Structured Troubleshooting in Process Design

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Summary

Senior-level process design courses have historically focused on large-scale chemical plant flow sheet development for grass-roots projects. While this is a worthwhile and necessary part of any chemical engineering curriculum, most new process engineers will not initially be placed in a design situation, but rather may be assigned small-scale troubleshooting projects as a means of introducing them to existing processes. To help students acquire experience at hands-on process problem-solving, we have added a series of structured troubleshooting exercises and a simplified problem-solving methodology termed "Fact-Based Cause Analysis" to our process design course. This paper describes our pedagogical approach to introducing students to troubleshooting, the types of exercises we used, and an evaluation of how the students viewed the usefulness of this portion of the design course.

Introduction and Background

Maturation of the chemical industry has been marked with several trends which affect process design:

- Plant designs are well-established for many chemicals, so that innovations or new designs are often done by senior engineering personnel. Younger engineers most frequently work with a senior mentor before they are assigned a major design. Many engineers may work on existing industrial processes without having the opportunity to perform a major plant design in their career.

- Sophisticated process simulators are readily available both to senior industrial designers as well as to undergraduates. These simulators have become so familiar that they are sometimes the first and only tool considered in a chemical engineering design problem.

- The challenge to chemical engineering education is the incorporation of engineering judgment to evaluate and to guide computer simulations. One prominent means to guide such judgments is engineering heuristics or rules-of-thumb which summarize best industrial practice. [1,2]

- The compiled heuristics to evaluate a complete chemical process are first applied to the unit operations which comprise that process. Here the heuristics can be applied to unit operation troubleshooting and de-bottlenecking which are common initial assignments of young engineers.

At the Colorado School of Mines (CSM) a process simulator (ASPEN Plus) has been integrated into every course in the chemical engineering curriculum via case studies beginning with recycle problems in the mass and energy balances course during the sophomore year. By the time the students have reached the senior design class, they have a number of experiences in simulation and have overcome the initial fear associated with the use of simulators. For some, the pendulum has swung to the use of simulators whenever possible, sometimes with minimal judgment imposed on the simulator results.

The object of our design course was to provide a process troubleshooting experience which would integrate and stretch our students' education, while reflecting some of the new trends listed above. At the same time, we wished to build upon the positive base of traditional design classes which have been time-proven for engineering students.

The Design Course

Process design at CSM is taught in one three-semester credit course meeting approximately four hours per week in a combined lecture, discussion, and computer laboratory setting. In the course, we try to blend traditional topics in conceptual and detailed process development, optimization, and engineering economics with more applied topics including de-bottlenecking of existing processes, using heuristics and engineering judgment to validate process simulator results, and process troubleshooting. Short exercises, process case studies, and open-ended projects for external clients are all utilized to provide students with ample opportunities to achieve the learning objectives summarized in Table I.

Table I
Process Design Course Learning Objectives

Apply process design principles to complete a conceptual design for the production of a specified chemical product.
Analyze an existing chemical process to determine ways to improve efficiency and reduce or eliminate bottlenecks.
Troubleshoot an existing chemical process by applying principles of engineering analysis.
Apply process design principles to complete a detailed, integrated design for selected portions of a given conceptual process design.
Use heuristics, successive approximations, and engineering judgment to design chemical process equipment.
Apply principles of engineering economics and management to process design analysis.
Demonstrate the ability to complete a design project to the satisfaction of an external client.
Be able to apply appropriate tools and skills (e.g. computer software, teaming, oral and written communications, etc.) for completing a project.

Teaching Troubleshooting in the Design Classroom

The goal of introducing troubleshooting exercises in the design course was to: 1) provide students with a structured problem-solving strategy they could use after graduation, and 2) to familiarize students with detail troubleshooting information for important unit operations including pumps, heat exchangers, and distillation columns. We used as exercises actual plant experiences documented by Woods [1] and one of us (AV).

