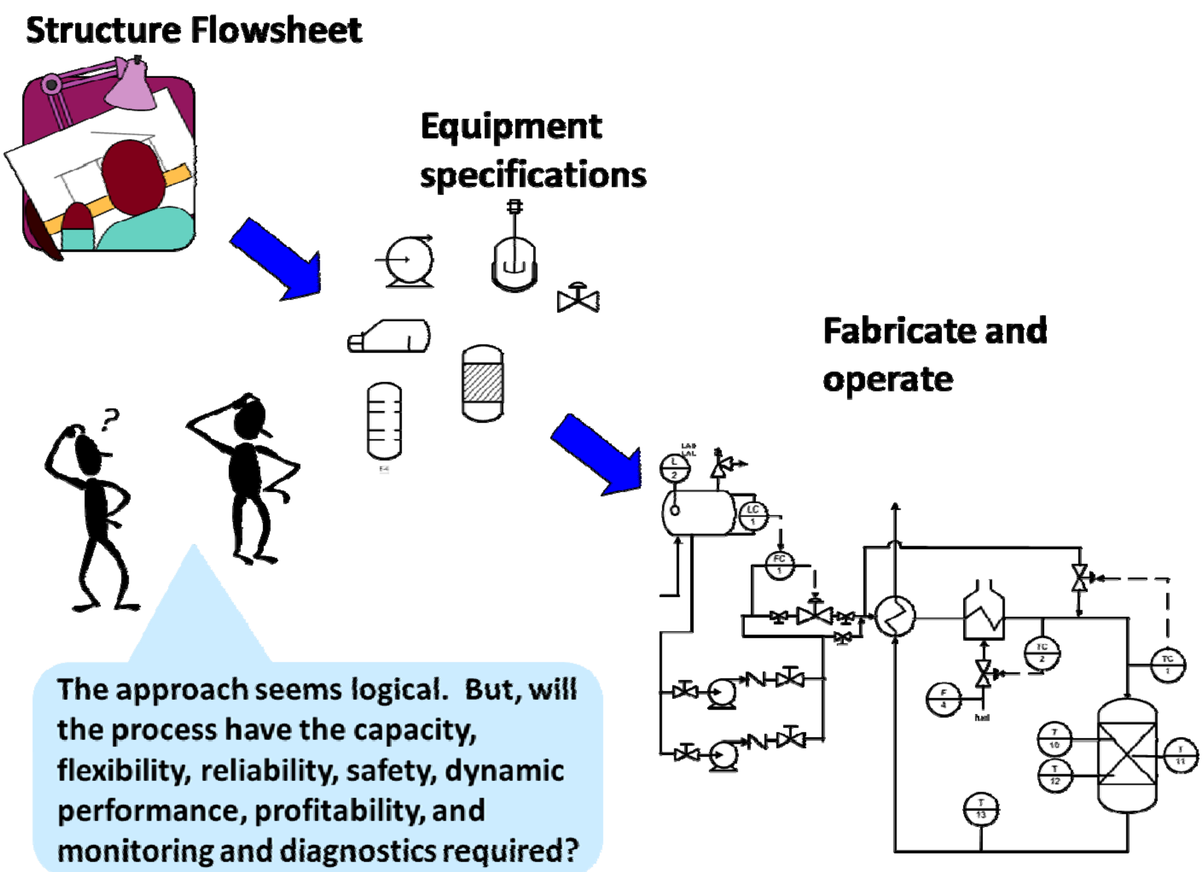
Operability in Process Design: Achieving Safe, Profitable, and Robust Process Operations

Chapter 1: Introduction to Operability



Thomas Marlin

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This material is provided to promote education in the general field of "process operability" via the Internet site www.pc-education.mcmaster.ca . It is one of the chapters of an integrated presentation of selected operability topics. The author would like to hear from readers on how they are using this material. In addition, he would appreciate suggestions for improvements and extensions. He can be contacted at marlint@mcmaster.ca .

Acknowledgements

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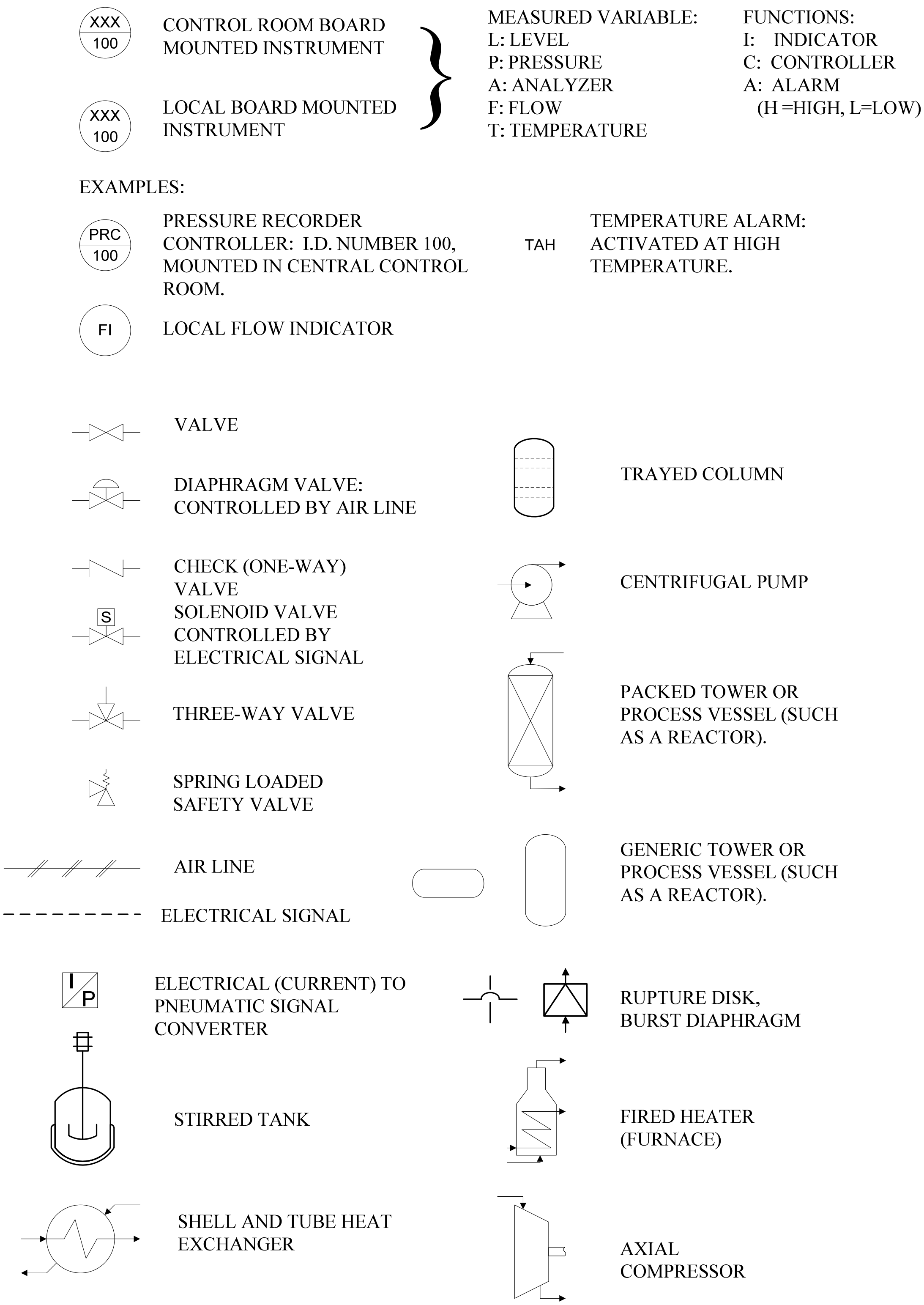
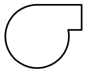
Symbols


XXX
100
CONTROL ROOM BOARD MOUNTED INSTRUMENT
XXX
100
LOCAL BOARD MOUNTED INSTRUMENT
MEASURED VARIABLE:
L: LEVEL
P: PRESSURE
A: ANALYZER
F: FLOW
T: TEMPERATURE
FUNCTIONS:
I: INDICATOR
C: CONTROLLER
A: ALARM
(H =HIGH, L=LOW)
EXAMPLES:
PRC
100
PRESSURE RECORDER CONTROLLER: I.D. NUMBER 100, MOUNTED IN CENTRAL CONTROL ROOM.
TAH
TEMPERATURE ALARM: ACTIVATED AT HIGH TEMPERATURE.
FI
LOCAL FLOW INDICATOR
VALVE
DIAPHRAGM VALVE: CONTROLLED BY AIR LINE
CHECK (ONE-WAY) VALVE
S
SOLENOID VALVE CONTROLLED BY ELECTRICAL SIGNAL
THREE-WAY VALVE
SPRING LOADED SAFETY VALVE
AIR LINE
ELECTRICAL SIGNAL
I
P
ELECTRICAL (CURRENT) TO PNEUMATIC SIGNAL CONVERTER
STIRRED TANK
SHELL AND TUBE HEAT EXCHANGER
TRAYED COLUMN
CENTRIFUGAL PUMP
PACKED TOWER OR PROCESS VESSEL (SUCH AS A REACTOR).
GENERIC TOWER OR PROCESS VESSEL (SUCH AS A REACTOR).
RUPTURE DISK, BURST DIAPHRAGM
FIRED HEATER (FURNACE)
AXIAL COMPRESSOR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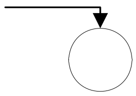
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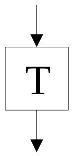

