A Framework for Computer Aided Modeling, Design, and Optimization of Integrated Industrial Systems

Eric D. Williams
Institute of Advanced Studies, The United Nations University

Matthias Troyer[1]
Institute of Solid State Physics, University of Tokyo

Contact Information: Eric Williams
Institute of Advanced Studies, The United Nations University,
53-67 Jingumae, 5-chome, Shibuya-ku, Tokyo 150-8304, Japan
williams@ias.unu.edu

Abstract

Computer aided modeling and design of industrial systems presents great potential for facilitating the construction of industrial systems which maximize utilization of materials, minimize emissions of harmful wastes, and preserve economic feasibility. A framework for modeling industrial systems that is to form the basis of a design system is described. The model takes an industrial system to be a collection of processes each characterized by their inputs and outputs of materials, energy, finances, and labor. A key concept is that of the *hierarchical* input/output table for materials and energy, which is formulated to facilitate the integration of industrial processes. The output of the model acts to evaluate the economic and environmental performance of the system, thus providing a means to compare different configurations. The model has a scale-invariance property that reflects the fractal nature of systems with nested flows. Suggestions are given for a computer design system for industrial clusters, wherein algorithms are used to search process databases to generate designs which link industries together to maximize utilization and profitability.

Introduction

The current societal-industrial system is unsustainable in that it consumes and emits vast quantities of raw materials and energy with little consideration of the long-term effects on humanity and eco-systems. The scale of human activities has reached the same order of magnitude as the scale of the earth's ecosystems and resources, thus creating the potential to significantly alter the earth to the detriment of future generations. Thus if society is to prosper in the long term, it is necessary to better understand and control the effects of humankind's actions on itself and the environment. The needs and wants of human societies are met through the actions of industry. Thus, a key point in progressing towards a sustainable society is finding means to reduce the environmental load of

---

[1] Affiliated with ETH, Zurich from September 1998

industrial activities. Current industry functions under the market system, which implies that the primary design consideration of industrial systems is the maximization of profit. Thus, how to progress towards sustainable industry in the context of the market system is a crucial question. One approach to addressing this issue is the integration of industrial activities.

As human knowledge progresses, we gain a greater understanding and ability to manage complex systems. In the context of industry and sustainability, Industrial Ecology (Frosch and Gallopoulos 1989), Industrial Metabolism (Ayres 1994), and Zero Emissions (Pauli 1996) have recently come forward as approaches addressing how a systems viewpoint can address the issue of sustainable industry. The common theme in these approaches is to look beyond the individual processes of extraction, manufacture, consumption, and re-use to consider how they link together to form a system. A typical industrial system today is "open", meaning that materials and energy are taken in and disposed of freely, the main constraint being the minimization of cost for producing a given product. Such open systems generally only utilize a small fraction of the input materials and energy, to progress towards sustainable industry there is clearly a need to "close" the system as much as possible. An important component of closing the cycle of materials and energy is the integration, or clustering, of industrial activities. Integration in this context is the linking of industrial processes such that interconnected whole utilizes materials and energy effectively and emits minimal waste. The key point is how outputs of a given process can be used as input for other processes, instead of being dumped or emitted and thus becoming waste. An especially attractive aspect of such linking is that as in many cases finding a use for wastes generates economic value, it has potential to increase profitability as well as reduce environmental impacts. Zero Emissions emphasizes this value-added use of outputs as inputs as a key to creating "industrial clusters", which are groups of industries linked together in symbiotic relationships to minimize waste and maximize profitability.

There is some tendency for industrial systems to self-organize towards integration, as evidenced by many examples of industries selling unused "wastes" for use in other contexts. Generally, these points of connection were established through bilateral recognition of the economic advantages between the two parties involved in the relevant processes. An example of where this bilateral self-organization has resulted in a high level of integration occurs in the industrial district at Kalundborg, Denmark (Ehrenfeld 1997). However, looking at industry overall, the average degree of integration would appear to be rather low in comparison with its potential. In addition to bilateral self-organization of integrated industries, which proceeds without any overall plan, it is important to consider the potential for achieving integration through careful organization of the system. This planning could be done through a multilateral process involving different parties, and/or through one or two parties having control over a series of processes. The modern oil refinery is an example of sophisticated process integration within a given industrial sector. Controlled design presents improved possibilities for discovering the economic and utilizational advantages of integration, as in many cases benefits will be realized not just at the exchange point of two processes, rather from a more holistic view of the system.

