stored in the GPLS model library. The scenario editor helps the user to specify the evaluation and optimization criteria. The scenario has to be consistent to the corresponding product lifecycle model. The simulation/optimization manager transforms the product lifecycle model into a model format suitable for computation (e.g. partial, differential algebraic equations) and stores it in the simulation/optimization model library. Once a simulation/optimization model is ready, simulation/optimization manager transform the scenario into the input variables, run the simulation using an appropriate solver and show the simulation result to the user.

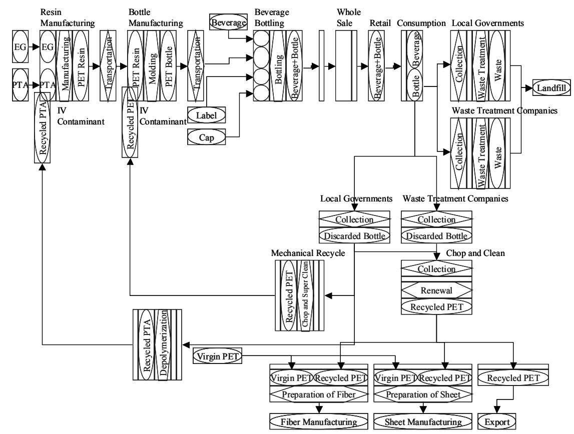
Figure 3 GPLS System



Modeling and Simulation of PET Bottle Resin Lifecycle

In order to examine the performances of GPLS system, a PET bottle resin lifecycle including a chemical and a material recycle has been modeled and a simulation has been executed. The examination shows that the GPLS system successfully computes material balances and quality changes of resin in a PET bottle resin lifecycle. The developed model addresses neither geographical distribution of UPs nor stock accumulation in UPs because the purpose of modeling and simulation here is examining the basic functions of GPLS system rather than obtaining the meaningful results. We are currently working to obtain more reliable process, logistics and inventory data for a meaningful assessment of PET bottle resin lifecycle.

Figure 4 PET Bottle Resin Lifecycle Model



Conclusion

This paper has identified and analyzed the requirements to LCAs. Based on the analysis, a novel lifecycle assessment system called GPLS has been developed. GPLS is unique because it can model dynamical changes of material flow, accumulation of stocks and material qualities, and evaluate the effects of supply chain management, regulations and management policies, geographical distribution of processing facilities as well as new products and processes. The GPLS model structure assures reusability and transparency of models. A GPLS system has been implemented and successfully computed material balances and quality changes in a PET bottle resin lifecycle.

Acknowledgement

This research is done under the framework of the Millennium Project funded by Japanese government. We thank Japanese government, Japan Chemical Innovation Institute and Society of Chemical Engineering of Japan for their support to this work.

References

Batres, R., Lu, M. L., Naka, Y. (1996) A Multidimensional Design Framework and its Implementation in an Engineering Design Environment, *Concurrent Engineering Research and Application*, 7, 43

Kobayashi, M. (2000) The Development of "NIRE-LCA ver. 3", *Proceedings of The 4th International Conference on Eco-Balance*, Tsukuba, Japan,