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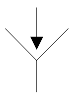
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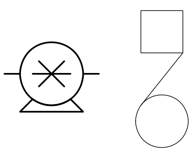
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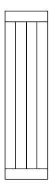
DISPLACEMENT
PUMP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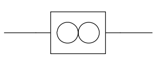
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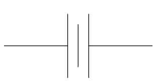
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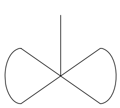
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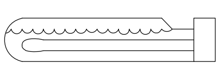
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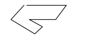
OR
REBOILER


FILTER AND DRAIN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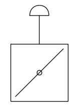
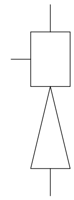

DAMPER
OR
BUTTERFLY VALVE


STEAM
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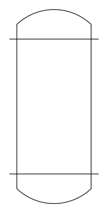
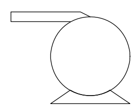

SHELL AND TUBE
HEAT EXCHANGER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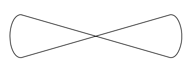
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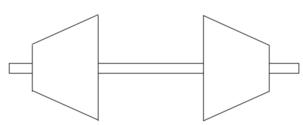

TURBINE USED TO
PROVIDE WORK
TO DRIVE
COMPRESSOR

Introduction to Operability

1.0 To the Student

Imagine that you have been given the task of designing an automobile, but you have never driven or even ridden in an automobile. You would apply your knowledge of mechanics to design a machine that would function well at 65 miles per hour (100 kilometers per hour), riding smoothly and efficiently. However, your design might not be able to accelerate rapidly enough, turn fast enough, perform acceptably on wet or icy roads, provide warning for low fuel, or provide other essential features that are required for an “operable” automobile.

As a student, you face a similar challenge when designing a chemical process. You have mastered many topics, such as material and energy balances, flowsheeting, and transport and reaction engineering. These provide the fundamental basis for the design, but much more is needed. Some important topics in the “much more” category are addressed in these chapters on “Operability in Process Design”. For each operability topic, the chapter introduces the issues involved, provides design approaches, and demonstrates application through numerous solved process examples.

This first module explains why operability is important (hint: conditions change continually) and introduces the eight major topics in operability. Each of these eight topics is addressed in a separate module. So, let’s get started by understanding the big picture about operability, without getting into too much detail in this module.

1.1 Defining Operability

We will start with the following concise definition of operability.

Operability ensures that the process has the capacity and flexibility to achieve a range of operating conditions safely, reliably, profitably and with good dynamic performance and product quality.

The definition provides a general goal but lacks specific objectives and performance measures that enable an engineer to ensure that operability is achieved by the final design. For example, do you think that you could have improved your automobile design based solely on reading this definition?

Before we expand on the definition, we will review the design procedure and how operability is integrated into this procedure. A generic flowchart of the design procedure is shown in Figure 1.1, *without operability being considered*. Process design involves a number of steps to specify the requirements, select process technology, establish major flows through material and energy balances, and define equipment that satisfy the flows and conditions. Subsequently, the process is constructed and is placed in operation, with start up usually occurring several months to years after the design was completed. You may be surprised to learn that the process may never operate under the most likely conditions anticipated during the design! Therefore, a process is designed for one (or a few) operating points can experience poor performance after startup.

It is the engineering practice of designing for a *single operating point* that is being questioned here, since it is not adequate for achieving operable plant designs.

Naturally, a necessary starting point for a design is a complete material and energy balance (a flowsheet solution) for a few typical conditions, but it is neither the conclusion of the analysis nor a proper basis for completing the design.

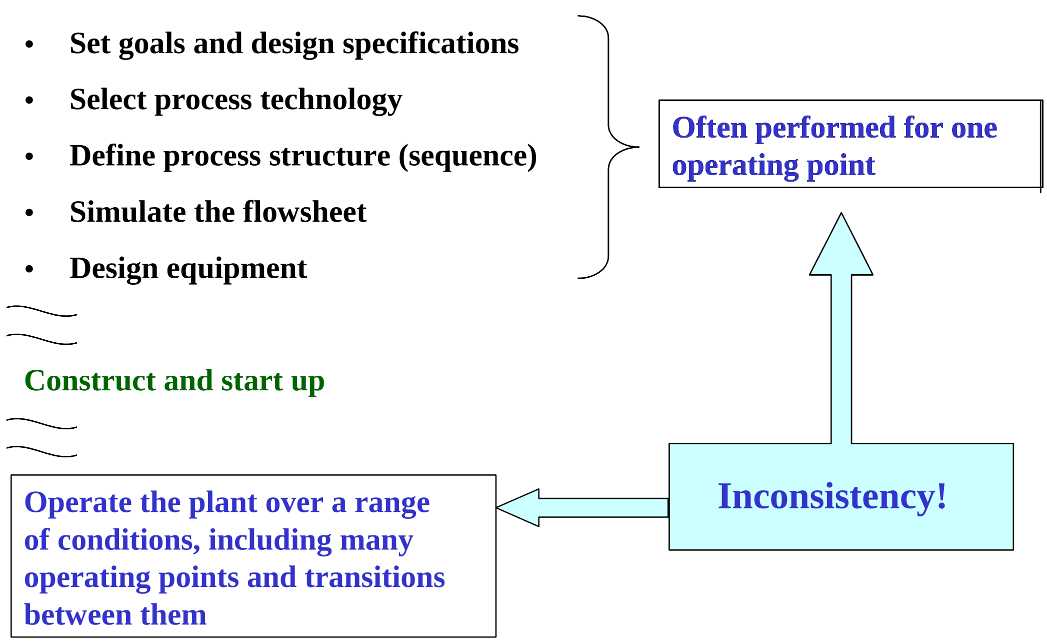
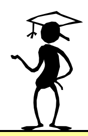


Figure 1.1 Simplified flowchart of the design procedure *without operability* showing the inconsistency between a *single-point design* and the actual process operation.

1.2 Sources of Variability

Let's consider some of the major reasons why actual operation will be different from an initial design (at a single point). Often, engineers refer to the factors in Table 1.1 as uncertainty in the design definition. While this is correct in one sense, many of these are certain to occur and are introduced by plant personnel. For example, start up and shutdown and changes to plant production rates will occur under the control of plant personnel. Other factors are not controlled by the personnel, for example, raw materials to some processes can vary significantly over the life of the process. Thus, all of the above factors introduce **variability,** i.e., differences between the assumed most likely conditions and actual conditions experienced in the plant. Some variability can be well defined during the design process (and are in a sense certain) while others can only be roughly estimated (and are uncertain).



Use this table to help you brainstorm when you analyze specific processes.

Table 1.1. Major sources of variability between single-point design conditions and conditions experienced in a process plant

1. **Changes introduced by plant personnel** – Plant personnel introduce changes to operating conditions such as production rate and product quality. The rate of production will change because of the market demand and of changes to prices of raw materials and products. Many plants can make products with a range of properties, and operations are changed to produce multiple products with the same equipment. Finally, many plants can satisfy demands through many operating conditions, and the engineers select the conditions that produce the greatest profit.
2. **Disturbances** - Many factors external to the process equipment affect the process performance, for example, raw material properties and cooling water temperature. Disturbances have differing magnitudes and frequencies; high frequency disturbances change often, while low frequency disturbances change slowly or infrequently.
3. **Model mismatch** – We predict the behavior of the process using the best available models and data; however, we recognize that these models cannot perfectly predict the behavior of the actual process when built. It is especially important to recognize that equipment performance changes, for example, heat exchangers foul and catalysts deactivate over time.
4. **Equipment malfunction** – While process equipment is generally reliable, faults occur and processes must respond safely to these faults. In many cases, we seek to continue operation, albeit at lower production rates and efficiencies, when equipment fails to operate as designed. Students are initially surprised to learn about the many types of equipment failures, especially the failures of equipment that are installed to prevent negative consequences of failures in other equipment.

5. **Human error** – Again, plant personnel are careful and responsible, but occasionally, they make mistakes, and we must design so that mistakes will not lead to catastrophic consequences. (*Have you ever made a typing mistake? If you made this mistake when operating a plant, it should not lead to hazardous conditions or extreme loss in profit.*)

1.3 Importance of the Design Specification

Clearly, if we are to design an operable process, we need to define a range of conditions over which the process will operable, i.e., we need to define the variability. The logical place in the design procedure is at the beginning in the Design Specification. All of the major factors affecting anticipated variability, e.g., source, magnitude, and frequency, should be defined in the Design Specification to ensure that the equipment will function as required over the anticipated range of variability.

