Process Control in Investment Casting

Why is it Important?

What is a Process?

What is a **Process**?

"Unique combination of machines, materials, methods, environment and people engaged in producing a measurable output."

Source: Wikipedia

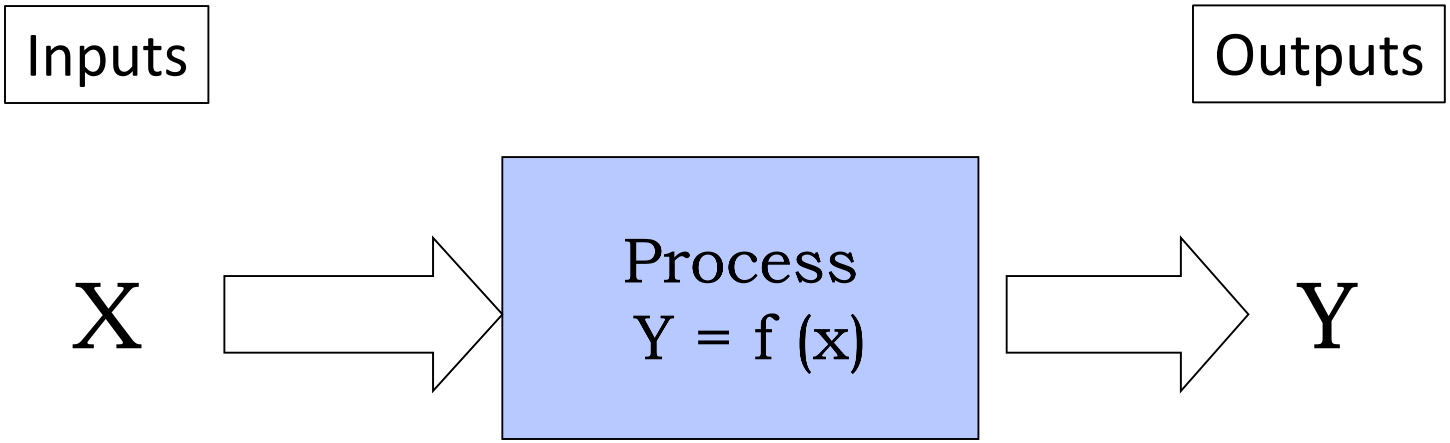
What is Process Control?

What is **Process Control**?

"Activities involved in ensuring a process is predictable, stable and consistently operating at the target level of performance with only normal variation."

Source: Business Dictionary.com

What is a Process?



