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OVERCOMING DECISION TRAPS IN SUSTAINABLE DESIGN

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Abstract

The call for sustainability has created opportunities for taking a more holistic view of design. However, it also poses challenges for designers who must often resort to heuristic decision rules in order to deal with its complexities. The problem is that these heuristics can lead to suboptimal designs. The decision traps encountered in sustainable design are identified as focus on end-of-pipe treatment, pollution transfer, objective isolation and status quo anchoring. An illustrative case study of a new technology to recover solvent emissions from manufacturing operations is presented. A normative decision tool in the form of multiattribute utility is used as a design evaluation methodology. Four different objectives of capital cost, operating cost, liquid recovery and environmental impact are integrated in the evaluation function. The resulting designs involving decision traps are seen to be of lower overall utility as compared to the design methodology that addresses these traps.

Keywords: design for recovery, volatile organic compounds, hazardous air pollutant, multiattribute utility, design optimization, sustainable design, activated carbon fiber

1. Introduction

The necessity of sustainable design is gaining worldwide recognition. Unfortunately, its complexity is acknowledged as well. Any sustainable design must simultaneously satisfy functional requirements cost-effectively. Designers deal with this new set of complexities through a traditional reductionist approach, breaking the problem into smaller sub-problems and hoping that if they solve each of these sub-problems in isolation, it will lead to the desired final product. Such reductionist approaches have tremendous appeal as they are particularly geared towards the existing organizational structures in industry. Moreover the heuristic method of dealing with sub-problems in isolation seems to be very practical at first glance. But unfortunately, it can lead to the products that do not reflect the true preferences of the customers, are not sustainable, or do not achieve the best level of sustainability possible.

This paper develops an approach to avoid the dilemmas arising from the use of such heuristics. The next section briefly reviews related research. Section 3 identifies the decision traps most commonly observed in sustainable design. Section 4 illustrates how normative decision theory can be employed to avoid the traps through a case study design of a solvent recovery system. Section 5 illustrates the existence of these decision traps, and how these can lead to erroneous decisions if a rigorously normative approach is not employed to evaluate design alternatives.

2. Related work

The challenging array of tasks faced by designers of environmentally benign systems is documented by [1]. Ernzer et al. [2] contend that the real problem is not a lack of design methods, but rather which mix of available methods to use. For the problem of recovery of volatile organic compounds (VOCs) from gaseous waste streams, the reduction in environmental impact (EI) is shown by [3], with a comparison of adsorption and absorption technologies. The feasibility of electrothermal desorption with activated carbon fiber cloth (ACFC) for recovery of liquid VOC is demonstrated by [4]. The ironic effect of treating pollution across different media is shown by [5] where attempts at reducing solid waste resulted in an increase in air pollution. [6] present a method to maximize annualized profit while placing constraints on the environmental impacts arising from the production process. Such a method neither considers additional attributes nor does it allow for trade-offs among attributes such as cost and environmental impact. We take the view that sustainable design processes should be driven from the very beginning by how the final product will be evaluated in terms of satisfying all customer needs, including sustainability.

3. Identification of decision traps

The work done at University of Illinois' Decision Systems Laboratory has helped us identify common decision traps that companies and individual decision-makers might fall into while dealing with complex issues of sustainable design [7]. This section discusses these decision traps.

3.1 Myopic focus on end-of-pipe treatment

The historical development of environmental legislation is primarily responsible for the myopic focus on end-of-pipe treatment. The legislation often specifies only the fractional reduction in emissions or the maximum amount of emissions allowed. Sometimes even the type of technology employed to achieve these emission standards is specified. This leaves very little incentive for companies to develop innovative techniques for reducing the overall impact of their manufacturing processes. Instead they are concerned only with regulatory compliance. However, expanding the myopic focus from end-of-pipe compliance to the entire spectrum of lifecycle stages might result in decreasing overall environmental impact. Framing the design problem correctly is also very critical. Framing the problem to deal with pollution after it is generated will result in an entirely different solution (end-of-pipe) as compared to a framing which seeks to avoid generation of pollution in the first place.

