

Systems Approach to Industrial Pollution Prevention with the Application of Fuzzy Set Methods

Wayne Woldt, Dr. Bruce I. Dvorak, and Jack Sheng

University of Nebraska – Lincoln, 253 LWC, Lincoln, NE 68588-0726, USA

Phone: (402) 472-8656, Fax: (402) 472-6338

e-mail: wwoldt1@unl.edu

University of Nebraska – Lincoln, W348 Nebraska Hall, Lincoln, NE 68588-0531, USA

Phone: (402) 472-3431, Fax: (402) 472-8934

e-mail: bdvorak@unlinfo.unl.edu

Phone: (402) 472-5501, Fax: (402) 472-8934

e-mail: jsheng@engrs.unl.edu

ABSTRACT: This study develops a framework and methodology to incorporate imprecise parameters from an industrial manufacturing product coating process into a formal system analysis. A system model is developed for the analysis of the solvent process loop. The imprecise variables associated with the coating process are managed by fuzzy set theory. The goal of this research is to develop a reliable method for industries to identify potential pollution prevention opportunities when exact or crisp operation parameters are either hard to obtain or unavailable.

KEYWORD: Fuzzy Set, Systems Analysis, Air Emissions, Pollution Prevention, Clean Technology

INTRODUCTION

The term pollution prevention, or clean production technology, describes the process of identifying methods of reducing or eliminating the generation and/or toxicity of wastes, which are typically a by-product of the production of a useful product. In industrial situations, pollution prevention can be accomplished through a wide range of methods, each specific to the industry's manufacturing process. Pollution prevention frequently is profitable for industries because it can reduce or eliminate regulatory monitoring and reporting requirements, bring in new clients who desire green business partners, saves money by reducing costs (raw material usage, waste disposal, environmental permitting, and liability for environmental damage and improper waste disposal), and enhances employee moral (eliminating workplace hazards). Pollution prevention can save industries between 3 and 6% of gross revenues (Liebl, 1996). Some examples of pollution prevention strategies are: substituting a less hazardous input to produce a less hazardous waste, modifying the manufacturing process (time, temperature, etc.) to produce a less toxic waste, designing new products with sustainability in mind, and adding telemetry to a process so less waste is produced. On a nationwide basis, industrial ecology holds great potential in terms of industries that can benefit significantly from tools that help identify cost effective methods of reducing pollution and its associated costs.

SYSTEMS ANALYSIS UNDER IMPRECISE CONDITIONS

Industries have a difficult time identifying pollution prevention opportunities and in quantifying the potential cost savings from these opportunities. The best method of helping industries is to provide them assistance from technical experts in pollution prevention. Unfortunately, it is not possible for university extension services and state and federal environmental regulatory agencies to supply such personalized support on a large scale. Instead, a wealth of "how to" manuals have been created, many specific to a narrow grouping of industries (e.g., metal plating). The use of these manuals requires a significant time investment, particularly to quantify the potential payback for

investing in pollution prevention. To reduce the initial time input on the part of an industry, the U.S. EPA has developed some computer software to help an industry identify potential pollution prevention solutions.

However, these existing pollution prevention assessment programs (such as those for mass balance and cost accounting) are somewhat difficult to use and require the user to determine the exact or crisp value for a large number of input parameters required to characterize the process streams and the system costs. Several spreadsheet-based financial analysis tools have been created (e.g., US EPA, 1992 and 1994). SWAMI (PEER Consultants, 1992) was developed for checking materials balances using crisp data and helps the user identify potential pollution prevention solutions. Other software such as P2-Edge (IJS Dept. of Energy, 1995) helps users identify general applications of pollution prevention for industrial processes. P2-Edge has the user rank each input as one of three levels, high, medium, or low, for all questions (such as the relative cost of each input or the quantity of the input). Unfortunately, exact values for the parameters required by the existing programs are often not readily available and can be costly and time consuming to determine, particularly when the industry does not see the potential payoff for such an assessment. Without accurate data, the use of the existing tools turns into a "What if" game where the user has no guidance in selecting reasonable input values and no way of assessing the "error margins" of the results.