The integration of industrial systems is a compelling idea, but how to progress towards realizing this potential in practice? Implementation requires, along with a concept, an appropriate "infrastructure". For instance, Just-In-Time manufacturing, now viewed as almost an essential technique for cutting costs in the automotive industry, would be but a fanciful idea without the production and inventory monitoring systems, communications infrastructure, and management mechanisms needed to implement it. In the present case, there is a need for a bridge between the concept of integration and practical designs for integrated clusters. The focus of the current work is to contribute to developing techniques for modeling industrial systems and designing them towards integration. The modeling system, as in the Life Cycle Analysis (LCA) (Curran 1996) of products, uses input/output tables and system process diagrams to calculate the flow of materials and energy of an industrial system. It will in general be implemented via a computer and provides quantitative information on the economic and environmental performance of a given industrial system, either existing or planned. The model is to be used in conjunction with a design system, wherein computer algorithms search process databases to find possible links between industries. Given a set of possible links, computer algorithms optimize process composition and size for minimal waste and maximal profit.

When addressing the issue of sustainability, economics, resource utilization, and environmental impacts are essential components, but it is also important to consider effects on society as well. The larger issue of what are the benefits and costs a given industrial system has on society as a whole is of course very complex and varies according to the value system applied. However, a more limited, yet very relevant question can be addressed. To what extent does the activities of an industrial system directly provide income to support human life? Concretely speaking, how many people are supported at roughly at what level? This societal aspect is also to be included in the modeling framework.

Modeling Industrial Systems

The system to be modeled is a specific network of linked industrial activities, which is to be collectively called the industrial system. The individual components are processes, which are connected together through flows of materials, energy and capital. A process refers quite generally to a transformation of materials, given the application of technology, labor, and capital. Inputs to processes come from natural resources or other processes and outputs feed into the market, other processes, or are emitted into the eco-sphere. An example of an industrial system, a concept for a Zero Emissions industrial cluster, is shown in Figure 1. The full input/outputs of the system are more extensive than those in the figure, they have been simplified for demonstration purposes. The individual processes are: malt barley farming, beer brewing, mushroom cultivation, fish aquaculture. Although this example is an agricultural system, the model and design system to be described are quite general, applicable to any industrial sector. The products produced for the market in this example are malt barley, beer, fish, and mushrooms. The key symbiotic links are: waste grain from the brewing process, which is low in starch but high in protein, is used as a medium for growing mushrooms. Warm wastewater from

