DECISION ANALYSIS FOR EQUIPMENT SELECTION

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Process design is the synthesis of a complete chemical operation as an assembly of unit operations. A key part of the design process is the selection, specification, and design of each unit operation so that the equipment will perform the specific function required.

The equipment used in a chemical plant can be divided into two classes: proprietary and nonproprietary. Proprietary equipment is designed and manufactured by specialist companies, and its detailed design is not normally the responsibility of the chemical engineer. The chemical engineer is, however, required to select and size the equipment required for a specific duty, to consult with vendors to ensure suitability, and to carry out any customization that may be required.[1] This paper will focus on equipment selection to meet the design requirements.

Process design and equipment selection by its very nature requires engineering judgment and subjective analysis, and is therefore a typical "semi-structured" task[2] in which neither judgment alone nor a rigorous procedure by itself is adequate. Equipment selection falls between structured (programmed) and unstructured (non-programmed) decision-making,[3] the complexity being principally a result of the large number of interacting criteria that have to be considered. In multiple-criteria decision-making problems, the engineer must combine conflicting measures to assess the desirability of different decision alternatives—in this case equipment types. Often, much of the knowledge and design experience in an engineering organization is not in a tractable form, but is based on the experience of individuals. This requires knowledge management[4] to develop some form of "institutional memory."

Selection of proprietary equipment therefore involves three aspects: first, a thorough knowledge of the types of available equipment and their characteristics; second, a methodology to balance multiple criteria, which may include a combination of technical, legal, economic, and social aspects for selecting the most appropriate among the available choices; and finally, a sensitivity analysis to ensure that the choice is robust.

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When educating students on solving a specific aspect of chemical engineering that involves design and, more specifically, the selection of proprietary equipment, the pedagogic focus is often on introducing and explaining the types of equipment available and their operating characteristics. This descriptive focus is further evident in numerous design and process engineering textbooks that describe in detail the equipment and its sizing, but only give fleeting reference to making a selection from different types that may all be suitable. Selection is often based on flowcharts that eliminate alternatives, or on tables of properties. In general, any analysis of the sensitivity of the selection to changing conditions or requirements is neglected.

From the point of view of both student and lecturer, the

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description of equipment application and sizing, while often interesting, is of less long-term and general value than either a robust methodology for making a selection between alternatives or for evaluating the robustness of that selection. The question is, however, how to teach the methodologies of equipment selection and analysis without neglecting the essential descriptive aspects.

In this paper, a novel pedagogic approach to this dilemma is offered in which students are first taught how to develop a multi-criteria selection procedure and then how to implement such a system in practice. Multiple criteria decision analysis (MCDA) is a methodology for making decisions, such as equipment selection, in a rigorous and justifiable way. A particularly straightforward MCDA technique for equipment selection is "value tree analysis," which treats decision-making as a weighting problem in which the criteria are structured hierarchically and weighted by their importance. The value of the various equipment choices is then calculated from the weighted sum of the criteria. A particular benefit is that sensitivity analyses can be performed to ensure decision robustness. Value tree analysis as applied to equipment selection will be discussed in greater detail later in the paper.

It is suggested here that by framing the equipment descriptions within a decision-making and analysis framework, a deeper understanding of the difficulties involved in making multi-criteria decisions will be imparted to the students, while the specific knowledge required to make sensible choices is emphasized.

The example used in this paper deals with the selection of appropriate equipment for pollution abatement by removal of particulates from gases. The use of computer-aided learning for design was tested previously[5] when a knowledge-based system was used to evaluate student designs after the event. The approach used in this study is significantly different, however—the student's task is to develop a decision system for a specific application, and learning occurs through collation and transformation of equipment information into a useable and relevant form.

The use of MCDA—and in particular quantitative value tree analysis—for making design decisions is, of course, not new. Ulrich,[6] for example, gives a very clear description of its use in selecting chemical engineering process alternatives. It is of interest that he considers the method useful for indicating the superiority of one alternative over another, but does not consider the sensitivity of the choice to changes in priority. Sensitivity analysis is strongly emphasized in the teaching example given here.