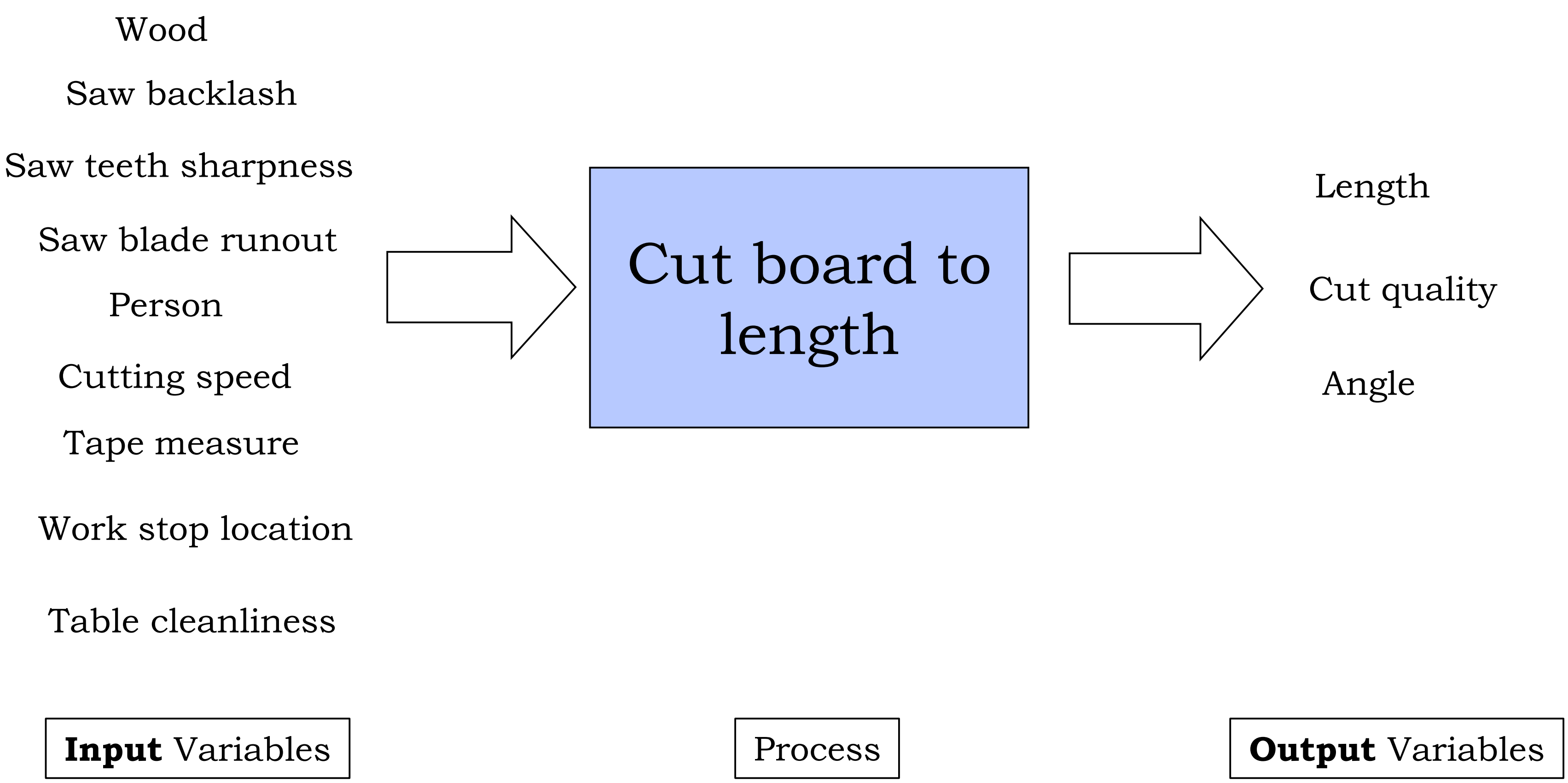
- Independent
- Cause
- Control

- Dependent on Input
- Effect
- Monitor
- Inspection

The **Output** of a process is a function of the **Inputs**

What is a Process?

Example; Cut multiple pieces of lumber to a specific length



Key Variables

In Process Control, we direct most of our effort toward the important or **KEY** variables. *"Vital few versus the trivial many."* How do we know which ones are Key?

Outputs that are important to internal or external customers are defined as Key Output Variables or **KOV's.**

Inputs that have a significant affect on one or more KOV's are defined as Key Input Variables or **KIV's.**

Key Variables

Example; Cut multiple pieces of lumber to a specific length

Input Variables

- Wood
- Saw backlash
- Saw teeth sharpness
- Saw blade runout
- Person
- Cutting speed
- Tape measure
- Work stop location
- Table cleanliness

Process

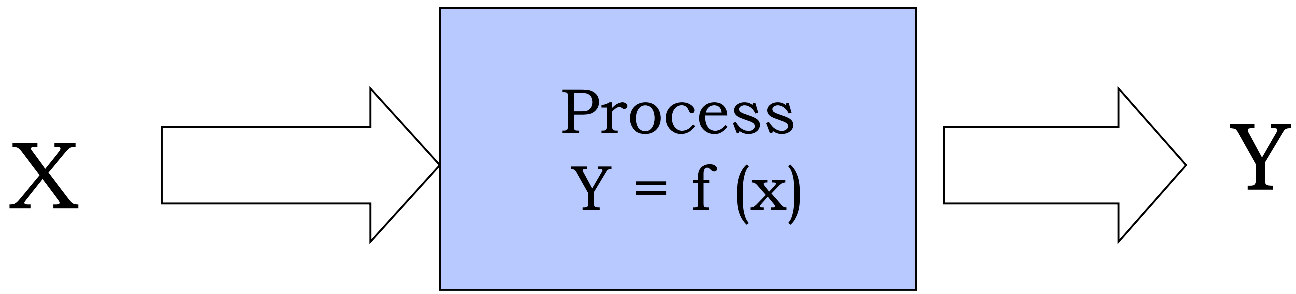
Cut board to length

Output Variables

- Length
- Cut quality
- Angle

Process Control Summary

The **Key Outputs** of a process are dependent on the **Key Input Variables**



- **KIV's**
- Independent
- Cause
- Control

- **KOV's**
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- Effect
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If all of the **KIV's** are identified and controlled within the proper range, the Key Outputs will be in control.