A possible alternative is to build upon these existing tools and techniques by incorporating the ability to utilize imprecision and subjective information as input to the systems analysis process. An attractive and innovative area of research is the use of fuzzy set theory to capture this imprecision and subjective information. The literature is just beginning to yield fruitful concepts, in terms of systems analysis techniques that utilize fuzzy information and can be integrated into the proposed systems analysis approach. The problem of system identification, which will be important in this project, has been presented in a fuzzy form by Chen et al. (1995). In this case the synthesis of a fuzzy closed-loop control system based on relational equations is performed in order to assure system stability. In addition, Mannle et al. (1996) describe a general approach to fuzzy modeling of a nonlinear, multiple input, single output system. They employ a powerful nonlinear optimization routine to solve the fuzzy system. Systems analysis has also entered the time domain in research reported by Muhlenfeld (1996) in which fuzzy identification and control and time-variant processes in a system is described. An important issue to be considered in this research is the dependency of system variables. This dependency has been described by Dou et al. (1997) and results from "compensation" between dependent fuzzy variables.

IMPRECISION INPUTS IN DECISION MAKING

It is well known that government regulations, along with industry's desire to produce products in an environmentally friendly manner while remaining competitive, have introduced a variety of new challenges into the industrial decision making process (Kennedy, 1993). These objectives often conflict with each other and have different measures of acceptability, making it difficult to find common ground for comparison and decision making. To further complicate the process, many of the defining parameters for a given objective are hidden (sometimes termed an externality), and/or difficult to estimate. Yet this information is critical to good decision making, and extremely important when considering competing alternatives from a pollution prevention perspective. In order to make more effective industrial decisions, a computer model is developed that is based on the concept of Multi-Criteria Ranking methods and builds upon initial modeling efforts (Woldt et al., 1998). In addition, since some of the data are quite uncertain, due to proximity in both space and time, the model will be able to consider information that may be described linguistically and characterized as "fuzzy". The methodology is referred to as LCA Decision and is based heavily on a multiple criteria ranking procedure termed composite programming.

By combining identification of pollution prevention solutions with an analysis of the costs and benefits of applying such a solution, a powerful tool will be available for industries to determine the most appropriate pollution prevention opportunity for implementation. The concept of this analysis tool is illustrated in Figure 1. As for the focus of the present research, it is targeted at developing a framework for incorporating imprecision using a systems approach to identify pollution prevention opportunities.