Initially we used Woods' expert system method of solving the troubleshooting exercises. [1] The method involves dividing the into three person groups with each student given a specific assigned role. One student was designated the problem-solver and was given a general description of the trouble-shooting problem along with a few pertinent facts. A second student was designated the system expert and was given the full troubleshooting problem description, the actual cause of the problem, and a proposed solution. The expert's role was to answer questions which would allow the problem-solver to determine a cause for the problem and then develop a solution. The third student was designated the observer whose role was to observe the progress of the troubleshooting process and review it for the group when the exercise was complete.

This method had merit in that each person in the group had a clear role to play in the exercise. It also allowed the teams to work autonomously without constant supervision by a class instructor. However, this arrangement was not optimum, given the limited amount of time available in class because problem-solvers had to work alone, not only to understand the problem but also to develop questions which would allow them to create a meaningful and useful list of possible causes. The system experts spent most of their time waiting for confused problem-solvers to come up with questions and the observer had very little to observe most of the time.

In subsequent exercises we designated the entire three student team as the problem-solvers while the instructors acted as the system experts and observers. This approach permitted the individuals in the teams to work with each other, to discuss and understand what was happening in each problem, and to better understand the cause analysis process.

Problem-solving methodology. After considering many problem-solving methods for use in the troubleshooting exercises, we chose a "fact-based cause analysis" based on its simplicity and familiarity by one of us (AV). The method consists of 6 key steps:

- Develop problem statement
  Students write a statement of expected operating conditions and a statement of the actual observed conditions. The gap between the two conditions is the troubleshooting problem to be solved

- Develop problem description
  Students develop a detailed description of all known facts associated with the problem. The problem description is continually updated through the course of the cause analysis as new information about the problem is discovered.

- Develop list of possible causes
  Students develop a "cause and effect" diagram describing all possible conditions which could cause the problem (and all associated facts). Here it is important to be diligent regarding suspending judgment, so that a complete list of all possible causes can be made. Items are added to the diagram without considering if there is supporting evidence for any of the possible causes.

- Determine most probable cause
  In this step, students systematically use evidence from the problem description to eliminate or retain possible causes. The most probable cause must be able to explain every fact in the problem definition.

- Testing and Verification
  In this step, students test the most probable cause by attempting to recreate the original failure using the original operating conditions. This step is not always possible or desirable in a classroom setting.

- Solution Development
  Once the most probable cause has been identified and (if possible) verified, students determine how to eliminate the cause, and to prevent re-occurrence.

For a solution to be deemed "most probable," it must:

- Be true
- Be relevant
- Explain why the problem occurred where it did and where it didn't
- Explain why the problem was as big as it was rather than some other size
- Explain why it happened when it did rather than some other time
- Explain why it was this problem rather than some other problem.

A valid solution must directly address and eliminate the most probable root causes of the problem. In addition to these basic concepts, we introduced the concept of data quality. In an academic setting, most of the information presented through reading or in class may be taken as fact, but this is not the case with information associated with real-world problems. Engineers in the plant must be able to evaluate the quality of the data or information they are presented with. The various levels of data quality are shown from highest quality to lowest by the data quality ladder:

- Fact - verifiable, accurate, precise, measurable
- Inference - logical deduction based on the facts
- Assumption - logical hypothesis that if true could explain the facts
- Opinion - gut feel and experience
- Belief - other opinions
- Hearsay - 2nd, 3rd, 4th hand information
- Guess - educated, wild, etc.

Only the top three levels of data quality may be used to troubleshoot process problems effectively and consistently. As students complete each successive troubleshooting exercise, they are confronted with more information of varying quality and they must first decide whether to rely on the information as they identify a most probably cause for each case.

Troubleshooting pedagogy. At the beginning of each troubleshooting class session, we hand out a short description of the exercise and give students approximately 5 minutes to familiarize themselves with the information. Student groups then begin working to define the problem, to describe what they know about the problem, and to generate a cause/effect diagram. Having groups work on large flip-chart paper mounted on classroom walls produced better diagrams than when the students worked at their desks. We observed, for example, that all group members could more easily see the developing cause/effect diagram on a flip-chart and make better suggestions for additions or improvements. Another benefit was that adjacent teams were able to look at the work of others and use that work to further their own analysis. After one or two exercises, groups began to work together sharing information and suggestions, much as would be experienced in industry.