Example 1.1 Defining sources of variability – A schematic of an olefin-producing process is given in Figure 1.2. The raw materials are hydrocarbon streams (from ethane to gas oil), which are thermally cracked at high temperatures and subsequently separated by refrigeration and distillation. Identify possible sources of variability that should be considered when designing the plant.

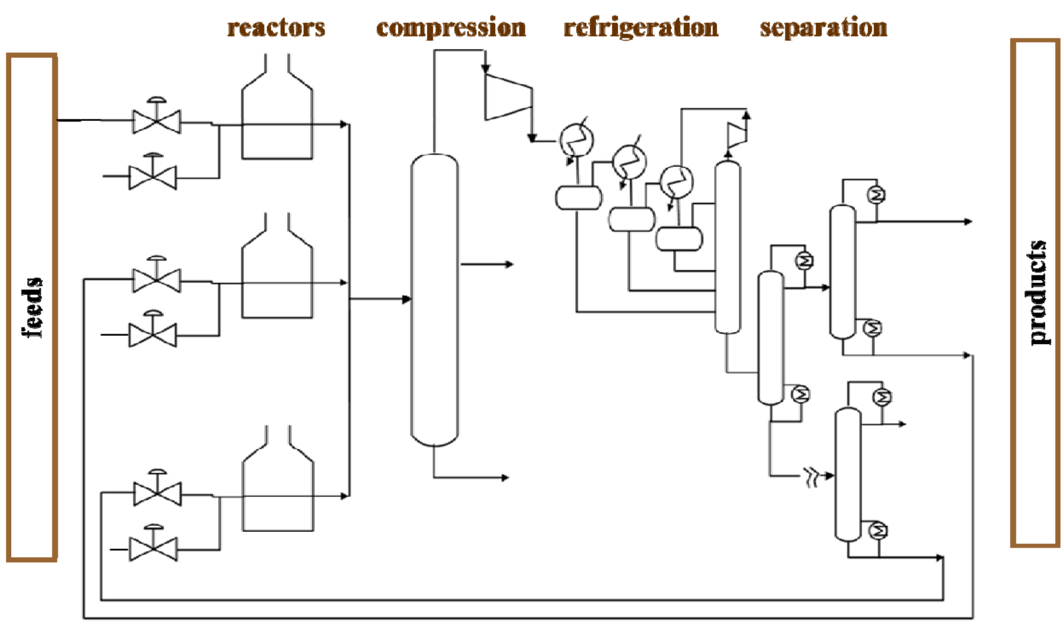


Figure 1.2. Simplified process schematic of an olefins-producing pyrolysis process used in Example 1.1.

Example 1.1 Solution

Some of the factors that could vary significantly and affect operability are noted in Table 1.2. To design the plant, we need to know for each source of variability (a) the occurrence frequency and (b) the magnitude of the change. For example, we need to know the time between deliveries of raw materials and the amount delivered, so that we can design storage facilities with the proper capacity. Naturally, we need to anticipate unusual circumstances, such as a delay in delivery, which requires that we have some raw material "safety stock" stored as well. The amount of safety stock is a business decision that finds a best tradeoff between the cost of storage and the value of sales and customer satisfaction.

Table 1.2. Some sources of variability between design conditions and actual plant conditions for Example 1.1*

1. Changes by Plant Personnel (meet product demands, achieve high profit, etc.)		
Feeds: Feed flow rate	Plant Operations: Reactor severity/conversion Reactor yields/selectivity Refrigeration temperatures Distillation pressures	Products: To storage or to pipeline
2. Disturbances (undesired and uncontrollable variability)		
Feeds: Compositions	Environment: Ambient temperature, e.g., • cooling water • need for steam tracing Disturbances, e.g., • rain storms	Utilities: Fuels Steam Recycles: Flow or composition
3. Model Mismatch (deviation of plant from design models)		
Reactors: Yields at specific operating conditions	Energy Units: Efficiency of furnaces Efficiencies of compressors	Separation: Condenser and reboiler duties for specific separation
4. Equipment malfunction (partial or total loss of function)		
Out of service: Failure (stoppage) of compressor	Leak: Heat exchanger leak	Loss of utility: Steam Compressed air
5. Human Error (inadvertent action)		
Improper operating condition: Too low a flow to furnace/reactor Too low a suction pressure to compressor	Rate of Change: Change conditions too quickly, e.g., feed flow rate	Incorrect variable: Manually close a valve that should remain open

* These answers are only a few of the possible correct responses. You may have discovered other correct answers; check with your instructor.

Clearly, we must know the variability before proceeding to design the plant. Much of the variability will be defined in the first stage of the design procedure in Figure 1.1, i.e., in the design specifications. Variability that is unique to the specific project is defined at this stage. Examples of project-specific variability are given in the following.

- The range or raw material composition
- The range of production rates
- Rate of change of equipment performance in chemical reactors due to, for example, catalyst deactivation
- Timing of deliveries of raw materials and dispatch of products (to determine capacity of storage facilities)

To ensure a proper design, all project-specific variability must be clearly and exactly defined during the initial stage of the design procedure and documented for use by the entire design team.

Unfortunately, not all variability is defined explicitly, so that the engineer must have experience with the equipment involved and the tacit assumptions employed in the organization. Examples of generic variability that are often not documented are given in the following (along with a design interpretation).

- Temperature of cooling water used for heat exchange (usually use a high value, e.g., 20 °C)
- Heat exchanger fouling factor (usually use highest fouling, giving lowest heat transfer coefficient, which occurs just before chemical or mechanical cleaning)
- Some equipment is expected to fail because of challenging environment, e.g., pumps handling slurries like wood pulp (usually provide a spare, installed pump)
- Control valves may leak (requiring isolation and by-pass valves so that a leaky control valve can be replaced while the plant remains in operation)
- Any valve could be closed (or opened) improperly by a computer or person (requiring safety equipment in response to excess pressure)

These examples indicate that we usually take a “conservative” approach by ensuring that the process will have the capacity when the variable experiences the extreme value within the anticipated range of variability. When the extreme value occurs, safety, production rate, and product quality goals can be achieved by providing extra capacity (e.g., heat transfer area) or backup equipment (e.g., bypass valves).

These are only a few of the many issues that design engineers are expected to know, and many more will be introduced in later chapters. We can see that an individual might not apply the same guidelines as expected by others in the design team. Therefore, it is good practice for engineers to clearly communicate the tacit assumptions used in their designs.

How can you learn all of these “unspoken” design guidelines? Don’t worry; you will be given many examples of variability with proper design responses in the subsequent Chapters. Also, you will not be expected to learn them all in this course. Covering this material will introduce many of the most common unspoken guidelines and will prepare to learn others as you enter engineering practice.

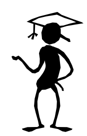
1.4 Operability Topics

As you experienced in Exercise 1.1, applying the general definition of operability to identify all major sources of variability is a daunting task. Therefore, we will improve the definition through a set of operability topics or categories, and we will study each topic in detail in subsequent chapters. The eight topics addressed in this book are listed in Table 1.2.

Operability involves responding to deviations from a base case operation. These can occur due to advantageous situations, such as increased market demands or lower purchase price of an alternative feed material, or due to an undesired situation, such as a decrease in equipment performance or equipment failure. In general, we would like to effect the operability changes in a manner that has the least negative impact on the plant operation and a manner that increases profit (or at least decreases loss). We desire to have a least impact on normal operations while achieving safety and other requirements. We note that shutting down part or all of a process plant can be very costly, since the time for shutdown and start up can be many days, during which no production is possible, and large quantities of off-specification material will be generated and must be disposed of.

Table 1.2 Operability Topics

1. Operating Window
2. Flexibility
3. Reliability
4. Safety and Equipment Protection
5. Dynamic Operation and Product Quality
6. Operation during transitions
7. Efficiency and Profitability
8. Monitoring and Diagnosis (including trouble shooting)



These are the basis of the entire Operability topic! Don’t memorize but use to aid your learning and problem solving.

As we cover each of these topics, we will first define the topic and see a few industrial examples. In addition, we will learn about the challenges involved in operating the process, so that we can appreciate how proper designs improve operations. Let's look at a process example and identify one operating issue for each topic.

Example 1.2 Sample operability issues – A prototype process is given in Figure 1.3. The feed liquid raw material is supplied from an upstream process (not shown), pumped from the storage vessel, preheated, fed to a packed bed chemical reactor where an exothermic reaction occurs, cooled, and flows to a product storage tank. For this process, identify at least one example of an issue in each of the eight operability topics in Table 1.2. (*You have not been given much detail about the process or at this point, specific designs for operability. Therefore, don't expect to get a perfect answer now; just do the best you can with the knowledge that you have. You will learn about solutions throughout this material on operability*.)