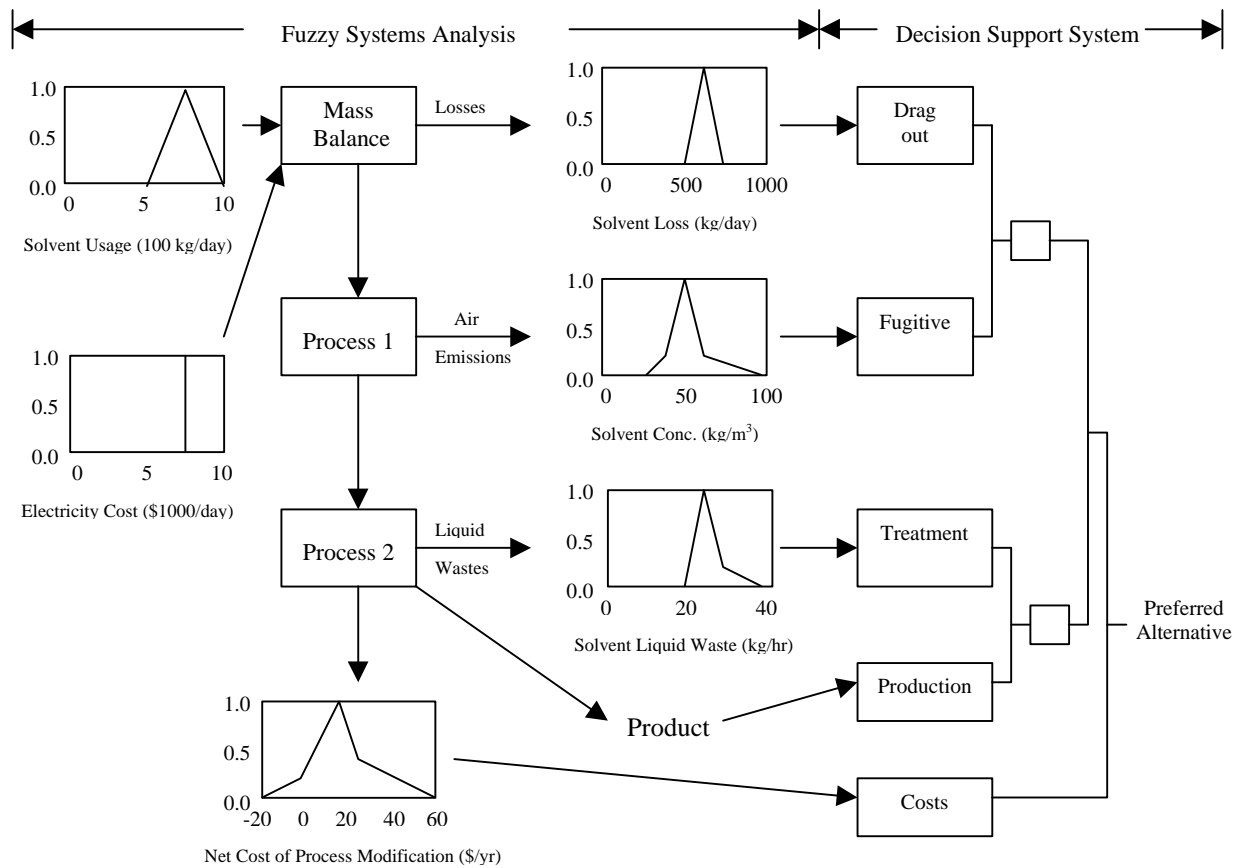


Figure 1. Schematic of relationship between fuzzy analysis and multi-criteria decision making.

METHOD OF APPROACH

Fuzzy analysis is used to incorporate imprecise inputs to the system. A simulation of the industrial system is performed with the MATLAB software (Fuzzy Logic Toolbox 2.0). Data collected from the solvent reclaiming process of a Mid-West manufacturer will be used in this study to model the sensitivity of variables in the system for varying conditions.

INDUSTRIAL PROCESS DESCRIPTION

The finishing process of this Mid-West manufacturer involved the application of a friction reducing coating to the product surface. The coating solution is a silicone based lubricant dissolved in a volatile organic carbon (VOC) solvent, which is prepared in the chemistry lab according to specific formulation and compositions. The concentration of the coating solution is maintained automatically with an inline monitoring and solvent make-up system for the purpose of maintaining consistent product quality. The industrial coating process used by this Mid-West manufacturing company could be summarized by the following steps: 1) maintaining coating solution concentration by addition of VOC solvent from the make-up tank, 2) application of coating solution of product surface, 3) deposit lubricant on product surface by evaporation of VOC solvent, 4) collection of VOC vapor via carbon adsorption, 5) regeneration of carbon adsorber by displacement of VOC on the carbon with steam, 6) condense the carbon adsorber regeneration vapors, 7) solvent/ water separation, and 8) transferring the reclaimed solvent to the make-up tank to be reused. The solvent usage and reclaiming process loop could be generalized by the following schematic flow diagram (Figure 2). To clarify the notations used in Figure 2, the following symbols were used in the flow diagram: 1) block arrows represent gaseous flow streams, and 2) the solid arrows represent liquid flow streams.