3.2 Pollution transfer across media and lifecycle stages

This trap is a result of taking a narrow approach to pollution prevention and is also related to the first trap mentioned above, since the decisions to reduce emissions are often mandated by legislation. This reactive mode of design tends to eliminate the use of regulated pollutants from the manufacturing process and substitute them with other, unregulated materials. For example, the United States Environmental Protection Agency's (USEPA) Toxics Releases Inventory data shows that almost all industry sectors reported a decline in toxic releases from 1988 to 1994. But when the USEPA added 286 more chemicals to the list of reportable chemicals [8], the rate of decline in releases was significantly reduced. This reflects the practice of simply substituting one toxic chemical with another toxic (but unregulated) chemical. Even if the materials used in the manufacturing processes are less toxic, the production processes used to manufacture these chemicals themselves may be generating more pollution. Another possibility is the transfer of pollution across the lifecycle stages. Changes in the manufacturing or usage stage may result in lowering the pollution for that stage, but increase the overall EI over the lifecycle. For example, a process may require a less hazardous chemical but more stringent operating conditions such as higher temperature and pressure to produce the final product, requiring more energy. Though this is not explicitly treated as pollution in most cases, it in fact causes more pollution during the lifecycle stage that generates the additional required energy.

3.3 Objective isolation

The decision trap of isolating objectives due to institutional barriers seems to be an endemic one. Different segments involved in the development process view product value differently. This is compounded by the fact that there are often communication barriers among these segments. Consider the nature and level of communication that exists among marketing, design, manufacturing and environmental departments of an organization. The marketing staff is concerned primarily with market share and profit margin. The design department strives to achieve all the functional requirements of the product with very precise specifications. The manufacturing department produces products with maximum quality. The environmental department is mainly occupied with compliance of rules and regulations governing the emissions from the manufacturing processes. The problem arises when each group makes decisions in isolation towards its own objective that might unnecessarily constrain the options of the other group(s). Moreover, it tacitly assumes that improvement in one objective will not adversely affect other objectives, which is seldom true. Organizing tools such as the House of Quality (HOQ) [9] can be useful in breaking down communication barriers and helping reduce the isolationist approach to design.

3.4 Anchoring on status quo

This is the most common cognitive bias and is often a result of the availability heuristic employed by decision makers when faced with complexity. The designer first begins by “anchoring” on an existing design, then modifying it as needed. The problem is that the “anchor” can influence or limit further design efforts in ways that prevent the best solution from being realized. The effect of this heuristic is most dramatically illustrated by [10], where experimental subjects attempting to estimate an uncertain quantity were inordinately influenced by a starting point “anchor”, even when they were shown that the anchor was not at all related to the problem under consideration. This behavior results in many limitations during the design process. The designers may be hesitant to develop new product configurations that prevent pollution, or more innovatively define the product in terms of its service. It thus limits the progression from “as-is” design to a more sustainable design.

4. Case study – Organic vapor control and reuse

A case study of a new technology for capturing and recovering organic vapor emissions that are typically generated when using solvents is used to demonstrate our normative approach to deal with decision traps. The technology uses activated carbon fiber cloth (ACFC) as an adsorbent to remove many volatile organic compounds (VOCs) and hazardous air pollutants (HAPs) from gaseous streams. The technology is under development at the University of Illinois and the results are demonstrated for a bench-scale unit (Figure 1). The unit consists of adsorbing and desorbing vessels containing ACFC arranged in the form of cylindrical cartridges. For the base case scenario (BCS) in this paper, each vessel consists of 2 cartridges of 20 cm length and adsorbent type ACFC-15 [11]. The system is designed for capture and recovery of benzene at a flow rate of 100 liters/m and a concentration of 1,000 ppmv. Benzene is listed as a Title III HAP by USEPA.

Figure 1. Bench-scale unit

4.1 Attributes and design decision variables

Four different attributes are considered. These are capital costs, annual operating costs, percentage organic vapor liquefied/recovered and environmental impact. Capital costs include system components and their installation. Operating costs include energy and nitrogen gas used during desorption. Energy is consumed during electrothermal desorption and to run a fan to regulate flow and overcome the pressure losses within the system.