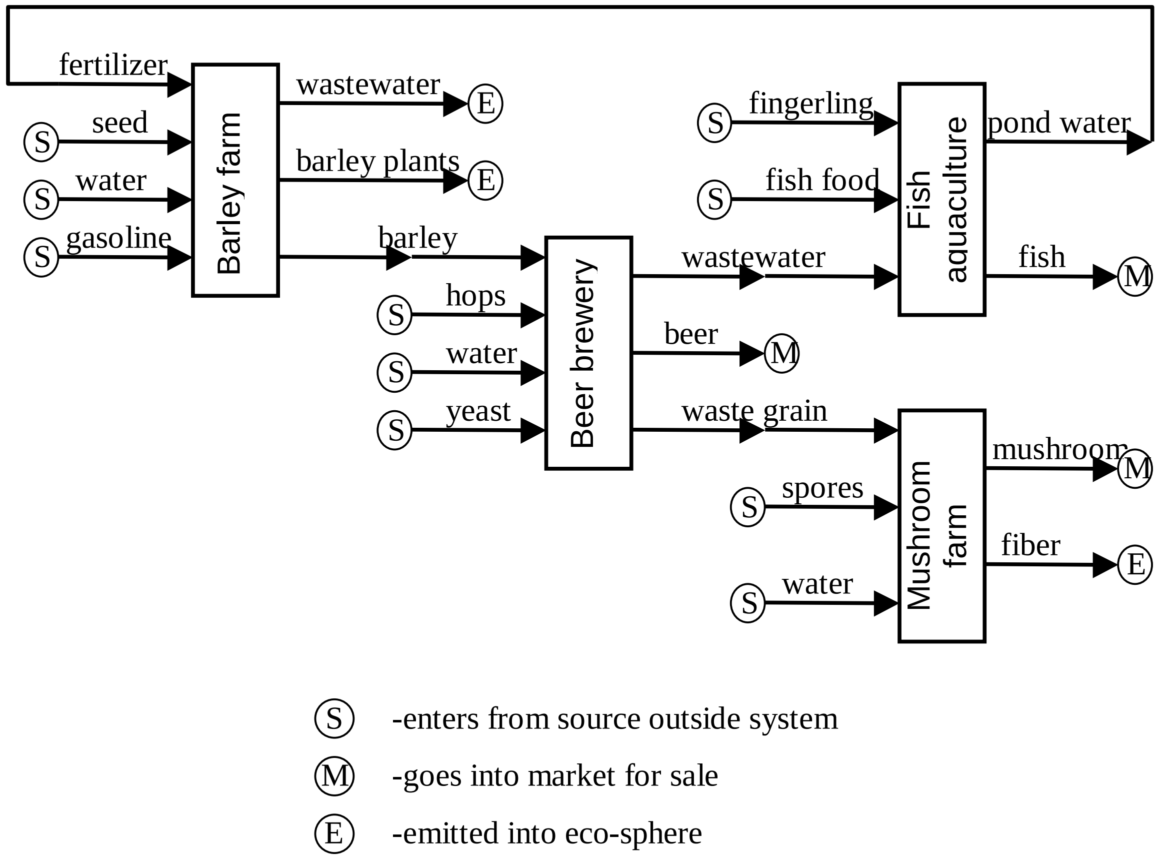

Figure 1: Industrial cluster based around beer brewery

from brewing contains many organic substances, resulting in a very high biological oxygen demand (BOD) and requires treatment before dumped. This water can instead be used in the aquaculture of fish, where its nutrient value serves as fish food, and its warmth reduces heating costs. In order to keep the model manageable, the system by has *cutoffs*, or rather processes that are not included in the system. In the example, the process for raising hops is not included. Cutoffs are imposed depending on the objectives in mind in creating the model, this is part of what is known as the “scope” or “boundaries” of the problem in the context of life cycle analysis of products (Curran 1996). Inputs and outputs into the overall system are designated as *external flows*, which range from raw materials or finished products from other systems, depending on the scope of the system being considered. *Internal flows* remain within the system. In the example, hops, for instance is an external input, while barley is an internal output of the barley farming process and an internal input of the beer brewing process.

The components of the model are divided into the three categories: processes, materials (and energy), and the system itself. The system is described by its component processes, the materials involved, and in the links between processes.

A process refers generally to a transformation of materials and energy, and is described by:

1. *Hierarchical* input/output tables of materials and energy;
2. Running costs to implement process;
3. Number of persons employed, fraction of costs expended on salaries.

All three items are in general non-linear functions of system size, an issue to be discussed in more depth later.

A *hierarchical* input/output table contains information on the input and output of materials and energy for a process. Its purpose is twofold. One is to keep track of material and energy flows in the industrial system, which is effected through listing the amounts of substances taken in and emitted. This is the same role as played by conventional input/output tables used in LCA. The other purpose is to facilitate the identification of value-added input uses of process outputs. An essential point is that although in many cases it is convenient to think of inputs and outputs as pure or elemental substances (or products), in practice they are always mixtures of substances, and the composition of this mixture is crucial with regards to its use as input for another process. The target of the hierarchical input/output table is to provide a description of input and output streams useful for the integration of processes. The most basic level is that of the input or output streams, which are utilized by the process physically separated from one another. Basic parameters of the stream are its phase (liquid, solid, gas, or mix), temperature, mass, and density. The mixture of substances inside a given stream is described hierarchically, according to different levels of organization of matter. The simplest non-trivial case is a mixture of simple gases (say a binary mixture of oxygen and nitrogen), for which the mixture is just described by the relative amounts of the gases (e.g. 70% nitrogen, 30% oxygen). For a more complicated mixture, for example an agri-business process output such waste grain from the beer brewing process, some insight and judgement must be called on to usefully characterize the substance. For instance, considering its possible value for providing nutritional value to other organisms (plant or animal), it is useful to break down the composition into relative contents of carbohydrates, proteins, and fiber. Then, this level of organization can be broken down further to relative amounts of the most important elements contained, carbon, nitrogen, and potassium. Obviously, there are subjective choices involved in organizing the hierarchical description of a mixture, and that the same mixture can be described in different ways. But any description that reflects the mixture nature of the stream is of potential value in identifying uses. A sample hierarchical input/output table appears in Table 1. The actual numerical values in the table are only approximate, the issue to focus on is the form. Note that for composition level 2 of the gas output stream that the composition of organic volatiles is only partially listed. Of course a complete breakdown of the mixture is preferable, but a listing of what is known is often useful and also clarifies the direction for future refinements.

Contrast the hierarchical input/output table with a typical one as used in LCA, as shown in Table 2. Such a table is useful for its intended purpose, which is to evaluate the environmental impact of emissions from the process. But the implicit assumption in such a table is that the non-product output streams will be emitted as a waste, and thus its focus is on finding the impact of that emission.