Once groups completed their cause/effect diagrams, they began the process of eliminating possible causes to obtain a most probable cause. This was initially a very difficult task for students because they had to learn a significant amount of "nuts and bolts" information about pumps, heat exchanges, and distillations columns and then apply this knowledge in a very methodological way to their cause/effect diagrams. We found that we had to provide handouts describing commonly observed process problems (effects) and the underlying mechanical faults (causes) for each type of equipment we included in troubleshooting exercises. Woods [1] has compiled a thorough list of common faults for pumps and we developed similar lists for heat exchangers and distillation columns.

During the task of developing a most probable cause, students also were initially reluctant to ask the experts for additional information and instead attempted to solve the problem with only the information provided in the written problem statement. We surmised that this behavior was probably a result of conditioning from solving traditional textbook homework problems in their previous engineering and science courses.

The final important step involves deciding upon a course of action to eliminate the identified most probable cause of the observed problem. Once the students have completed the task of identifying the problem's cause, the solution is often simple and obvious, much as it is in industrial situations.

An Example Troubleshooting Exercise

During the semester, students completed a total of 6 troubleshooting exercises, progressing from a relatively simple pumping problem involving air intake into a water pipeline via a vortex to more complex problems involving problems with heat exchangers, distillation columns, and combinations of these units. Each of these exercises not only helped students become more comfortable implementing fact-based cause analysis but also reinforced their understanding of concepts they had seen in previous courses such as fluid mechanics, heat transfer, mass transfer, and unit operations laboratory.

To illustrate how a fact-based cause analysis is applied to a process troubleshooting problem, we will describe one of the exercises we used and present examples of the cause/effect diagrams students produced. The problem statement given students was provided by Woods [1]:

> A centrifugal pump has been installed to pump water from a holding basin through a filter and on into the process. Often we bypass the filter and just pump out of the basin to an atmospheric drain. The system head curve (and thus the design conditions) is 12.5 L/s against a total head of 10.5 meters. A pump has been selected to operate most efficiently at this condition. Everything works fine when the liquid is directed through the filter. However, when we bypass the filter and try to pump out the basin, we can only pump down to a water level of 3.3 meters below the centerline of the pump. This leaves 1.2 meters of water in the bottom of the basin that can't be pumped out.

Solving this problem involved identifying possible causes that the pump does not functions properly at higher flowrates (when the flow bypasses a filter system). Figure 1 shows a complete cause/effect diagram illustrating the relationships among possible causes identified by students. Eliminating causes that aren't supported by the facts provided by the problem statement and system experts (instructors), the most probable cause can be identified — namely that a vortex develops in the basin at high flowrates, causing air to be introduced in the pump suction resulting in diminished pump performance. Once the most probable cause was been identified, solving the problem is straightforward—install a vortex breaker at the basin exit line.

Figure 2 shows an example of a student-prepared cause/effect diagram for the basin pumping problem. Notice that this diagram includes most of the important factors which could cause diminished pump performance although some of the details are missing or not completely correct. Since the basin pumping problem is the first troubleshooting exercise we complete, we found it necessary to help students develop their first cause/effect diagram by giving them the top two levels of the diagram. In later exercises, students are required to complete the diagram without prompting and, with practice, are able to do so.