Process Control Summary

Summary

The Key Outputs of a process are controlled by the Key Input Variable (***KIV's***).

If you control all of the ***Key Input Variables*** within the proper range, the Key Outputs will be in control.

This is a major tenant of ***Process Control.***

Process Control Summary

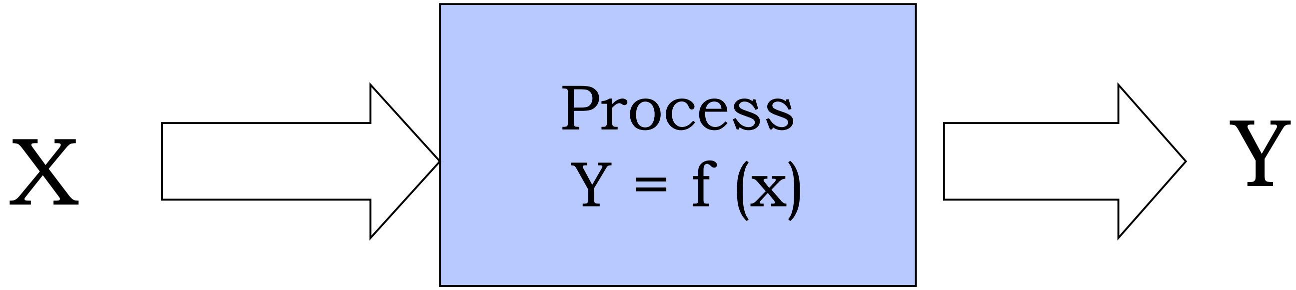
If a Key Output Variable is out of control, then one or more of the following is true;

1. One or more of the KIV's are not being ***controlled*** within the required range.
2. The ***required range*** of one or more KIV's has not been optimized.
3. ***All*** of the KIV's have not been identified (there are more KIV's).

Monitoring Key Output Variables

Monitoring and Feedback

Monitoring the results of the Key Output Variables provides process control feedback. This data will provide a regular report on the stability and control of the process.



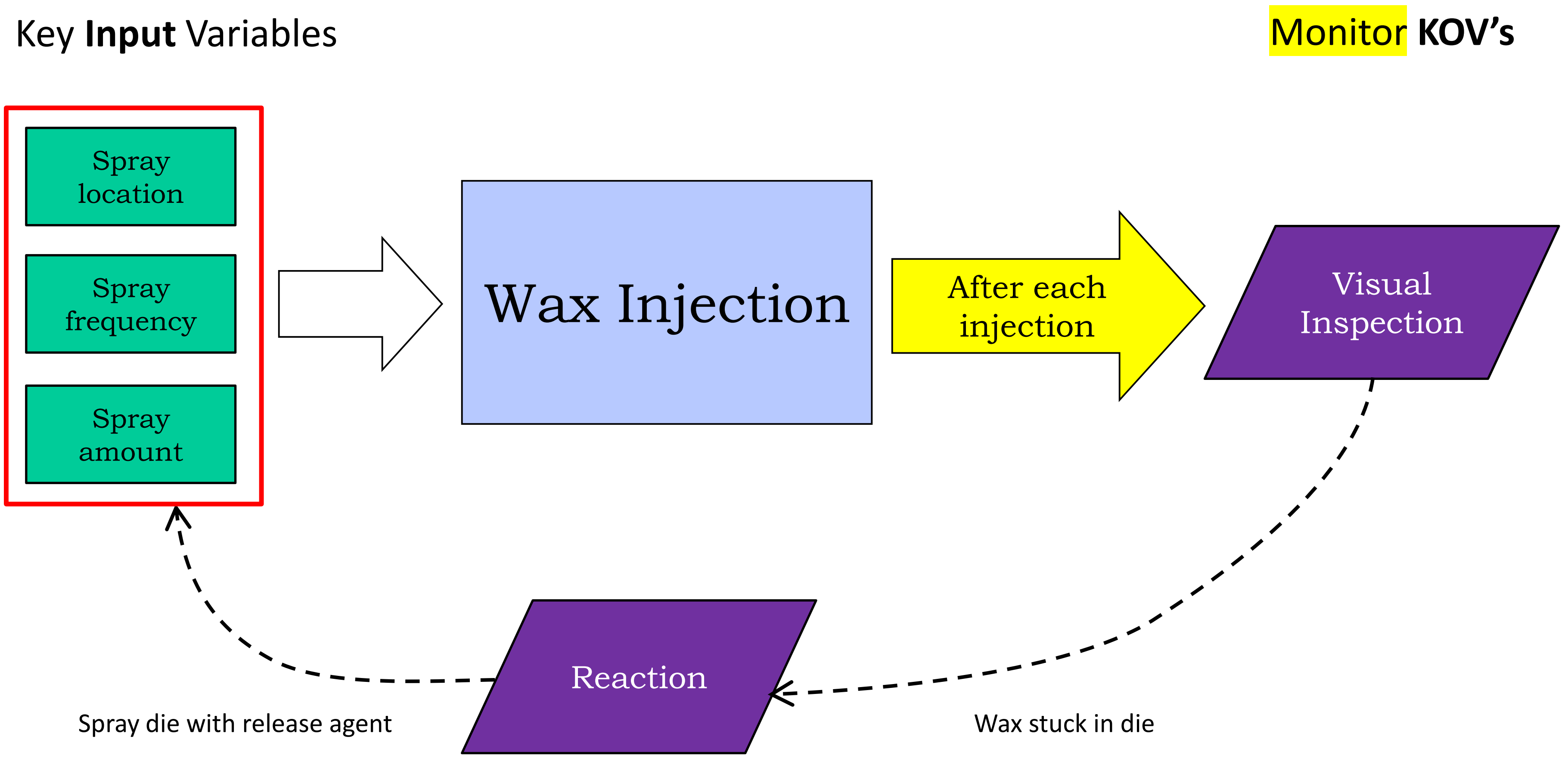
- **KIV's**
- Independent
- Cause
- Control