Output stream 1: from closed fermentation	Composition(level 1)	Composition (level 2)
Phase:gas Temp: 25C Mass: 38kg	80% carbon dioxide	
	10% dry air	
	5% water	
	5% Organic volatiles	2%: s-methyl methionine, 2.5%:dimethyl sulfide
Output stream 2: Wastewater from brewing	Composition(level 1)	
Phase: liquid Temp: 30-40 C Mass: 9000 kg pH: 5.0-6.5	98% H_2O	
	.5% sugars	
	.9% proteins	
	.4% carbohydrates	
Output stream 3: Spent grains after worter tun	Composition level 1	Composition level 2
Phase: solid Temp: ambient Mass: 250 kg	60% H_2O	
	10% proteins	50% ruminant digestible
	15% fiber	
	10% carbohydrates	
	5% fats	

Table 1: Selected outputs from a *hierarchical* input/output table
from production of 1000 kg of beer

Emissions to Air	Amount	Comments
carbon dioxide	30 kg	
s-methyl methionine	30 grams	
dimethyl sulfide	47.5 grams	
Liquid Emissions		
Wastewater	9000 liters	(BOD 7 kg/m^3)
Solid Emissions		
Waste grain	250 kg	Inert

Table 2: Selection of input/output table for production of 1000 kg of beer

For each material appearing in an input/output table, the following data is required:

1. name and description,
2. unit of measurement,
3. buy and sell price for market items,
4. cost of disposal,
5. environmental impacts involved in the emission of a unit amount of the substance.

The environmental impact involved in the emission of a given amount of a substance is has been under intensive study, especially in the context of Life Cycle Analysis (Curran 1995), which endeavors to quantify that impact. There have been many systems developed to convert an emission amount into a numerical environmental impact, a common approach is to first separate environmental impacts different categories of phenomena, such as global warming, acid rain, and human and eco-system toxicity, eutrophication, etc. Then within the context of a single phenomenon, the contribution of a given emission can be estimated. Some systems, such as Eco-Indicators 95 (Goedkoop 1995), assign weights to the various phenomena in order to arrive at a unified environmental impact index. In the above description for a material, either separate impact values for the different phenomena or a unified index can be applied.

Given the above information on processes and materials, the configuration of the overall system is specified by the size of each process and in how it is connected to other processes. For bookkeeping purposes, it is useful to also introduce source and sink processes. Sources represent points where materials, either raw or finished products, flow into the system from outside. In the language of the model, this is represented by an input/output table with no inputs and one output, and size. Sinks represent materials or products leaving the system, and thus possess one input and no outputs, and size. The two basic types of sinks are the market and the eco-sphere. Context dependent sub-categories are also helpful, for instance in what aspect of the eco-sphere an emission takes place: solid waste dump, local water stream, the atmosphere, etc. Depending on whether the model is being used for evaluation or as part of a design system, the process sizes can either be input manually, or else generated by an optimization algorithm.

Given the system configuration described above, the model generates the following output:

1. Amounts of materials and energy input into the overall system
2. Amounts of products generated for sale on the market
3. Amounts of emissions of into eco-sphere
4. Estimated profitability of system. This is determined according to:

   Profitability = Revenues – Expenses.

   Revenues are calculated according to the formula

$$\text{Revenues} = \sum_{\substack{\text{products}\\ \text{to}\\ \text{market}}} (\text{amount produced})\,(\text{sell price})$$

and expenses are given by

$$\text{Expenses} = \sum_{\substack{\text{input}\\ \text{materials}}} (\text{amount used})(\text{buy price}) + \sum_{\substack{\text{system}\\ \text{processes}}} (\text{size of process})(\text{unit running costs})$$
$$+ \sum_{\text{wastes}} (\text{amount emitted})(\text{cost of disposal}).$$

5. The total estimated environmental impact of the system. In the case of a scalar impact (one weighted impact taking into account various phenomena), the formula is:

$$\text{Impact} = \sum_{\substack{\text{ecosphere}\\ \text{outputs}}} (\text{amount emitted})\ (\text{impact/unit emission}).$$

6. Employment involved in the system.

The variables chosen as well as the standard of accuracy that data must meet, vary with the purpose with which one is constructing the model. For a qualitative picture, the above variables with rough values of data should suffice. But if a more quantitative description of economics is being sought, for instance, precise data as well as additional variables, such as variables describing investment costs and depreciation of equipment are needed. Also, the input data can be very process and location specific. A different design of beer brewery will have somewhat different inputs and outputs and materials and operating costs can be quite different according to the location.

Scale Invariance Property and Fractals

The output for the overall system is of the same form as that of the initial data for an individual process. That is, the output for the overall system yields hierarchical input/output tables of materials and energy, the prices of inputs, the market values of product outputs, etc. Thus the overall system can be thought of as an elemental process, with input data given by the output of the model describing the internal structure. This is the basis for the "scale invariance" of the description of the industrial system. This scale invariance has the consequences:

- The same description or model can be used for industrial systems at different scales of resolution,
- The fine resolution description of a system flows naturally into that for larger scale systems.