Another important consideration is the recovery of adsorbed organic vapor resulting from electrothermal desorption. Most traditional air pollution control technologies for organic vapors are mainly destructive in nature and do not recover the vapor. Examples of such technologies are fixed or fluidized bed catalytic incinerators, thermal recuperative incinerators and biofiltration. Traditional adsorption technologies capture the pollutants in a non-destructive manner, but pollutant recovery involves further processing and is often not undertaken. Electrothermal desorption of ACFC leads to the condensation of organic vapors in the adsorber vessel itself, thus eliminating the need for additional processing steps to recover the vapor. The liquid recovery is defined as the fraction of adsorbed vapor that is available as liquid at the end of the electrothermal desorption process. Liquid recovery merits inclusion as a separate attribute since it is the motivating goal of this new technology.

For this case study, the scope of environmental impact (EI) analysis is limited to the operation of the system and does not include impacts due to the manufacture and disposal of system components. It is recognized that a more thorough life cycle analysis should ultimately be performed. The reason for this focus is to illustrate primarily the differences in the use stage of the system. There are three sources of EI during system operation. New organic solvent will be required to replace the fraction that is not liquefied and hence can not be recycled within the manufacturing process. The other EIs are due to energy consumption and use of nitrogen as the inert medium during electrothermal desorption.

Annual operating cost and EI are defined as attributes in this analysis, but these can easily be expanded to include other lifecycle impacts without any loss of generality of our method. Capital cost and operating cost are considered separately to reflect the reality that manufacturers often treat them separately in ways not reflected in traditional "time value of money" methods. It is also important to note the conflicting nature of the attributes. For example, solvent recovery rates can be improved by increasing operating temperatures, but energy consumption then also increases. This results in two very different environmental impacts; those resulting from elimination of the solvent from the waste stream for reuse, and those resulting from energy consumption. Higher energy consumption also increases operating costs. The attributes are functions of design decision variables and other system parameters. The design decision variables are vessel material (y_1), adsorbent type (y_2), cartridge arrangement (y_3), number of adsorbing vessels (y_4), number of desorbing vessels (y_5), adsorption cycle time (y_6), desorption cycle time (y_7), cartridge aspect ratio (y_8), power application (y_9) and heating time (y_{10}).

4.2 Multiobjective optimization problem formulation

The decision problem can now be formulated to identify which combination of capital cost, operating cost, liquid recovery and EI is best in view of the unavoidable trade-offs that exist among them. Multiattribute utility analysis (MAUA) is used for modeling the preferences for competing objectives. The best choice is determined by a number of factors. The single attribute utility functions model the decision-maker's nonlinear preferences towards risk, and the multiattribute utility objective function allows for trade-offs among the attributes. It is a rigorously normative methodology based on the axioms of utility theory. The multiplicative form in equation (1) can be used after conditions of preferential and utility independence are verified. The goal is to determine the set of decision variables that maximize overall utility.

$$\text{Max } U(X) = \frac{1}{K}\left\{\left[\coprod_{i=1}^{n}(Kk_i U_i(x_i(y)+1)\right]-1\right\} \tag{1}$$

Subject to

$$x_{i,l} \leq x_i(\boldsymbol{y}) \leq x_{i,u} \qquad \text{for all attributes i} \tag{2}$$

$$y_{1,j},\ y_{2,k},\ y_{3,m} \in \{0, 1\} \quad \text{for all j, k, m} \tag{3}$$

$$\sum_{j=1}^{5} y_{1,j} = 1 \tag{4}$$

$$\sum_{k=1}^{4} y_{2,k} = 1 \tag{5}$$

$$\sum_{m=1}^{4} y_{3,m} = 1 \tag{6}$$

$$1 \leq y_4 \leq 3 \tag{7}$$

$$1 \leq y_5 \leq 3 \tag{8}$$

$$y_7 \leq y_6 \leq 480 \tag{9}$$

$$30 \leq y_7 \leq 120 \tag{10}$$

$$1 \leq y_8 \leq 30 \tag{11}$$

$$0 \leq y_9 \leq 7 \tag{12}$$

$$60 \leq y_{10} \leq 300 \tag{13}$$

where

$U(X)$: overall utility of a design alternative

$U_i(x_i)$: single attribute utility function for attribute i

k_i : scaling constant for attribute i reflecting acceptable trade-off

K : normalizing parameter which is calculated from equation (14)