EQUIPMENT SELECTION USING CONVENTIONAL AND MULTICRITERIA DECISION ANALYSIS

Conventional Selection Procedures

Conventionally, the selection of gas-cleaning equipment for pollution abatement is largely qualitative and highly subjective. As an example, Table 1, abridged from Muir,[7] shows the problem attributes to consider and the qualitative measures within each attribute. Although not shown here in full, two tables of attributes to consider are given, with 11 primary and 14 secondary attributes.

When using a table-based approach to make equipment selection, the less-suitable equipment is progressively eliminated until a final choice is made from the remaining selections. It is evident that it will be difficult to make and justify a choice between types of equipment based solely on such tables. In part, this is due to the highly qualitative measures

TABLE 1
Qualitative Equipment Selection Criteria
(A limited selection taken from Ref. 7)

	Smallest particle size to be collected		*Gas temperature inlet to collector*		*User preferences (if practical)*	
Attributes	1-10 micron	Sub micron	>400°C	Near Dewpoint	Dry Product	Low Initial Cost
Alternatives						
Cyclones	Care	Beware	√	Care	√	√
Wet Electrostatic Precipitator	√	√	Beware	√	Beware	Unlikely
Aggregate Filter	√	Care	√	Care	√	√

Key

√	*Can generally cope with the process requirements if well designed*
Care	*Special attention required in plant design and operation to prevent problems*
Beware	*Could lead to severe operational difficulties; alternatives that avoid the problem are normally sought*
Unlikely	*On purely economic grounds, alternatives are generally favored if suitable*

used in each attribute considered and the fact that they cannot readily be weighted by their importance to the particular design problem. Further, and of increasing importance, is the need for decisions to be justifiable. Qualitative selection procedures make objective justification of choices at a later date difficult.

Multi-Criteria Decision Analysis (MCDA)

In multi-criteria decision analysis using a value tree, the *objective* is the final choice—in this case the most suitable type of equipment for the specific situation. Each type of equipment is an *alternative* and is described by a number of *attributes*, as shown in Table 1. Each attribute has a real value, for example its capital cost.

Attribute values are scaled using a value function to bring them to a common relative value range, usually between 0 and 1. The value functions can be linear or nonlinear and can be positively or negatively correlated with the attribute values. For example, a high real-capital cost can be scaled linearly to have a low relative attribute value, while a high real-operating cost may be scaled nonlinearly. In the simplest form, the decision problem is defined by weighing the importance of each attribute to the specific situation. For example, both capital cost and technical complexity may be rated very low when retrofitting gas-cleaning equipment to an old plant. The objective is achieved by considering the weighted sum of attributes for each alternative.

A critical and largely neglected aspect of equipment selection and design is the sensitivity of the decision to changing circumstances and process conditions. For example, when selecting equipment for pollution mitigation where public health may be at risk, choosing equipment that fulfills only current legal requirements is highly risky. Changes in legislation, economics, and process conditions may lead to significant changes in specifications that must be met; choosing equipment with excess capability in the short-term may be a better long-term economic and political decision. Sensitivity analysis is not readily performed when confronted with highly qualitative selection criteria, such as shown in Table 1. When using MCDA, sensitivity analyses can be performed by considering the effect of changing each weight in turn on the decision made.

The use of a robust decision-making procedure makes the potential for improving selection greater and the use of MCDA more attractive, not only for the design process itself but also for teaching and demonstrating the importance of sensitivity analysis during the design process. For teaching purposes, the procedure for developing an MCDA system was formalized into a highly structured, procedural approach, summarized as "The 5 Stages to Multi-Criteria Decision Analysis":

1. *For each alternative (equipment), allocate a numerical value to each of the attributes (e.g., capital cost)*
2. *Scale the attribute values to a common range by applying an appropriate scaling function*
3. *In the context of the problem under consideration, allocate importance weightings to each of the attributes*
4. *Calculate the total weighted attribute scores for each alternative. The highest scoring alternative(s) form the basis of the initial selection*
5. *Perform a sensitivity analysis to assess the robustness of the decision*

The 5-stage procedure and its application to pollution-abatement equipment selection will be described in greater detail in the following sections.