Scale of resolution here means the scale at which the system is divided into processes and flows. For example, in the example of industrial cluster involving beer brewing, beer brewing was considered as a elemental process, but in fact can also be considered to be a system with sub-processes and flows between those processes, as shown in Figure 2.

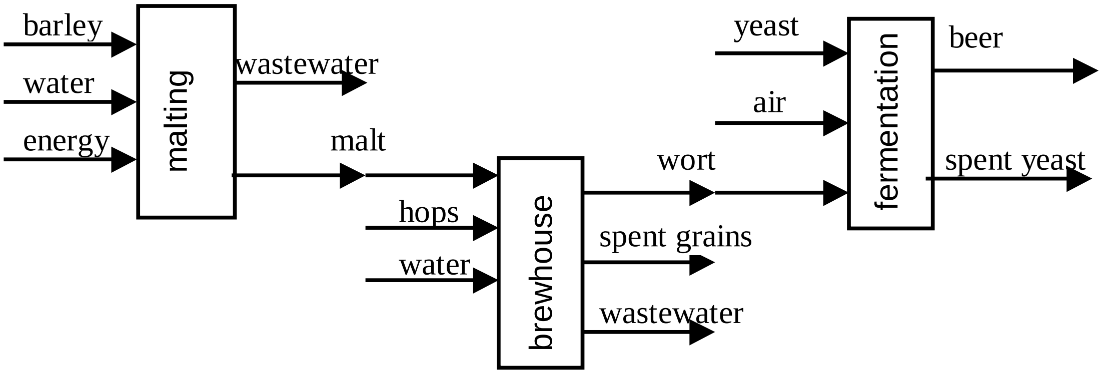

Figure 2: Internal process structure for brewery

In this finer scale of resolution, the brewery is composed of the processes of malting barley, heating malt, hops and water together to make wort, and then the fermentation of that wort with yeast. Conversely, the whole industrial cluster could be thought of as an elemental process, which is then connected with other systems, such as the "processes" producing wheat, fertilizer, etc. Such is illustrated in Figure 3.

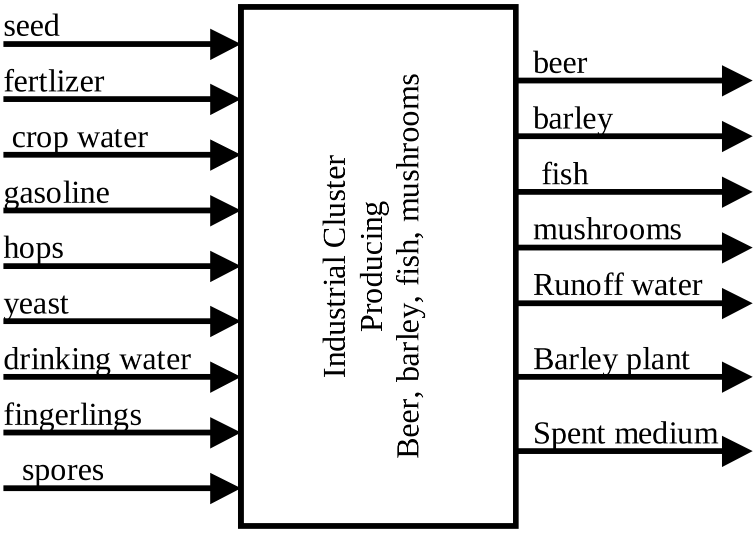

Figure 3: Beer brewery based cluster viewed as single process

This coarse grained analysis could be extended to such macroscopic levels as describing input-outputs at the national level. Regardless of the scale of the building blocks, the same description can be used, and in fact all information from finer grained descriptions translates directly into information for coarse-grained descriptions, an extremely useful property. This indicates an efficient method to organize the work involved in gathering the necessary data needed to describe a system. First, break the system into sub-processes and connections between sub-processes. For each sub-process, the specialists in that area are charged with determining the input/output tables of materials and capital for that sub-process, a manageable task for which they are the most suited for. Then the sub-processes can be simply integrated together to provide the description of the overall system. Such a gathering of flow data is in line with the increasing trend towards documentation and analysis of a given industry's internal processes, as reflected by the increasing implementation of ISO 9,000 and 14,000 series standards as well as by the increasing use of LCA. An analysis of the internal structure of an industry has proven to be extremely useful for understanding how to optimize the system.