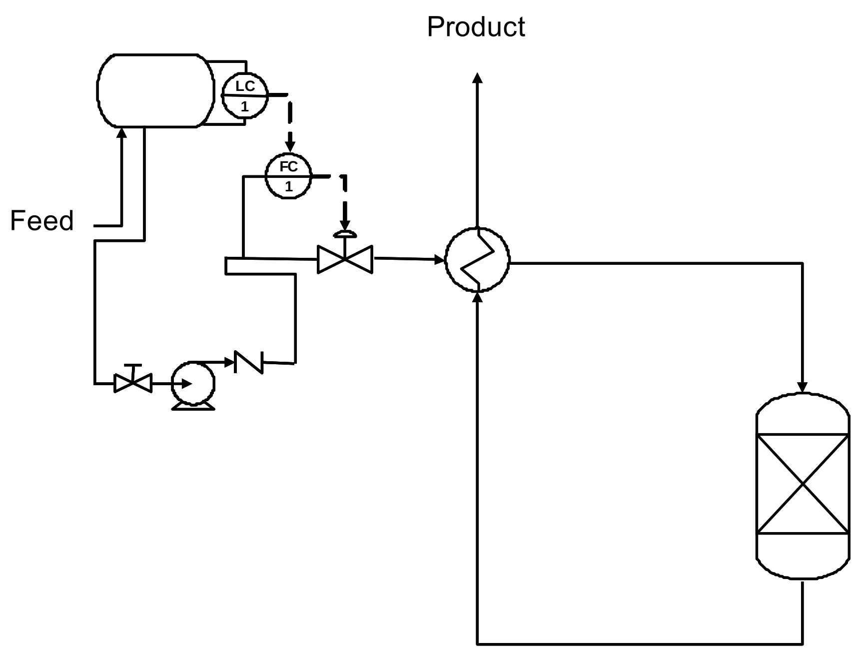


Figure 1.3a. Prototype process for use with Exercise 1.2.

Example 1.2 Solution

The following solutions provide one important issue per operability topic. Many other answers are possible, so if you didn't choose the answers given here, you could still be correct.

1. Operating Window

Here, we ensure that the equipment will function properly over the anticipated range of operation. One common change in process plants is the production rate. When the feed flow to this process changes, which is achieved by equipment not shown in the drawing, the flow rate from the feed drum to the reactor must respond to become equal to the feed rate at steady state. Usually, process plants do not operate from zero to design flow; a more common range would be 60% to 110% of the base case design flow rate. Since we do not have detailed information about the process for this brief example, we will accept this approximation.

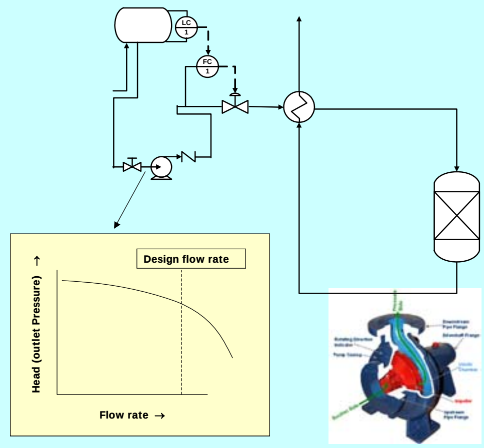


Figure 1.3b. Operating window for Example 1.2. Pump from Fantagu (2008)

Therefore, the equipment should be able to achieve the maximum flow rate. The pump must be able to provide the required outlet pressure to achieve at least 110% of the design flow rate. Figure 1.3b shows a typical pump performance curve for a constant-speed centrifugal pump (Peters, et. al., 2003; Chemeresources, 2009). We note that the outlet head decreases as the flow rate increases and that it decreases rapidly at a specific (stonewall) flow rate. We must select a pump with a head large enough to overcome the system resistance and a stonewall flow rate well beyond the anticipated maximum flow rate.

2. Flexibility

Based on the results of the operating window, the combination of the constant-speed centrifugal pump, flow sensor and control valve must be able to achieve the expected range of flows. In Topic 1, we have ensured that the pump will provide adequate outlet head. The sensor must be able to measure the flow from 60% to 110%, which is a ratio of maximum to minimum flow rate of about two. This ratio can be achieved by the most common flow sensor, an orifice meter (Marlin, 2009); so, we will select this low-cost measurement technology. (Note that sensor accuracy is also important and would be considered along with other factors in selecting a flow sensor (Marlin, 2009).)

Now, we must provide an adjustable element to influence the flow rate so that we can maintain it at the desired value. The most common manner for influencing flow is an adjustable valve, much like the home facet but with additional features that enable automatic adjustment, rather than hand adjustment.

A typical control valve is shown in Figure 1.3c. The selection of the body (through which the fluid flows) and the actuator (which adjusts the stem position) depends upon many factors such as fluid properties (Marlin, 2009).

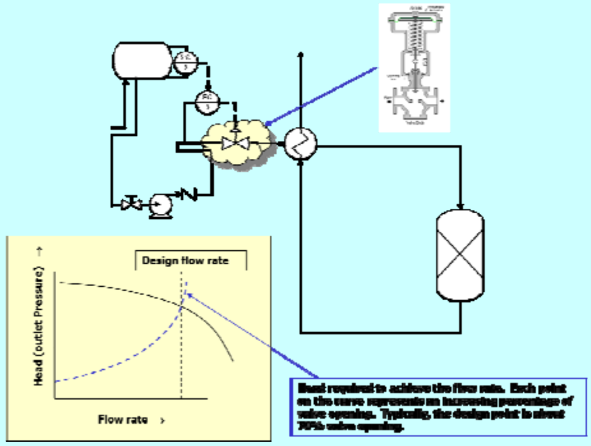


Figure 1.3c. Achieving flexibility for Example 1.2. Valve from Beychok (2012)

3. Reliability

Reliability enables plant personnel to reduce the occurrence of faults and when a fault occurs, to either (a) maintain operation automatically or (b) quickly restore operation through intervention by plant personnel. Let's look a situation in which the pump motor failed. For the original design, spare equipment would have to be transported to the location in the plant, installed and placed in operation, which could take a long time. A common design approach is to provide installed spare equipment for selected equipment that fail relatively often. With a spare installed pump, as shown in Figure 1.3d, the process can be placed quickly back into operation.

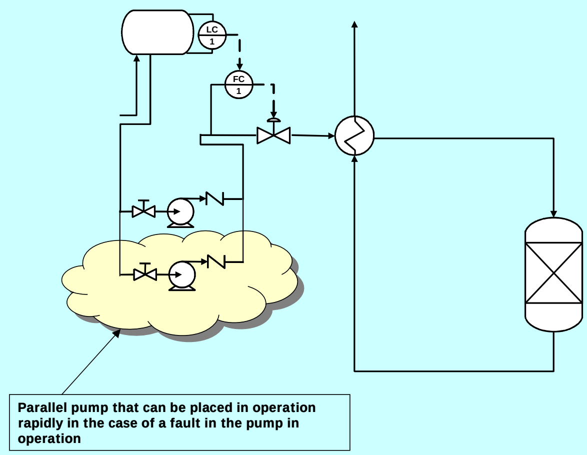


Figure 1.3d. Reliability for Example 1.2.

We note that this solution involves some time without flow through the reactor. If this were not acceptable, an automated system would have to start the backup pump based on, for example, the pressure at the exit of the pumps.

4. Safety and Equipment Protection

Process equipment is physically robust, usually made of metal and designed to withstand pressures occurring in the process. However, all closed vessels are designed to operate safely over a *limited range* of pressures, and pressures in excess of the design limit can lead to rupture, which would damage equipment, release process materials and place personnel in danger. Therefore, we must provide an emergency release path for fluids to prevent dangerous pressures. In the example, the drum is a closed vessel that could experience high pressures; therefore, we provide a safety valve that opens automatically to allow flow out of the drum. Naturally, we must route the fluid to a safe location for storage or neutralization.

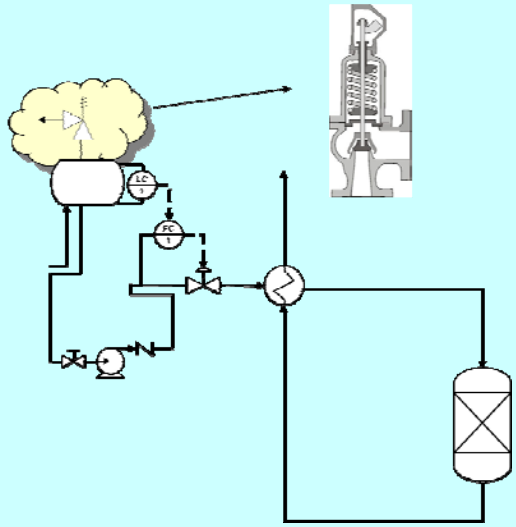


Figure 1.3e. Safety through pressure relief in Example 1.2. Safety valve from Rasi57 (2012)

A typical safety valve is shown in Figure 1.3e. One key feature of this valve is that it does not require external power, e.g., electricity, to function, so that it is very reliable (Crowl and Lovuar, 1990). More details on safety valves are provided in Chapter 5.