$$K = \left[\prod_{i=1}^{n} (Kk_i + 1) \right] - 1 \tag{14}$$

The set of constraints shown in eq. 2 includes two types. The first defines the negotiable attribute range between the lower (worst tolerable) and upper (best achievable) bounds, as shown in Table 1 along with the assessed scaling constants. The second defines the cause and effect relationships between the design decision variable vector $\mathbf{y} = (y_1, \ldots, y_{10})$ and the attributes x_i. The EI associated with energy and nitrogen use and production of unrecovered benzene is estimated using *SimaPro 5* [12]. The Eco-Indicator points (Pt) provide a single metric to combine EIs arising from a variety of processes, materials, and usage and disposal methods. Other environmental impact assessment tools could be employed if desired.

Constraint eqs. 3–13 are determined using data from the existing bench-scale unit. Eqs. 3–6 force the model to choose only one each from 5 alternative vessel materials, 4 adsorbent types and 4 cartridge arrangements. Eqs. 7–13 specify physical limits on the decision variables. Desorption cycle time is maintained between 30 and 120 minutes while adsorption cycle time should always be more than the desorption cycle time, but less than 480 minutes. Cartridge aspect ratio ranges from 1–30. Maximum power applied during desorption is 7 watt/g and heating time is between 60 - 300 seconds. There are also constraints on other system parameters such as superficial gas velocity, pressure drop, voltage and current application. The assessed single attribute scaling constants from Table 1 are used in eq. (14) to determine a K scaling value of -0.932.

Table 1. Attribute ranges and scaling constants

Attribute	**Attribute Range**	**Scaling constant k_i**
Capital cost, $	1350 – 2250	0.65
Annual operating cost, $	50 – 125	0.45
Liquid recovery, %	30 – 75	0.6
Annual environmental impact, Pt	17 – 50	0.35

5. Results: Comparison of decision trap outcomes and model outcome

This section compares designs obtained as a result of a decision trap with a base case scenario (BCS) obtained with the normative model described in eqs. 1-14 above. The first column of Table 2 shows the optimal set of 4 BCS design decision variables and attribute levels resulting from the model, whose overall utility is 0.95. Several detrimental effects of the first decision trap (focus on end-of-pipe treatment) are avoided since the ACFC system recovers the emitted solvent for reuse, and can thus be considered an integral part of the manufacturing process.

5.1 Pollution transfer trap

This trap fails to recognize the EI of transferring pollution from one medium to another, or between lifecycle stages. In this case the recovered solvent is eliminated from the waste stream and reused, but the desorption process requires energy whose generation creates its own EI. Columns 2 and 3 of Table 2 show the detrimental effects of ignoring the EI of energy consumption. Figure 2 compares the single and overall utilities of each alternative, each on a common scale from 0 = worst to 1 = best. Column 2 of Table 2 shows the optimal design if the EI of energy consumption is ignored. Compared to the base case, this solution at first appears to be superior, because capital costs, liquid recovery, EI and overall utility improve. However, column 3 shows that if this same design is now correctly re-evaluated to include the EI of energy consumption, the EI worsens and the overall utility decreases from 0.95 for the base case to 0.90. So, if the designer ignores the transfer of pollution from one medium to another, it may not only increase environmental impact (29.8 Pt vs. 27.7 Pt), but decrease overall utility as well.

Table 2. Pollution Transfer Trap

	Base Case Scenario	**Energy consumption impact ignored**	**Energy consumption impact included**
Adsorption cycle time, minute	100.8	82.4	82.4
Cartridge aspect ratio	10.7	13.8	13.8
Power application, watt/g	4.8	5.5	5.5
Heating time, sec	300.0	267.7	267.7
Capital costs, $	1,426	1,381	1,381
Annual operating costs, $	89.6	104.9	104.9
Liquid recovery, %	73.2	75.0	75.0
Environmental impact, Pt	27.7	11.5	29.8
Multiattribute Utility	0.95	0.96	0.90