The above discussion reflects a general property of systems of nested flows, be they industrial or biological. A system with nested flows is one in which the system is composed of structural units but also each structural unit has its own composition. There are flows between the larger units and also within, thus there are flows within flows. Nested flows constantly reoccur when examining biological systems. For instance, consider the Krebs Cycle, which is one component of the cycle that converts glucose and oxygen to carbon dioxide, water and various energy rich molecules (Keeton 1983). Within the overall functional unit that achieves this conversion, there are smaller ones that carry out individual steps of the process and each individual sub-process also displays its own flow of inputs and outputs. Nested flows of complex systems resemble in many ways the patterns observed in fractals. Fractals are geometrical objects that have the property that they display the same pattern over different length scales (Mandelbrot 1984). An example of a fractal is shown in Figure 4. Fractal designs occur frequently in nature, such as in the structure of fern leaves. The fractal nature of the nested flows in complex systems, quite aside from its aesthetic quality, aid in organizing the description of such systems.

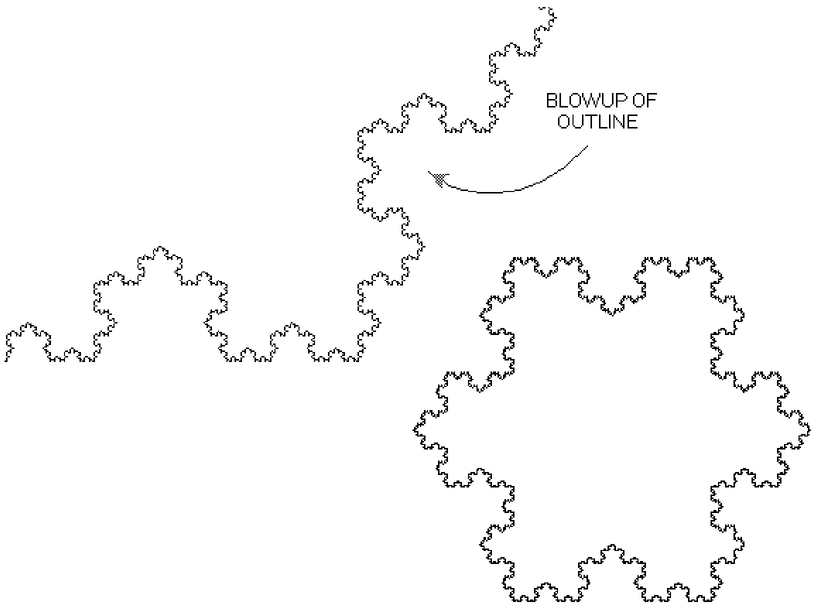

Figure 4: Example of a fractal - the Koch curve

Design and Optimization of Industrial Systems

Given the above modeling system, what role can it play in facilitating the integration of industries? Three major aspects are:

- I. Aid in the identification uses of process outputs as another process's input,
- II. Evaluation of the environmental and economic performance of proposed designs for integrated systems,
- III. Computer aided design of an integrated system via optimization algorithms.

Establishing economically feasible output to input uses is a cornerstone in building integrated industries. A major barrier to the creation of such links is the sequestration of knowledge. Such links often cross industrial sectors, so unless there is communication between the two sides, the parties involved simply do not know of the possibilities of cooperation. The establishment of a cross sectoral database of hierarchical input/output tables can play an important role in facilitating information exchange and thus the formation of links. Those involved in a given process could examine the database for industries that could use their waste streams as inputs. In addition to the database, a means of searching the database is important. Algorithms can be designed to match output streams to input streams. As such streams are generally very complex objects, it will in general be impossible to provide a perfect match, but it is possible to narrow the field of possibilities to a workable number. The real feasibility of a link is determined through discussions and development carried out by the parties involved in the two given processes.

Another use of the model is in evaluating proposed designs for integrated systems. Evaluation is an important component of the design process. For the design of products, Computer Aided Design (CAD) systems are currently in extensive use to test the performance of product designs, reducing considerably the need to build prototypes as well as expanding the space of designs one can feasibly consider. Evaluation tools are even more important in the design of industrial systems, as the scale of investment of capital and labor is greater. Computer modeling of industrial systems can play an analogous role to that for products. Given a proposal for an integrated industrial system, the key characteristics, profitability and the utilization of materials, can be estimated through modeling the economic and materials flows as described above. Different combinations can be tested, and configurations sufficiently promising to be worthy of more in-depth study can be identified.

The model also provides a language on which to base a design system for the algorithmic optimization of the profitability and utilization of an industrial system. Let the sizes of the processes in a system be variable, denoted say by $s_1,\ldots,s_N$. The profitability and environmental impacts of the system then become functions of these sizes. To optimize the system, find the values of the sizes that maximize the function

$$\text{Profitability}(s_1,\ldots,s_N) - \alpha\ \text{Impact}\ (s_1,\ldots,s_N),$$

where profitability and impact are computed according to the model prescription described above. α is a parameter that converts the impact parameter into a monetary value. Maximizing a negative number times a function is equivalent to minimizing the function, so the maximizing the above formula endeavors to maximize profitability and minimize impact. There is as yet little agreement on how to assign a monetary value to an environmental impact, but this is not an obstacle. If the integration of the industry is in fact generating a positive economic outcome, then the system configuration resulting from the optimization will be *essentially independent of* α. Thus, one can test whether the integration is stable economically or not by performing the optimization for various values of α.