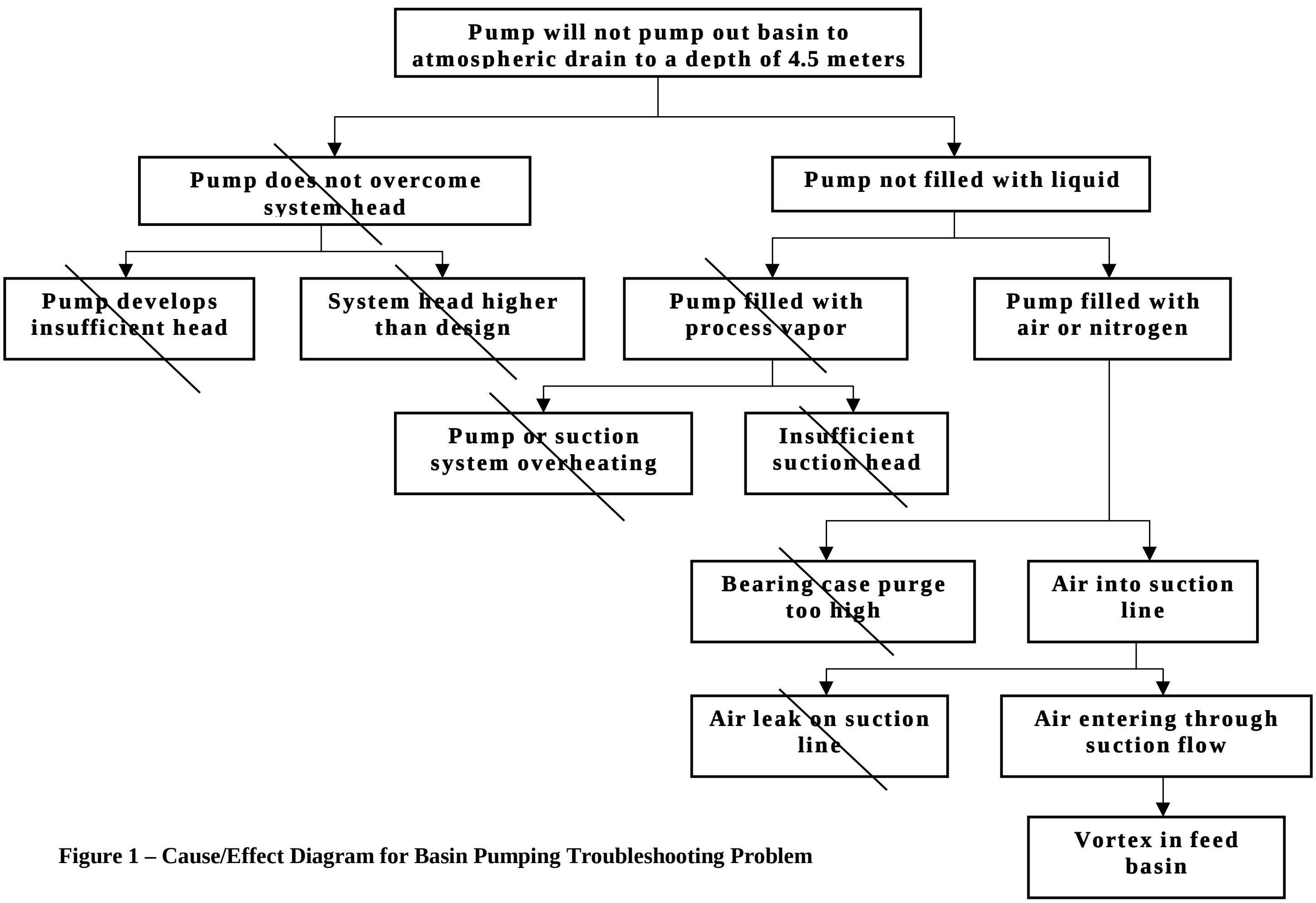

Figure 1 – Cause/Effect Diagram for Basin Pumping Troubleshooting Problem

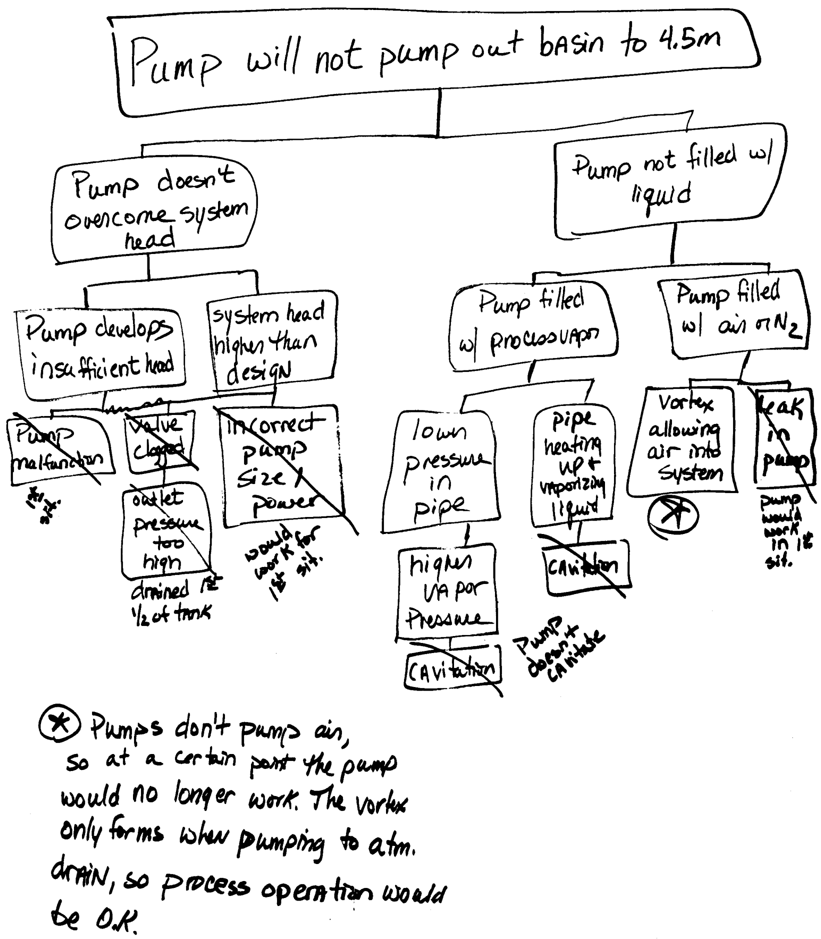

Figure 2 – Student-Generated Cause/Effect Diagram for Basin Pumping Problem

Evaluation

To help us better understand the how students viewed the value of the troubleshooting exercises in the course, we administered an end-of-semester anonymous questionnaire. When answering the question "What was the most valuable part of the course for you? Why?" approximately 87% of the students responded that learning about fault-based cause analysis, cause/effect diagrams, and the troubleshooting exercises was most valuable. Only 7% of the students stated that troubleshooting was the least valuable part of the course and in each case, these students commented that they found the exercises useful but thought we did too many of them. Typical written comments from the students included the following:

- "Makes us realize that what we have learned has other applications; sharpens critical thinking skills."
- "Exercises helped me develop skills in handling problems instead of just relying on one solution."
- "I learned more about processes doing the troubleshooting exercises than in any other classes."
- "Good to see what problems engineers come across."
- "Troubleshooting was valuable because the principles and tools learned have universal application."