- **KOV's**
- Dependent on Input
- Effect
- Monitor
- Inspection

An effective KOV based feedback system will have:
- Minimal time from processing to inspection.
- Clear reaction plan

Monitoring and Feedback

Example; Visual inspection of wax patterns



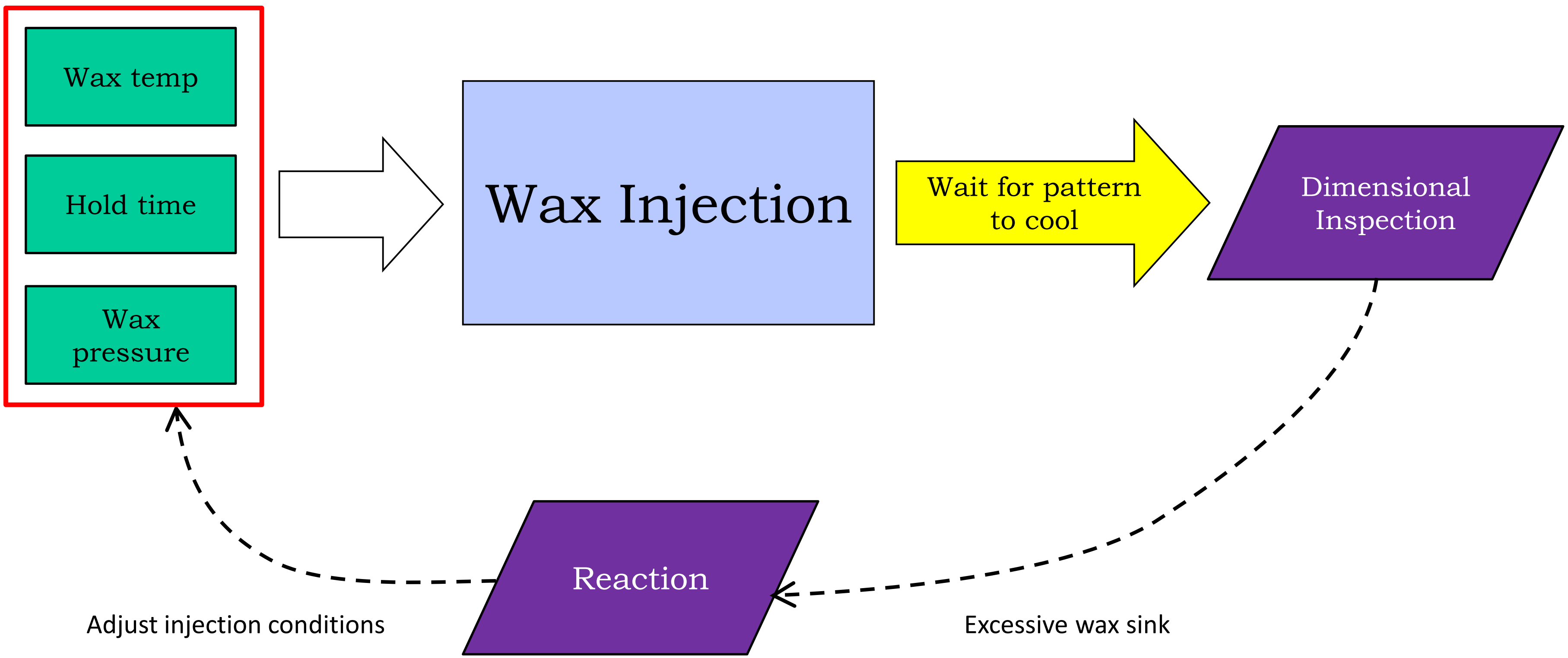
Timely and direct feedback. Pass / fail data