The mathematical optimization for a wide variety of systems can be carried out using a straightforward extension of the simplex method. The simplex method allows for the for optimization of a general *linear* multivariable function $F(s_1,\ldots,s_N)$, where each of the variables is restricted to lie in a interval $l_i < s_i < u_i$, where l_i and u_i are lower and upper bounds on the variable (Nash, 1996). In the present context, this corresponds to systems where say the running costs for production is a linear function between upper and lower bounds on the size of a factory or process, as illustrated in figure 5. The lower and upper bounds corresponds to the smallest and largest reasonable sizes of factories. The optimization of such a form of profitability has its uses, but one can also address cases where the optimization problem will be nonlinear. Due to effects of economies of scale, running costs are often nonlinear functions of the size of a factory. A simple approach to handle this non-linearity is to break the possible system sizes into separate sub-intervals and take the cost/unit production, etc. to be distinct linear functions over each sub-interval. The simplest case of this to allow for a system size to be zero, or in within a given interval, as shown in figure 6.

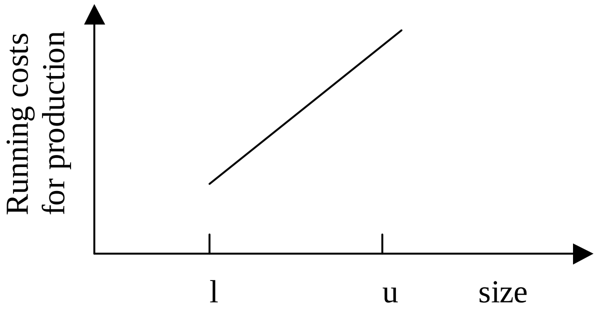

Figure 5

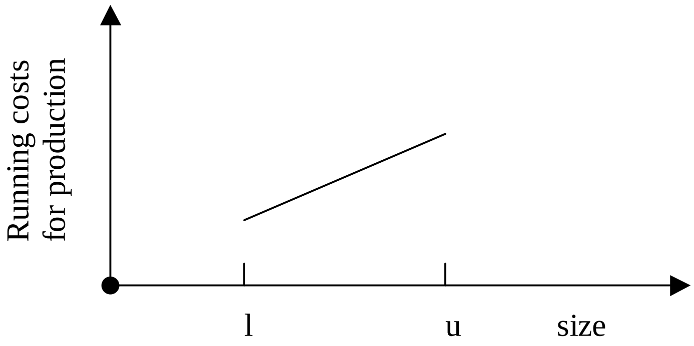

Figure 6

This allows processes to be cut from the proposed set if they do not favor optimization. To optimize such a system, one applies the simplex method twice, once assuming a size of zero, again assuming a size within the interval, and then one compares the value of the optimization function in both cases. A more complicated case would involve three intervals, e.g. running costs as shown in figure 7. In this case, the

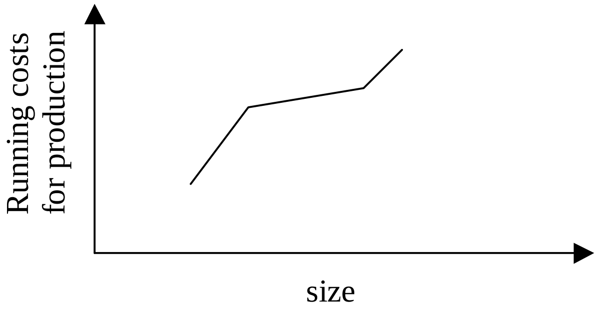

Figure 7

running costs increase sharply for of a smaller size factory, but level off in an intermediate range, but then climb again sharply for a very large facility. This roughly models the common situation where the cost/unit production falls for a larger size factory but climbs again if the facility becomes exceedingly large. If all N processes in the system have this structure of cost function, one performs the optimization 3^N times, once for each possible configuration of subintervals, and then compares all these results to find to the optimal set of sizes.