Now that we have learned how to effectively incorporate troubleshooting into the course, we plan to formalize our assessment of student troubleshooting skills by creating scoring rubrics which will allow us to more reliably document improvement in students' abilities to use fact-based cause analysis to systematically solve process troubleshooting and similar "real-world" engineering problems.

Conclusions and Lessons Learned

We have successfully introduced process troubleshooting into our traditional process design course to provide students with experiences and strategies which will help them solve "real-world" practical process-related problems when then begin their engineering careers. Use of a structured problem-solving procedure based on development of cause/effect diagrams and identification of the most probable cause helps student solve a wide variety of troubleshooting exercises, each of which is a much different challenge than textbook problems students are familiar with. We also found that students required a significant amount of background knowledge describing characteristics of common faults for pumps, heat exchangers, and distillation columns. Without this information, students could not successfully solve the exercises, because the required "nuts and bolts" knowledge is generally not presented in traditional engineering science and unit operations courses.

References Cited

[1] Woods, D. R., Problem-Based Learning: How to Gain the Most from PBL, Griffin Printing Company, Hamilton, Ontario, 1994.

[2] Turton, R., Bailie, R.C., Whiting, W.B., and J.A. Shaeiwitz, Analysis, Synthesis, and Design of Chemical Processes, Prentice-Hall, Upper Saddle River, New Jersey, 1998.

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