STRUCTURE OF THE TEACHING EXERCISE

The teaching module consists of two three-hour sessions. Previously, these were divided as follows:

Session 1
- *Introduction to gas pollution problems, processes, and equipment*
- *Performance description: quantitative measures*
- *Other selection criteria: qualitative measures*

Session 2
- *Detailed equipment descriptions*
- *Equipment selection by elimination*
- *Selection of equipment: industrial examples*

It was decided that all the above material should be retained under the MCDA-based format. Since, in addition, decision making and MCDA had to be introduced, the following structure was implemented:

Session 1
- *Introduction to gas pollution problems*
- *Detailed introduction to processes and equipment*
- *Performance description: quantitative measures*

Self-study: *Detailed equipment descriptions*

Session 2
- *Other selection criteria: qualitative measures*
- *5 Steps to an MCDA system*
- *Decision support systems: example (restaurants)*
- *On-line MCDA demonstrations:*
  - *Restaurant selection*
  - *Gas-cleaning equipment selection*
- *Student MCDA development exercise*

It can be seen that in the MCDA framework the basic descriptive element has been retained, but the detailed descriptions are relegated to self-study. Note further that a simple example is used to introduce the MCDA concepts and that this is augmented with an on-line demonstration. A further demonstration shows an MCDA for equipment selection.

The module concludes with a computer exercise in which

the students have to develop an MCDA of their own, on a topic of their own choosing. Examples of systems that have been implemented, in addition to equipment selection, are the selection of computers, cars, and jobs.

THE TEACHING AND LEARNING EXPERIENCE

This section describes in more detail the teaching of the MCDA approach following the 5-stage format and its application to the pollution abatement problem. Some of the interesting problems and findings that were encountered are detailed, and the difference in the learning experience it brings to the students is illustrated. A class example of selecting a restaurant to suit a particular occasion is also detailed.

The 5 Stages to MCDA

The first two steps of the procedure are:

- *Stage 1*
  Score each alternative (equipment) against each of the lowest-level attributes.
- *Stage 2*
  Bring the score of each alternative to a comparable scale by applying an appropriate scaling function.

The first two stages lead to development of an equipment database where the various pieces of information about the same attributes for all the available types of equipment are collated and brought to a common scale. During a teaching course, this defines the scope of the lectures and ensures that all the appropriate information is available for all the equipment to be discussed. Since the more tedious, descriptive material could be relegated to self-study in this way, the class time could be devoted to more interactive and exciting demonstrations, which is more satisfying for both students and lecturer.

The MCDA approach also gives a clear structure in which the need for (and importance of) quantitative performance measures can be explained. Particular emphasis is needed on converting qualitative data to quantitative values and on the transformations required to bring all the data to a common scale. Referring again to Table 1, the qualitative measures associated with the efficiency of removing specific particle sizes can be quantified by introducing the partition curve, its calculation and interpretation. Similarly, the equipment capital and operating costs become true financial costs but must be scaled to a common throughput rate.

Transforming the other qualitative measures in Table 1 (*e.g.*, gas inlet temperature, dry product) is more difficult and involves some subjectivity, but it can be seen that, in general, the qualitative criteria can be transformed to 0% or 100%, *i.e.*, the equipment is either unsuitable or suitable based on that attribute alone.

Emphasis is given at this stage of the lectures to the concept of the "institutional memory" and knowledge management.[4] Using MCDA, an internally consistent database of equipment and their attributes is generated as a result of the above two stages, which captures this expertise in a form that is consistent and directly useable by the whole organization.

It is of interest that, for the students, the least difficulty was with the mathematical transformations used for scaling, while the greatest was with allocating quantitative values to qualitative information as shown in Table 1.

- *Stage 3*
  Allocate importance weightings to each of the attributes. This is done in the context of the process under consideration.

Stage 3 is the first point at which the process design requirements are considered. Here an "importance weighting" is allocated to the scaled score, which quantifies its importance to each possible equipment choice. By explicitly making the distinction between the scaling (Stage 2) and weighting (Stage 3), the scoring of an attribute and its significance is decoupled, separating the process selection from the equipment that can be used.

In the pollution abatement example, two highly disparate process examples were used for illustration: sawdust from a sawmill and catalyst dust in the offgas from a refinery. The students generally have either visited such plants or are able to visualize the problems. The sawmill produces a relatively coarse dust and requires a low-cost/low-maintenance solution in which the dust has to be kept dry. In contrast, the dust in the refinery may be extremely hazardous and therefore requires equipment with a high efficiency, and neither cost nor moisture is important.