Extending the above discussion, one can readily optimize any system described by piecewise linear functions. Any nonlinear function can be approximated by a piecewise linear one, and in the case of modeling industrial systems, this approximation can be made accurate enough for all practical purposes. However, as seen above, the number of optimizations required grows exponentially with the size of the system, with the base being the number of subintervals chosen. For large systems with complex nonlinear behavior, it may be more appropriate to directly optimize the nonlinear problem without conversion to a piecewise linear one. There are techniques for optimizing nonlinear systems as well, however it is not generally known if a global minimum exists or not. In the current context, though, it should be emphasized that if optimization yields a design that appears both profitable and relatively waste-free, ignorance of whether it is a true global minimum or not does not detract from the value of the design.

Regarding the present status and future work in this direction: A basic software engine implementing the described modeling and optimization system is complete. Data on example industrial systems is being collected and application of the model and design system will appear in future articles.

Generalizations

The modeling and optimization system described above prescribed a specific set of variables to describe an industrial system, largely in the context of describing a local industrial cluster. Both the scope of the system considered, as well the description of the internal functioning of the system can be modified to suit the context of the problem under consideration. A few possible modifications will be discussed here, the point is that a useful system is adaptable to the purpose and circumstances of its use.

Regarding a the scope of system considered, thus far systems starting from raw materials to the production of market products was considered. However the interaction between production, consumer use, recycling, and re-manufacture can also be described. Such aspects can be taken into account by adding in appropriate process diagrams for the market, use, and post-use of products.

With respect to the internal description of, transportation of materials between sites, can also be included. The geographical distribution of elements in an industrial system can be quite important: availability, costs, and revenues of a given process vary considerably from place to place. In a spatially spread out system, the cost of transportation and its environmental impacts become important. The effect of transportation is included into the model by the addition of transportation processes between sites, and inserted into the process diagram for the system.

Conclusions

This work has outlined an overall framework for the modeling and design of integrated industrial systems. In the context of academia, it can be used for the formulating of simplified models that aid in the identification of symbiotic links between process and in the evaluation of economic and environmental performance of designs for industrial clusters, and in generating optimal designs. In order to a construct real integrated system that can function in the market, however, requires an intimate knowledge of the industry, which includes access to detailed process and market information. What actor is in the best position to find matching industrial partners, and carry through the design and optimization of an integrated system? The natural answer is industry itself, though there are obstacles, primarily arising from the division of industry into distinct production niches. In order to connect processes across sectors, cooperation is required, which includes exchange of information. However, intra-niche competition forms a barrier to a sharing of information that facilitates inter-niche symbiosis. Large corporations are engaged in a multisectorial range of industries, and thus within the firm there is the potential to integrate activities within their domain. However, an important trend to identify is that industry increasingly outsources planning, restructuring and design to consulting firms. They are potentially the ideal agents to facilitate the creation of symbiotic industrial clusters. Consulting firms interact with many different firms on a confidential basis, thus having access to the information needed to carry out design and optimizations of realistic systems. Additionally they are able to assemble an interdisciplinary team of experts that is required to engineer such process-to-process connections.

Modeling of industrial systems is of course an immense field, and in the Life Cycle Analysis of products, materials, energy, and economic flows are often calculated in a manner similar to what was discussed. What then, are the key points being made here? All stem from the central question being asked: how can quantitative system approaches facilitate the integration of industry? From this question it follows, for instance, that the extension of the usual input/output tables to hierarchical ones is crucial for the identification of output to input uses of materials. Also, shifting one's perspective towards the profitability and impact of a multi-product system leads to allowing process sizes to be variable, and thus available for optimization. The proposal that integration should be economically favorable suggests a natural optimization method. And in order to make the management of process and system information manageable, it is useful to recognize the fractal nature of the system's nested flows.

References

Ayres, R. and U. Simonis. 1994. Industrial Metabolism: Restructuring for Sustainable Development. Tokyo: UNU Press

Curran, M. 1996. Environmental Life Cycle Assessment. New York: McGraw Hill

Ehrenfeld, J. and N. Gertler. 1997. "Industrial Ecology in Practice: The Evolution of Interdependence at Kalunborg", *Journal of Industrial Ecology* 1 (1): 67-79

Frosch, R.A. and N. Gallopoulos. 1989. "Strategies for Manufacturing." *Scientific American* 261 (3): 144-152

Goedkoop M.J., M. Demmers M. and M.X. Collignon M.X. 1995. The Eco-indicator 95, Manual for designers. NOH report 9524; PRé consultants; Amersfoort (NL). ISBN 90-72130-78-2

Keeton W. and C. McFadden. 1983. Elements of Biological Science. 3rd ed. New York: W.W. Norton & Company, Inc.

Mandelbrot, B. 1984. The Fractal Geometry of Nature.W.H. Freeman Press
Nash, S. and A. Sofer. 1996. Linear and Nonlinear Programming. McGraw-Hill

Pauli, G. 1996. Breakthroughs: what business can offer society. Haslemere: Epsilon Press