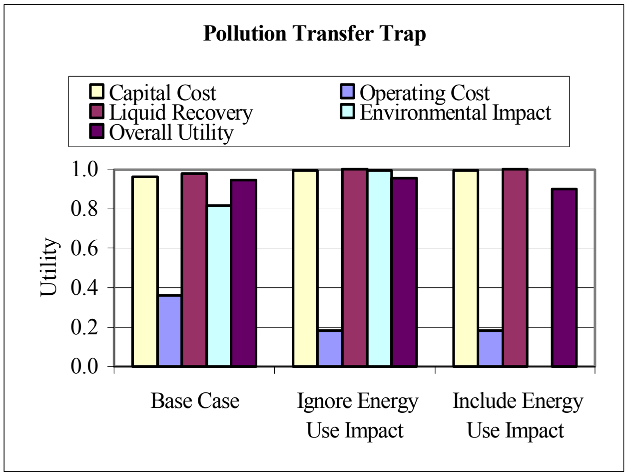


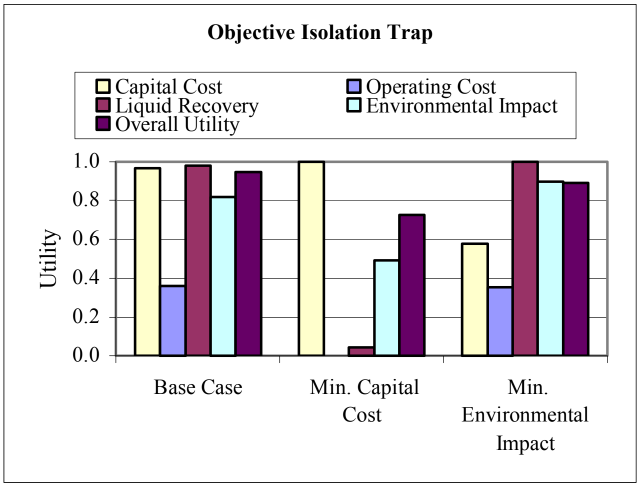
Figure 2. Utilities for Pollution Transfer Trap

5.2 Objective isolation trap

The detrimental effects of objective isolation (an overemphasis on achieving only one aspect of performance at the expense of others) are shown in columns 1 and 2 of Table 3. Minimizing only capital costs (column 1) indeed lowers them from $1,426 for the base case to $1,345. However, this slight 6% improvement significantly worsens operating cost, EI, liquid recovery, and overall utility (from 0.95 to 0.73), as shown in column 1 and Fig. 3. Similarly, column 2 and Fig. 3 show that EI minimization to 23.9 Pt also results in higher capital costs, lowering its overall utility from 0.95 to 0.89.

Table 3. Effects of the Objective Isolation Trap and the Status Quo Anchoring Trap

	Effects of Objective Isolation Trap		**Effects of Status Quo Anchoring Trap**	
Decision Variables and Attributes	***Minimize Capital Costs***	***Minimize Environmental Impact***	***Series-parallel arrangement with 4 cartridges***	***ACFC-20 Fiber Cloth***
Adsorption cycle time, min.	58.2	131.5	63.8	98.3
Cartridge aspect ratio	13.7	3.8	8.5	3.3
Power application, watt/g	6.2	4.9	6.2	5.7
Heating time, sec	103.8	300.0	300.0	252.9
Capital costs, $	1,345	1,839	1,791	1,818
Annual operating costs, $	125.0	90.2	125.0	64.9
Liquid recovery, %	32.5	75.0	31.5	43.5
Environmental impact, Pt	38.9	23.9	35.7	29.0
Multiattribute Utility	0.73	0.89	0.54	0.79