5. Dynamic Operation and Product Quality

Certainly, we must produce products with acceptable quality to achieve profitability. Therefore, we must maintain the reactor conditions near their proper values. From reaction engineering, we know that temperature strongly affects chemical reactions. So, we must be able to influence the reactor temperature, without changing the production rate. Here, we decide to place an adjustable by-pass around the feed-effluent heat exchanger. By adjusting the opening of the by-pass as shown in Figure 1.3f, the ratio of heated to cold feed can be adjusted to achieve the desired reactor feed temperature.

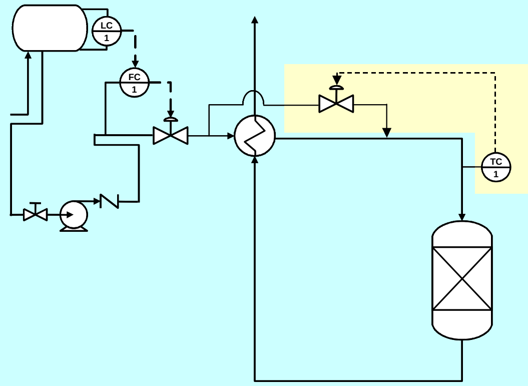


Figure 1.3f. Product quality control for Example 1.2.

We note that this design change adds additional flexibility to the process operation. It is not so important under which operability topic, e.g., flexibility or profitability, that we introduce the design feature. However, it is essential that we include the feature!

6. Operation during transitions

The process must be started up! During normal operation, the reactor feed is heated using the hot reactor effluent. However, during startup, no heating would be available. Therefore, the design engineer must provide a heating source to increase the reactor feed temperature during startup. The proper heating source depends upon the required temperature and other factors. Here, we will assume that the temperature is higher than can be provided by steam, so that we will include a fired heater as shown in Figure 1.3g.

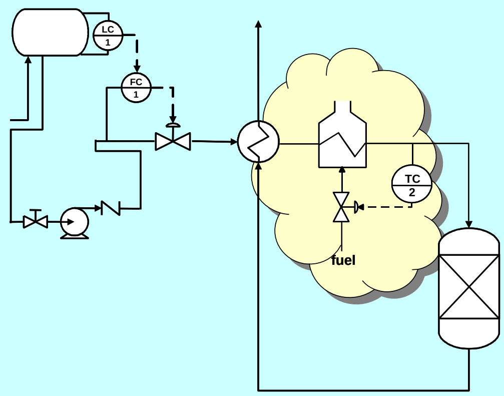


Figure 1.3g. Transition operation for Example 1.2.

7. Efficiency and Profitability

A feed-effluent heat exchanger provides heating and cooling without operating cost; thus, this design occurs frequently in process plants. However, the design has the disadvantage of having "positive feedback" for some disturbances, which is especially pronounced for highly exothermic reactions. For example,

- a small increase in the temperature in the reactor leads to a larger increase in the reactor effluent temperature.
- the effluent temperature increase leads to an increase in the reactor feed temperature, because of increased driving force of heat transfer
- the increase in feed temperature causes a further increase in reactor temperature

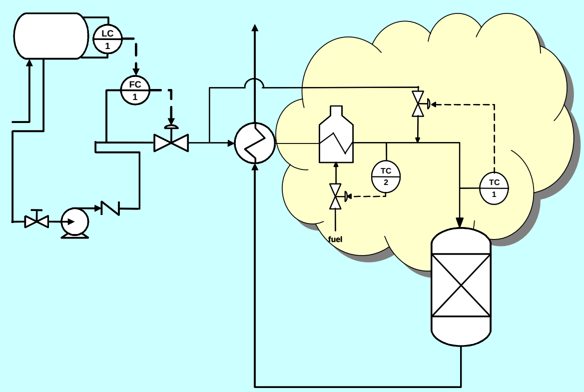


Figure 1.3h. Dynamic operation for Example 1.2.

This behavior can cause variability in product quality and in the extreme, can cause severe oscillations and instability in the reactor temperature.

The process design needs a method to substantially reduce the positive feedback. In fact, we have included a method in Topic 5. The temperature control by adjusting the very fast-responding by-pass can "trap and eliminate" the disturbance, preventing it from affecting the reactor feed temperature. The resulting design is shown in Figure 1.3h.

What about efficiency? We observe that the process design heats part of the reactor feed and then mixes it with the colder bypass material. From thermodynamics, we would expect that this design is inefficient, so we would like to minimize the mixing of hot and cold streams while retaining some essential bypass for quick response to disturbances. One way to achieve efficiency is by adjusting the fired heater outlet temperature to as low a value as possible, which reduces fuel to the heater.

How low is possible? We want a small bypass, but never allow the bypass valve to be closed. Therefore, we can implement a control system (not shown on the diagram) that would maintain the bypass valve at a small amount open (for example, 10% open) by adjusting the fired heater temperature controller set point. This will maximize feed-effluent heat exchange and minimize fuel use, while maintaining the bypass open. Note that reducing fuel also reduces the "carbon footprint" (CO_2 effluent) from the process.

8. Monitoring and Diagnosis (including trouble shooting)

Packed bed reactors often experience flow mal-distribution, which can lead to significant temperature variability in exothermic reactors. If a local hot spot occurs, catalyst could be damaged and worse, the temperature rise could spread to a larger segment of the reactor, which could lead to damage to the vessel and hazards to personnel. Therefore, many temperature sensors have to be installed in the reactor for local temperature monitoring as shown in Figure 1.3j.

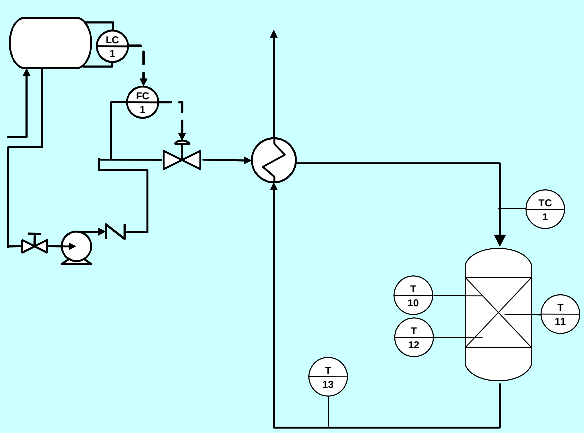


Figure 1.3j. Monitoring for Example 1.2.

These sensors could be used for alarms, feedback control or automated emergency shutdown. For example, if used for alarms, a high temperature alarm (blinking light and audible signal) would draw the operating personnel's attention to this measurement. The person would begin a trouble-shooting procedure addressed in Chapter 9 to decide on an appropriate response, which could be to lower the reactor inlet temperature.

Naturally, all of the design modifications for operability would have to be included in the final design. Since we have considered only one issue for each of the eight factors, we expect that the final design would require many more modifications to achieve acceptable operability. A more complete (but still not completely operable) design is given in Figure 1.4. We note that the design in Figure 1.4 has changed substantially from the original proposal in Figure 1.3a.

Before completing the design, we must ensure that modifications for one topic have not introduced operability deficiencies in other topics. For example, the pump selected for the operating window should operate near its maximum efficiency at the base case design flow rate, and the duplicate pumps should have sufficient isolation valves so that either pump can be taken out and replaced while the other pump and entire process continues in operation. Clearly, designing for the topics in a sequential manner will not result in an acceptable design. Iterations will be required, and an experienced engineer can look ahead to ensure that appropriate changes are often included together to address multiple operability topics.

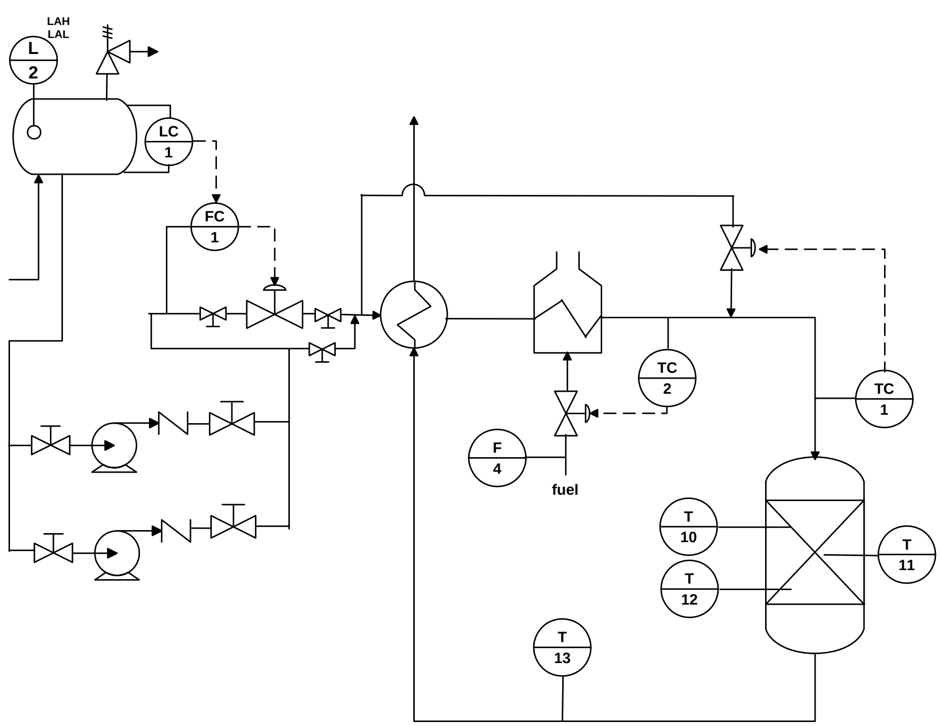


Figure 1.4 A modified design for the process in Example 1.2 with many operability issues addressed.