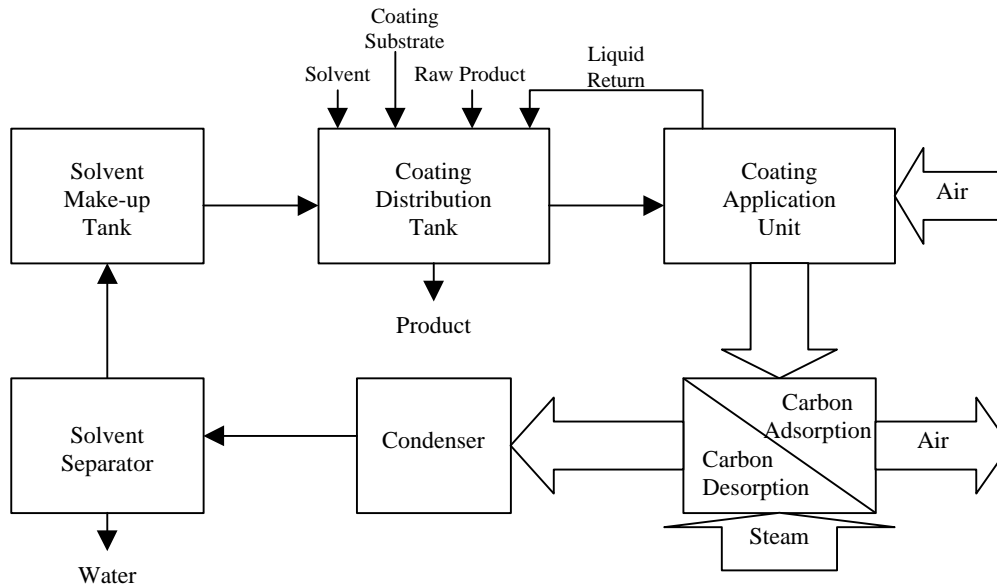


Figure 2. Schematic flow diagram of VOC solvent usage.

The focus of this research will be concentrated on accounting for the VOC solvent in both liquid and vapor phases. Since application of the silicone based coating onto the product surface is accomplished by evaporative deposition, one area of the research will focus on physical variables that contributes to solvent evaporation. These variables are then be incorporated into transport equations to describe the operation of the system. A second area of interest involves identifying factors that lead to fugitive emission. VOC concentration measured at designated points outside the boundaries of the operating system to determine solvent loss from manufacturing operations and help to account for solvent usage. The goal of this study is to identify potential opportunities to prevent waste generation.

SYSTEM ANALYSIS

The first step in initiating a system analysis is accomplished by establishing the boundaries for the system and sub-systems. A system model consist of five different components for the purpose of distinguishing operational functions. Since these components are defined by the boundary conditions, each of these components are determined specifically for the sub-system. When the sub-systems are properly coupled, the system operation could be described in an orderly manner. These components are as follows: 1) the input, 2) the state, 3) the state transition function, 4) the output and 5) the output function. The application of system analysis to the “Coating Application Unit” of the coating process used by the Mid-West manufacturing company would provide the following factors to each component.

1. Inputs are data submitted to the system for analysis. Inputs are functions of time, $I(t)$, and in the “Coating Application Unit” comprise of process operating conditions: production rate, coating mixture feed rate, and process air flow rate.
2. The state is a function of time, $S(t)$. It could best be describe as the status of the observed system at that one moment in time.
3. The state transition function is used to determine the state of the system at one time period in the future. This function is expresses mathematically as $S(t+1)=f[S(t), I(t)]$.
4. The outputs are products and emissions leaving the system. This function is expressed as dependent on time, $P(t)$.
5. The output function interprets the impact that the system have its surroundings. This could be beneficial, economical, and social. The mathematical expression is given as $P(t)=g[S(t), I(t)]$.

Inputs and outputs for the Mid-West manufacturing company's product coating process is illustrated in a schematic diagram in Figure 3. The diagram in Figure 3 presents a spatial representation of the system at a moment in time, "t". In real time operation, components (input, output, and state) are viewed as functions varying with time.