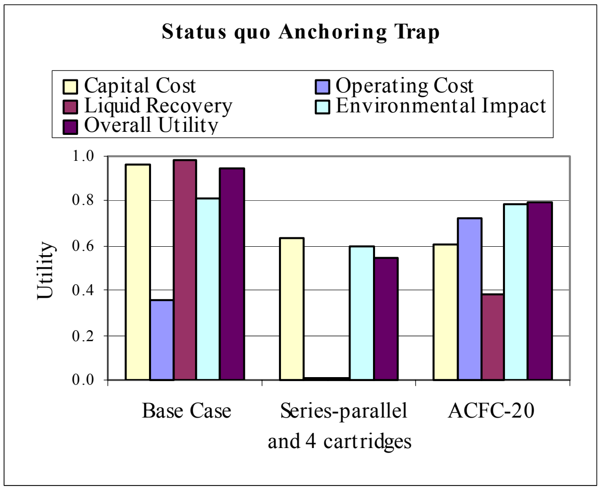


Figure 3. Utilities for Objective Isolation Trap

Figure 4. Utilities for Status quo Anchoring Trap

5.3 Status quo anchoring trap

The detrimental effect of anchoring on the status quo of the existing bench-scale unit is illustrated in Columns 3 and 4 of Table 3, and also in Fig. 4. The bench-scale unit employs ACFC-20 adsorbent and has four cartridges per vessel placed in a series-parallel arrangement, with two sets of two-series cartridges placed in parallel. Column 3 and Fig. 4 show that specifying the 4 cartridge series-parallel arrangement as a constraint worsens all four attributes of the optimal solution, and worsens the resulting overall utility from 0.95 for the base case to 0.54. Similarly, column 4 and Fig. 4 show that specifying ACFC-20 (the bench-scale adsorbent) as a constraint worsens three out of the four attributes, and worsens overall utility from 0.95 to 0.79.

6. Conclusions

With the evolution of environmental legislation from control to producer responsibility, as well as competitive market forces, the need to integrate environmental issues at the design stage is becoming more urgent. This paper identified common decision traps encountered in the sustainable design. Identification of these traps is a starting point for a better understanding of the design process and the importance of design decisions for the entire lifecycle. A normative methodology for design evaluation is utilized to frame the problem such that the decision traps are avoided. Starting with a succinct definition of the decision problem, the methodology progresses through successive steps of defining design objectives, identifying trade-offs among objectives and evaluating design alternatives. The case study of a new organic vapor control technology demonstrated how the overall worth of a design is reduced if these decision traps are not properly addressed at the design stage. Including environmental impact as a distinct attribute ensures that the product is sustainable, while other objectives of cost and product performance also contribute towards how the product is valued by customers.

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References

[1] Thurston D., Gutowski T., Murphy C., Allen D., Bauer D., Bras B., Piwonka T., Sheng P., Sutherland J. and Wolff E., "U.S. National Science Foundation Panel Report on International Environmentally Benign Design and Manufacturing", Proc. of ICED'01, Glasgow, 2001, pp. 605-612.

[2] Ernzer M., Oberender C. and Birkhofer H., "DFE for Companies – An Easy-to-Use Individualized Method Mix for DFE", Proc. of ICED'01, Glasgow, 2001, pp. 589-596.

[3] Shonnard D. and Hiew D., "Comparative Environmental Assessments of VOC Recovery and Recycle Design Alternatives for a Gaseous Waste Stream", Environmental Science and Technology, Vol. 34, 2000, pp. 5222-5228.

[4] Sullivan, P., Rood, M., Hay, K. and Qi, S., "Adsorption and Electrothermal Desorption of Hazardous Organic Vapors." J. of Environmental Engineering, Vol. 127(3), 2001, pp. 217-223.

[5] Carnahan, J. and Thurston, D., "Trade-off Modeling for Product and Manufacturing Process Design for the Environment", J. of Industrial Ecology, Vol. 2(1), 1998, pp. 79-92.

[6] Fu Y., Diwekar U., Young D. and Cabezas H., "Designing Processes for Environmental Problems" in "Process Design Tools for the Environment", Taylor & Francis, New York, 2001.

[7] Mangun D. and Thurston D, "Decision Traps in Design for Environment and the Effect on Product Design", University of Illinois Technical Report, Department of General Engineering, Urbana, 2001.

[8] United States Environmental Protection Agency, "59 Federal Register 61432", USEPA, Washington, D.C., November 30, 1994.

[9] Hauser J. and Clausing D., "The House of Quality", Harvard Business Review, 1988, pp. 63-73.

[10] Kahneman D., Slovic P. and Tversky A., eds., "Judgment Under Uncertainty: Heuristics and Biases", Cambridge University Press, New York, 1982.

[11] American Kynol, Inc. Home Page, http://www.kynol.com

[12] PRè Consultants Home Page, www.pre.nl/simapro/default.htm

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