These two process examples clearly illustrate the importance weightings, as (for most attributes) the needs are very different. For example, in Table 1, the importance ranking for the attributes of "submicron" and "dry product" will be at opposite ends of the scale for the sawmill and the refinery.

- *Stage 4*
  The weighted attribute scores are added to give an overall score for each alternative. The highest scoring alternative(s) form the basis of the initial selection.

At this stage the attribute values of all the equipment choices are weighted by the importance to the sawmill and refinery. Considering the alternatives given in Table 1, the appropriate equipment choice for each application is very clear.

The mathematical function used for making the selection was also found to be of great interest. Conventionally, a simple

Continued on page 109.

Decision Analysis for Equipment Selection

Continued from page 103.

weighted sum is used. In cases where any choice is completely inappropriate, however, the form does not reflect this. Therefore, it must be emphasized that, since the MCDA methodology evaluates all the equipment available, completely unsuitable equipment may still appear as a possibility based on other attributes, and the answers must be interpreted intelligently. Ulrich[6] describes an elegant approach to interpreting the results in which the attributes are divided into "wants" and "musts." Equipment that does not satisfy the "musts" is eliminated before considering the remaining alternatives. Again, this modification was not difficult to explain and was readily understood.

► *Stage 5*
A sensitivity analysis is performed.

Sensitivity analysis was found to be difficult to convey adequately without the benefit of a demonstration. An on-line demonstration during the lecture is highly effective for illustrating the importance and benefit of sensitivity analysis. The further benefit of performing this on-line is that the number of equipment alternatives is far greater, and the best choice is less obvious.

The importance and utility of sensitivity analysis can be shown using the refinery case study. For example, either filters or electrostatic precipitators (Table 1) may be a suitable solution for the problem. The optimal choice, however, can be changed by changing the importance weighting given to submicron particles. This may be the result of future changes in legislation or adverse publicity—both graphic illustrations.

Additional Teaching Example: Choosing a Restaurant

If required, the 5-step procedure can be illustrated quickly and simply using the example of selecting a restaurant. This is a particularly good class example, as it allows vivid scenarios to be painted, *e.g.*, dinner with a partner or the boss, a quick meal before theater, etc. Further, the institutional memory concept became very clear, and the students suggested that it could be used as the basis for an Internet restaurant selection facility. With relatively few attributes (*e.g.*, cost, quality, and service) and a small number of restaurant types (*e.g.*, fast food, steakhouse, and expensive), a simple sensitivity analysis can be performed during the lecture.

A number of complex issues are also highlighted using the restaurant example—in particular the importance of clarity in attribute specification. For example, the attribute "Duration of meal" could refer to either long or short, and is better stated as "Meal takes long," which may be weighted high or low. This example attribute can also be confused with "Service quality," which is best incorporated as a further attribute.

On-line demonstrations and exercise

An excellent set of on-line decision support tools has been developed by the Helsinki University of Technology and is available at no cost on the Internet.[8] From this toolbox, WEB-HIPRE was used for on-line demonstrations. The output from WEB-HIPRE is highly visual, particularly in regard to the sensitivity analysis, which aids understanding. Further, the system is intuitive to use, and the students can readily develop their own systems during the exercise.

Course assessment

Examining the course has been made more flexible with the MCDA approach. Instead of relatively predictable descriptive examination questions, MCDA can be used either as a project assessment, or more flexibly in a conventional examination. Student feedback to date has been very positive, and the course rating has improved markedly. It is clear that the students find the approach novel and useful, and the teaching enjoyable.

CONCLUSIONS

The use of MCDA as a framework for teaching the selection of equipment for gas pollution abatement was very successful. In particular, two aspects were highlighted that otherwise would not have been—the development of an "institutional memory" and the importance and utility of sensitivity analysis. The students enjoyed the class, and the use of interactive computer techniques was found to be exciting.

It has been stated[9] that a hard problem addressed with support for successfully solving and reflecting on the problem will lead to deep, transferable knowledge and skills. It is believed that the MCDA approach gives the support required, and that this approach is particularly appropriate for the teaching of "hard problem" design-type courses.

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