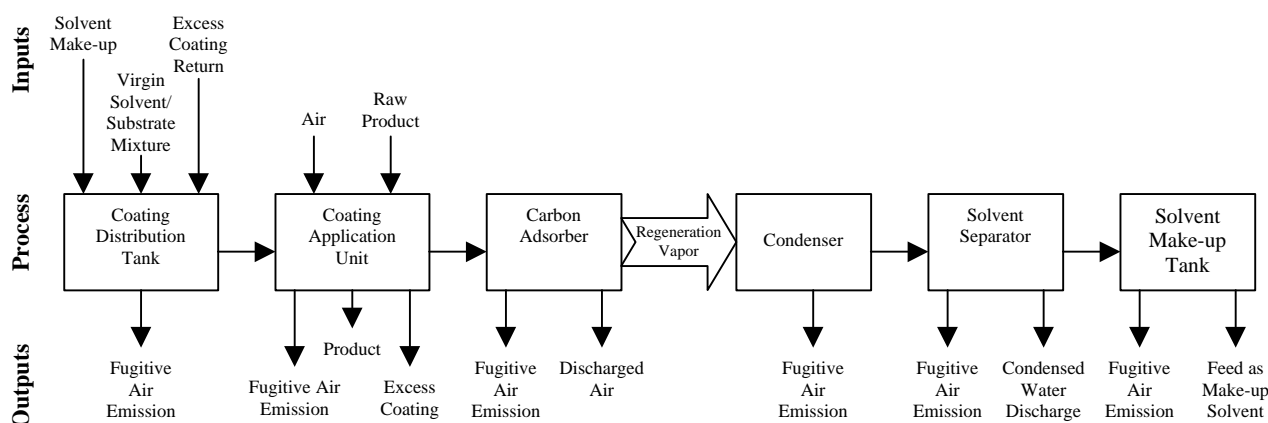


Figure 3. Schematic diagram of modeling components.

FUZZY SET THEORY AND APPLICATION

Fuzzy set theory is the application of fuzzy logic concepts by using mathematics to describe uncertainty and imprecision of a process. Unlike the traditional modeling methods, fuzzy modeling describes the system variables in terms of fuzzy sets rather than numerical values. These fuzzy sets could include both numerical and symbolical entities. The scope of fuzzy modeling is broadened by its flexibility to treat the fuzzy sets as either numerical or symbolic entities. Thus, the role of fuzzy sets is developing a bridge to narrow a traditional gap between numerical and symbolical computations (Pedrycz, 1995).

The essence of fuzzy set theory is the concept of membership functions, which could be simply described as the degree of belonging-ness. The membership functions characterize the range of imprecision with a range from 0.0-level membership (highest level of imprecision) to 1.0-level membership (highest level of precision). For an element to be a member of the fuzzy set, it must have a numerical value of 0.0 to 1.0. In the case of an element restricted to either a value of 0.0 or 1.0, the fuzzy set theory simply reverts back to the classical set theory. Thus, fuzzy set theory provide a way for industries to model their processes with the flexibility of handling imprecise variables for identifying pollution prevention opportunities.

SUMMARY AND CONCLUSIONS

Pollution prevention efforts have been effective and beneficial for Nebraska industries and small businesses. The University of Nebraska – Lincoln and partner organizations were instrumental in providing both technical and compliance assistance to Nebraska industries and small businesses. To share the benefits of implementing pollution prevention measures with other industries, the US EPA have published volumes of manuals and developed computer software to assist industries in identifying pollution prevention opportunities. Unfortunately, these software analysis required the user to input exact or crisp numbers, which are hard and often impossible to quantify in an industrial process setting. Thus, characterizations of process streams and system costs is not very accurate, which does not present itself as a reliable tool to convince industries to implement the suggested pollution prevention options.

In this paper, a framework and methodology for consideration of imprecision in modeling industrial processes is presented. The methodology centers on a systems approach to account for imprecision in the industrial process operation parameters with the support of fuzzy set theory. The industrial process selected for this study is a Mid-West manufacturer's product coating process. A production system model is developed to simulate the solvent process loop. Inputs are entered as fuzzy sets with the help of a fuzzy logic tool kit. Outputs from this simulation should also produce imprecise results. The benefit of this approach is the flexibility of the model to process information when crisp

parameters are not available or hard to obtain. Work continues on implementation of the framework and methodology presented in this paper.

This research serves as a precursor in the development of a pollution prevention opportunity ranking tool. This research will provide potential pollution prevention opportunities for consideration. The final portion of this project is the development of a tool to analyze all the pollution prevention options and decide on the best alternative using multi-criteria decision making.

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