After reviewing the previous example, you might be overwhelmed by the scope of the operability subject. Also, you might feel that operability is a myriad of “tricks” that can only be learned through years of engineering practice. So, let’s clarify the goals of the learning experience.

1. The purpose of this book is to provide you with guidance on how to identify important operability issues and to design processes to achieve good operability.

In fact, the primary contribution of this educational material is to provide you with a structure for analyzing any process system, or put another way, it provides you with a generic set of questions to ask about a process.

2. Many realistic solutions are provided, and you might apply these solutions directly as you practice engineering. However, you will undoubtedly need to research and learn additional solutions for the specific technologies you encounter in your careers.

By learning operability here, you will dramatically accelerate your lifelong learning.

3. You have learned about power theories, such as material and energy balances, rate processes, equilibrium, and dynamic stability. Designing for operability requires that you apply theory to build a deep understanding of the physical equipment.

As you learn operability, you will have the opportunity to refresh your previous learning about the engineering sciences. You will also gain a new respect for the ingenuity applied in designing complex equipment.

4. Operability involves an analysis of the entire process system. Even if the design individual equipment appears satisfactory, the integrated plant might not function well.

5. Finally, experience has demonstrated the applicability of operability concepts to a wide range of process technology. You will need this combination of knowledge and skills regardless of the industry you work or engineering role you fulfill in the organization.

1.5 Matching Response to Variability

We have seen that a great many sources of variability exist and that many of these occur frequently. You might reach the conclusion that plant operation is very challenging and perhaps, not even possible due to this variability. You would be correct if the plant design were performed without considering the variability. However, achieving good plant operation is possible when the plant design provides adequate process capabilities. The proper plant design provides moderate responses, i.e., adjustments, for the most common, small-magnitude variability. Also, it provides the ability to maintain production when moderate variability occurs. Most importantly, it provides the capability to respond aggressively to the infrequent variability that might lead to personal injury and/or damage to equipment.

When considering the responses to variability, it is useful to group the eight operability topics. The first, equipment capacity, is always relevant because adequate capacity is required for all other topics. The remaining seven operability topics can be organized into the following three groups.

- "Control" – these three topics principally relate to moderate adjustments (flexibility, process control, and transitions),
- "Emergency response" – these three topics principally relate to medium and large adjustments (safety, reliability and monitoring/troubleshooting), and
- "Optimization" – this one topic relates to very slow responses (efficiency/profitability).

We will concentrate on the control and emergency response groupings in this section, assuming that the proper equipment capacity has been provided in the design.

Matching response magnitudes with variability magnitudes is shown schematically in Figure 1.5. Since the vast majority of variability occurs in the small-magnitude region, we observe that the "control" topics respond frequently to maintain the process at or near best operation. As the variability magnitude increases, more aggressive adjustments are required to ensure feasible operation and safety. For medium magnitudes of variability, the plant can be maintained in operation when proper responses are implemented, but the full production rate and maximum efficiency usually cannot be achieved. For large magnitudes of variability, people and equipment are protected by aggressive actions, which might involve the shutdown of part or all of the plant.

We recognize that the figure provides a simplified presentation of a complex issue. In reality, all types and magnitudes of variability occur continually, and the automatic controls and plant personnel introduce adjustments in response to the variability. One of the key plant design goals is to introduce the smallest, least costly and least disruptive adjustments that achieve safe, reliable, and profitable plant operation. Therefore, the figure shows the adjustment magnitude is matched with the variability magnitude.

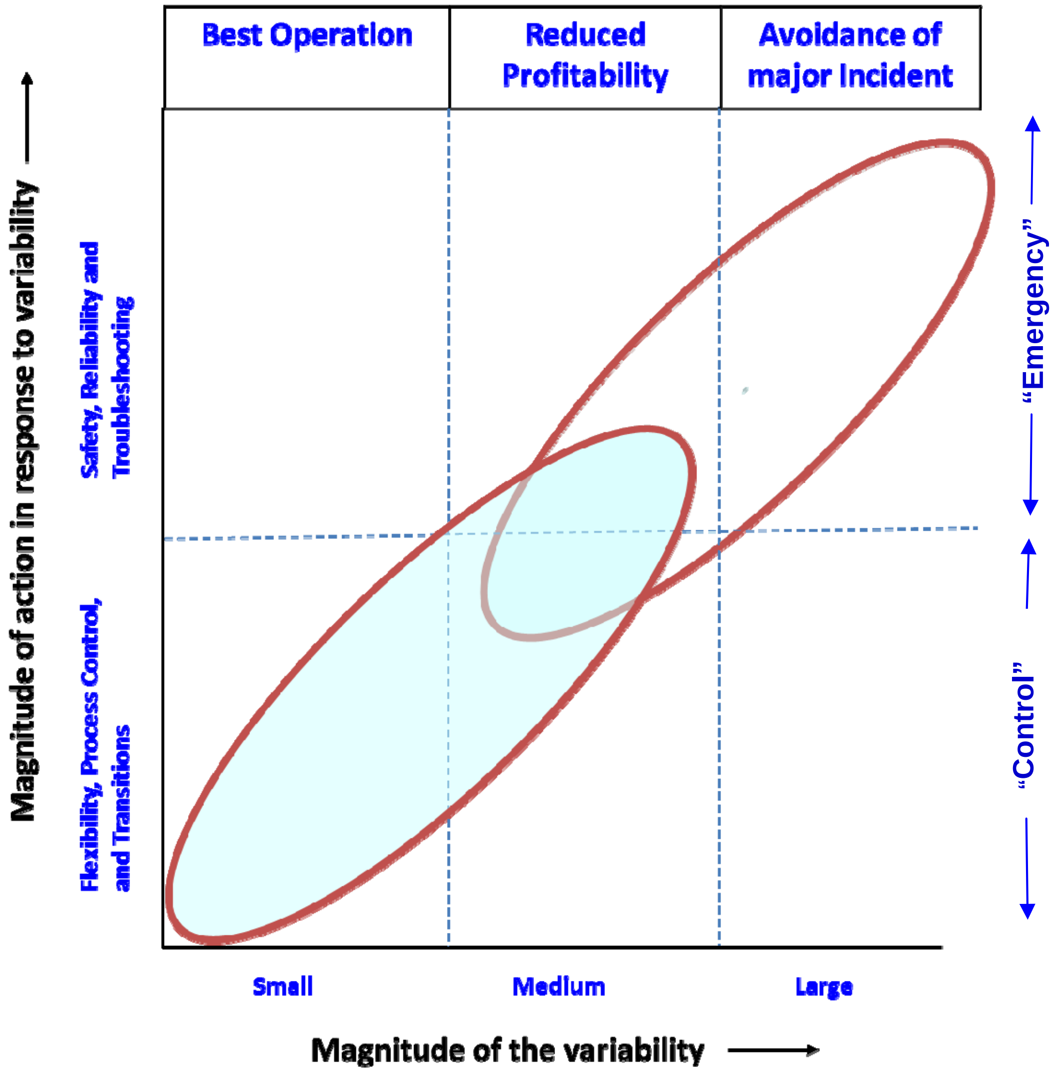


Figure 1.5. Matching adjustment magnitude to variability

The concepts shown in Figure 1.5 are further elaborated in Table 1.3. The table gives some examples of the variability and adjustments for each of the magnitudes. Generally, the smaller adjustments involve changes to continuous variables, such as control valve stem positions. Medium adjustments can involve shutting down equipment temporarily for maintenance, starting backup or supplemental equipment (such as pumps), and purchasing backup fuels; these adjustments involve a combination of continuous and discrete changes. The large adjustments must be implemented for protection of people and equipment, many are discrete responses, like stopping fuel to a boiler, but some involve continuous variables like recycle around a process to achieve a minimum flow rate.

Table 1.3. Operability for ranges of variability.

<table>
<tr><th colspan="3">Magnitude of the variability</th></tr>
<tr><th>Small</th><th>Medium</th><th>Large</th></tr>
<tr><th colspan="3">Examples of the variability at each magnitude</th></tr>
<tr><td>• Feed composition
• Production rate changes to match sales
• Cooling water temperature
• Heat exchanger fouling
• Catalyst deactivation
• Measurement errors within typical accuracy limits
• Deviation from equipment design calculations, within the expected uncertainty
• Instrument fault in monitoring equipment</td><td>• Equipment (pump, heat exchanger, etc.) out of service for planned maintenance
• Extremely high cooling water temperature due to high ambient temperature
• Air compressor work limit due to high ambient temperature
• Rotating machinery experiences excessive vibration at high load
• Instrument fault in modulating control</td><td>• Low or no cooling water flow rate due to pumping fault
• Limited steam use possible due to emergency stoppage of one or more plant boilers
• Unanticipated equipment failure (pump, heat exchanger, etc.)
• Loss of containment leading to process materials released to the environment
• Incorrect valve manually opened due to human error
• Instrumentation fault in safety-related control</td></tr>
<tr><th colspan="3">Typical adjustments in response to variability</th></tr>
<tr><td>• Adjustments by automatic control to control valve stem positions
• Laboratory data as basis for adjustments to operating conditions to achieve desired product quality, reactor conversion, separation purity, etc.</td><td>• Startup redundant equipment
• Adjust production rate to achieve feasible operation
• Quickly repair/replace faulty equipment</td><td>• Prevent hazardous operation through
- alarms
- automated controls to stop operation
- pressure relief
- adjustments to prevent equipment damage
• Limit damage
- fire protection barriers
- limits to spread of fluids
- automatic water release to douse fire</td></tr>
<tr><th colspan="3">Operating goals that can typically be achieved</th></tr>
<tr><td>Best operation

Adjust operating conditions to achieve product quality, production rate and efficiency.</td><td>Manufacture products with reduced profitability

Adjust operations to accommodate reduced process capability while maintaining product quality. Production rates and process efficiency might be lower than best operation.</td><td>Avoid major incident

Adjust operation substantially to protect people and equipment. Continued production might not be feasible. Partial or complete plant shutdown is possible.</td></tr>
</table>

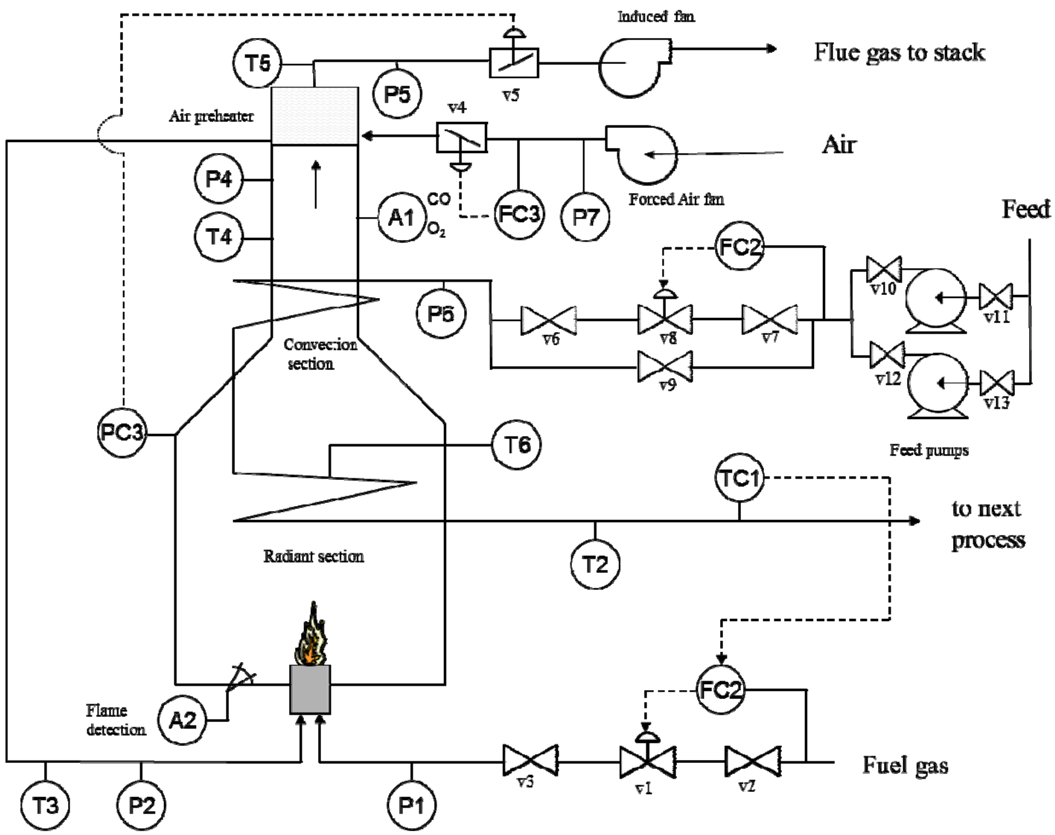


Figure 1.6. Simplified drawing of a process fired heater for Example 1.3.

Example 1.3 Operability design features for a fired heater. A fired heater is included in a design to raise the temperature of a fluid higher than can be achieved by heat exchange with steam. A simplified drawing of a fired heater is given in Figure 1.6. Much more detail would be included in a completed design, but the drawing is adequate to demonstrate one example of design for each of the operability topics.

The solution for Example 1.3 is presented in the following.

Operability topic	A typical source of variability	Design feature to address the variability
Capacity	Air temperature	The air compressor would be designed for the highest ambient temperature, which requires the greatest work to achieve the desired outlet pressure for the design flow rate.
Flexibility	Variable flow rates	Automatic control valves (v1, v4, v5, v8) are provided to achieve the desired flow rates by adjusting the resistance to flow.
Reliability	Pump motor fault	Two feed pumps are provided in parallel with isolation valves so that one can function while the other is repaired.
Safety	Flame out due to low air flow rate	A flame detection sensor is provided to immediately determine the loss of flame. (This would be used in an automatic control system to immediately stop the fuel flow rate. In addition, an alarm would alert the operating personnel.)

Dynamic operation and control	Disturbances in the air temperature and fuel composition (heat of combustion)	The outlet temperature is measured and regulated by a feedback controller that adjusts the fuel rate to the burner.
Transition	Startup of the heater from ambient temperature	The fluid outlet temperature sensor, T1, would have a small range around the normal operating temperature to provide good accuracy. For example, the range might be 400-450 °C. To measure the temperature during startup, the additional T2 sensor would have a range from 0-500 °C.
Efficiency and profitability	Disturbances in the air temperature and fuel composition (heat of combustion)	A best (or optimum) flue gas excess oxygen concentration yields the highest thermal efficiency and minimizes fuel consumption. The flue gas oxygen concentration is measured and controlled by adjusting the air flow rate.
Monitoring and diagnosing	Coke formation in the radiant section pipe (tube)	Tube metal sensors are welded to the pipe. High tube metal temperatures indicate that the heat transfer is poor. Prolonged operation at high metal temperature can lead to pipe failure.

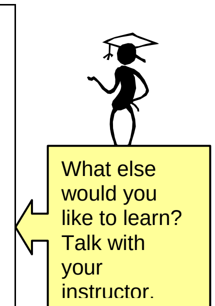
1.6 Learning Objectives

It is often useful to state learning objectives in three categories (Rugarcia et. al., 2000). These categories - attitudes, skills, and knowledge - are presented in Table 1.4 for the operability material in this book. Attitudes influence how we approach new challenges, so that we accept the importance of operability in all processes and are willing to invest the effort to perform appropriate analysis and design. Skills enable us to effectively apply our knowledge in solving unique problems. Finally, operability involves specific engineering knowledge that builds on prior studies and enables us to design processes that are safe and operable.

Table 1.4 Learning Objectives for Operability

Attitudes	Knowledge	Skills
• Process operating conditions and goals change frequently • Process behavior never matches theoretical predictions* • Operability is essential and cannot be "added on" after equipment design has been completed	• Defining sources of variability in plant operation • Standard designs to attenuate the effects on plant behavior of variability in eight major categories • Applying principles to develop non-standard designs in response to variability	• Problem solving process operations • Achieving a good solution to a problem with multiple criteria (e.g., economic and safety) • Managing a team project (e.g., HAZOP) • Communicate the design via oral presentations, reports and drawings

* Except fundamentals like material and energy balances



Before completing this brief introduction, you might be interested in some important issues that justify your effort in learning this material on operability.

- **Operability is widely applicable** – Operability requires good applications of principles that you have been studying for several years. Here, you will take a “problem-based” approach, in which you will decide which fundamentals to apply to each design issue. (*Whereas, in the past, you were pretty sure that you used heat transfer material in the heat transfer course.*) Importantly, you will be able to transfer your learning one type of process to another.
- **Operability involves qualitative analysis** – Many of the solutions involve modifications to the process equipment and its structure. Thus, you will be asked to decide where valves are needed, what type of valve body, and whether or not they should be actuated for remote operation; this complements prior material in previous courses that addressed calculating piping and valve opening diameters and pump power.
- **Operability provides insights into potential careers** – This material will provide examples of how you can apply engineering knowledge in some typical engineering careers. After studying the basic engineering sciences, you might think that options are limited to being an expert in heat transfer, fluid flow, and so forth. Here, you will concentrate on issues such as (but not limited to) safety, reliability and process diagnostics. All engineers need basic knowledge in all topics so that they can work in teams on these topics, and some engineers will select to specialize in one of them.
- **Many engineers manage plant operations** – Every process is “*designed once and operated for decades*”. Therefore, many more engineers have careers in plant operation, managing the operations of existing plants, than in process design. The same operability issues are relevant for design and for operating the process over many tens of years. Therefore, learning operability will also prepare you for working in operating process plants as a manufacturing engineer

1.7 Summary and Reflections

This chapter has provided you with a brief introduction to the concept of operability of process plants and introduced specific topics that will be addressed in detail in subsequent chapters. Let’s recall the prototype flow chart for the design procedure in Figure 1.1, which did not include operability. It would be ideal for engineers to consider operability at each stage of the design procedure; however, there is no recognized, systematic manner for integrating all stages of the design procedure. Therefore, in this presentation, we will use the procedure shown in Figure 1.7, which indicates the operability analysis is performed after the basic process design has been completed and before, or more correctly, as the equipment is specified. When operability deficiencies are identified, the engineer must return to a prior stage and iterate until the entire process design is satisfactory.

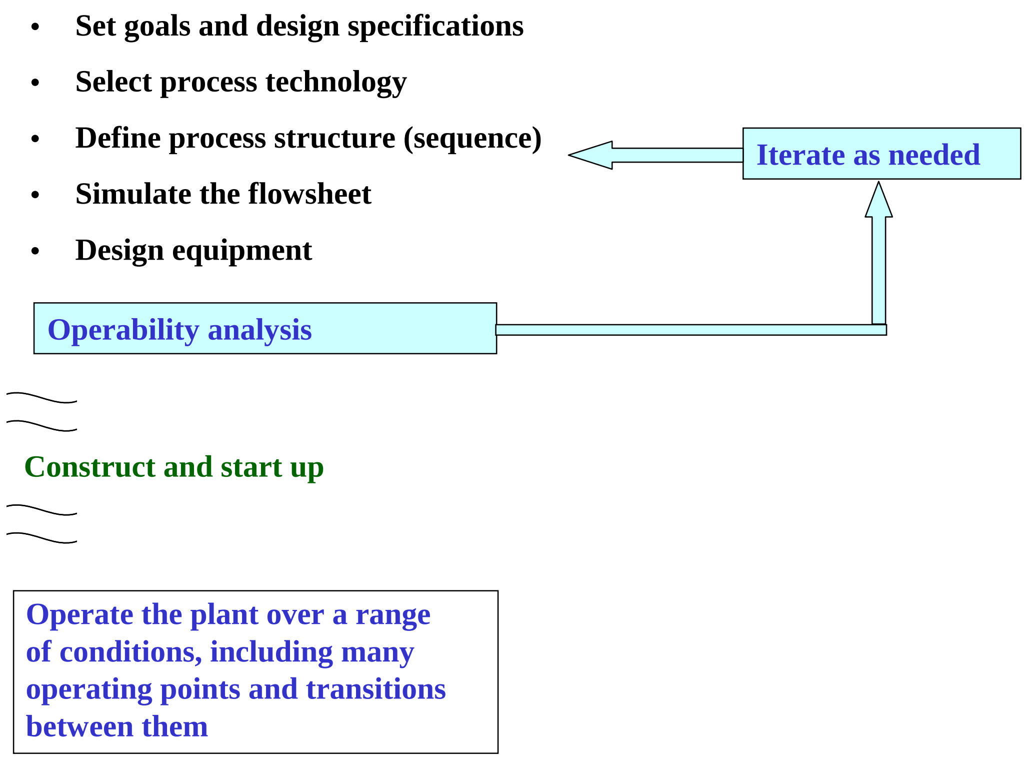


Figure 1.7. Simplified flowchart of the design procedure including operability analysis.

As we use the flowchart in Figure 1.7, we should keep in mind the following.

- Engineers use forethought to avoid deficiencies at every stage of the design process, which substantially reduces the number of iterations, but even the most skilled engineer cannot eliminate iterations entirely.
- The final design must be satisfy all operability requirements. This requirement may increase the number of iterations. For example, a combustion sensor added for monitoring efficiency could introduce a source of ignition, which would be a safety concern and require iteration to the safety issues.
- After the plant has been constructed and is being started up, new operability deficiencies may (and usually do) become apparent. These could be due to oversights during the design procedure, lack of conformance to the design decisions when building the plant, and/or changes not anticipated during the design specification, such as major differences to the raw materials available. Thus, an additional round of iterations typically occurs during the plant startup and for an extended period thereafter.

Therefore, let's recognize that the flowchart in Figure 1.7 is simplified and does not represent the thinking required for solving complex problems by a skilled design engineer, which you will be after graduation and some practical experience. However, it is useful for providing a general sequence of design stages and for showing the need for iteration.

The eight operability topics are presented in detail in the following chapters. So, when you are satisfied with your learning in this chapter, let's move on to the next chapter that covers the operating window, which defines the acceptable region within which the process can operate.

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Test your Learning

Let's not be concerned with memorizing the list of topics, but rather concentrate on applying your engineering skills to problems in each category. The following questions can be answered by an individual or a small group of students.

1.1. Every chemical engineering student has learned about some basic unit processes that are widely applied in practice. Select one of the following units, locate a design (from a textbook, engineering handbook, or internet) and identify at least one example for each of the eight operability topics.

a. Continuous stirred tank chemical reactor
b. Semi-batch fermentor
c. Distillation tower
d. Vapor recompression refrigeration system
e. Boiler with heat from combustion of fuel gas

1.2. Professionals are involved with developing interns and new graduates to become members of the profession. Although you haven't yet completed your education, you can start to help others. Assume that you have been asked to prepare a 15-minute presentation about operability for the second-year chemical engineering students at your university.

a. Define the learning goals for the lesson
b. Define the knowledge that you expect the students to have before you teach them
c. Prepare a lesson including visual aids and a workshop that can be performed by the class (working in groups) after you have completed your lesson. The students should be able to complete their workshop within 10 minutes
d. Prepare a "debriefing" question and answer session that you would hold with the students after the workshop. You may prepare visual aids that you could use to assist your explanations.

1.3. Example 1.2 has provided one example operability issue for each of the eight topics for the reactor with feed effluent heat exchange. Extend the example by identifying one additional issue per topic and proposing a design modification for each issue.

1.4 Operability is important because things change; therefore, the concept of variability was introduced in this chapter. Select a process, and find a typical plant design process flow diagram from a textbook, engineering handbook, or Internet. For the process you have selected, identify many sources of variability that require operability analysis. Some example processes for which ample information is easily acquired include the following.

a. Ammonia production
b. Ethanol from corn
c. Hydrogen production
d. Waste water processing (municipal or industrial)
e. Polyethylene production using fluid bed reactor

1.5 Lessons include a few key concepts and lots of details to interest the students and demonstrate concepts through examples. An important learning skill is identifying the key concepts. Prepare a very brief summary of the key concepts in this chapter.

1.6 Section 1.1 contains a textbox with a brief definition of operability. Based on your understanding of the topic so far, provide a definition in your own words.

1.7 Section 1.2 contains Table 1.1, which gives five categories of sources of variability between the base case design and actual operating conditions in a process plant. As a brainstorming exercise, identify additional categories of variability. For each new category, provide a specific example.

1.8 Example 1.3 presents one source of variability and a design to address this source. For each of the eight operability topics, suggest another variability source and propose a design to address your new source of variability.

1.9 A strategy for efficiency and profitability is described in the solution to Example 1.2. Sketch a control design that would automatically implement this strategy.

Additional Learning Topics and Resources

We cannot address every important topic. Here, citations are given to some related material that the students might want to learn about.

Sustainability is an important issue in process design. It is not included in operability because sustainability is more directly addressed in many of the earlier stages of the design procedure shown in Figures 1.1 and 1.5, such as selecting process technology. However, designing and operating sustainable processes will likely increase process integration and provide even greater challenges for operability. A useful introduction to sustainability in process engineering can be found in the following references.

> http://www.naturaledgeproject.net/Whole_System_Design.aspx

> A series of articles in the January 2009 issue of *Chemical Engineering Progress*, volume 107, on pages 33-63.

Sources of Variability: There is always an issue about the appropriate range of variability considered in process design. Too narrow and the process will not function well; too broad and the design will be very expensive. We will see many examples in the subsequent chapters, and you will rely on industrial experience when you become a practitioner. In this material, we will limit ourselves to variability that occurs for business reasons (e.g., changing production rates and feed materials) or from *unintentional or unavoidable* faults and errors (e.g., equipment fouling and sensor failure). We will not address issues involving protection against *intentional damage* due to misguided employees or terrorism, which at one time was unthinkable, but is now unfortunately part of our concerns. Some of the approaches and analyses presented here should be applicable to these rare but critical scenarios; however, methods for appropriate analysis and design are only now being developed. For discussion of these issues, please refer to the following reference.

> Abrahamson, D. and A. Sepeda (2009) Managing Security Risks, *Chemical Engineering Progress*, 105, 7, 41-47.