Monitoring and Feedback

Example; Dimensional inspection after wax injection

Key **Input** Variables

Monitor **KOV's**



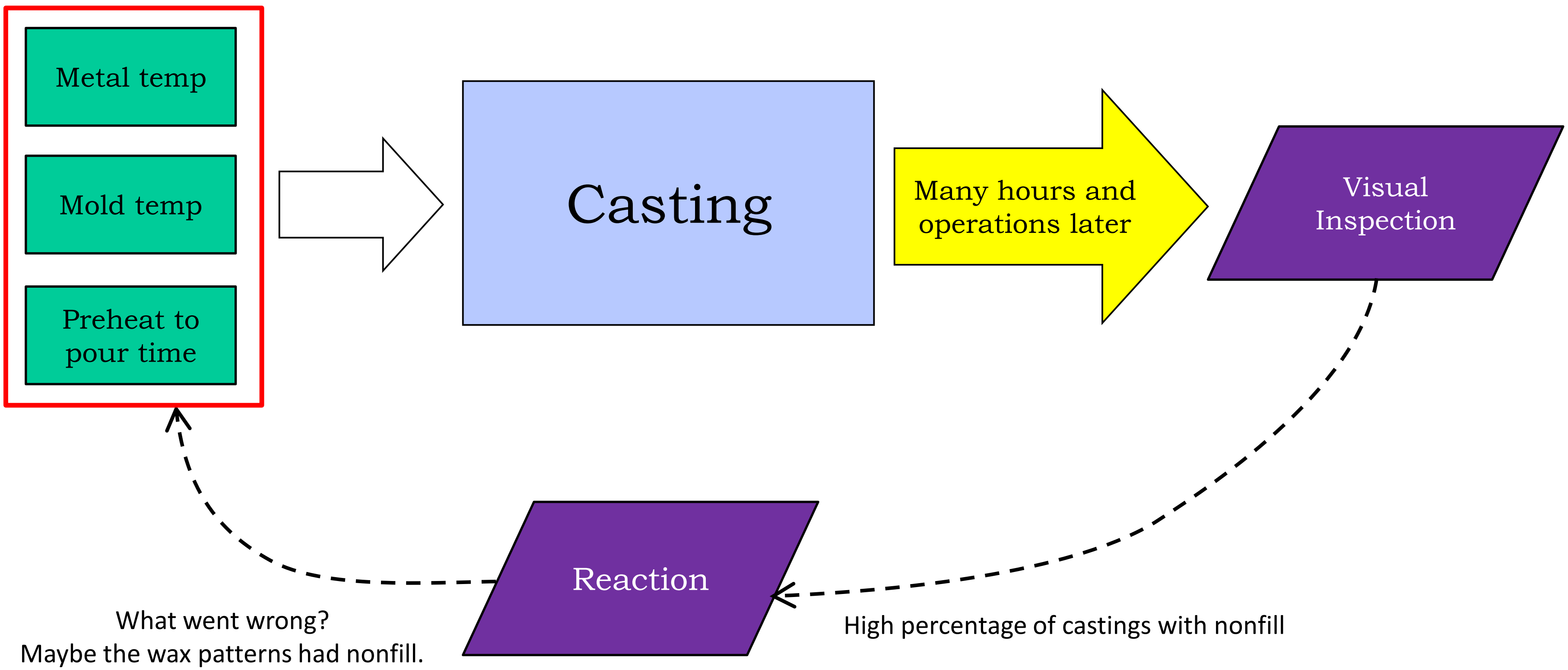
Delayed and indirect feedback. Continuous data

Monitoring and Feedback

Example; Visual inspection of castings

Key **Input** Variables

Monitor **KOV's**



Extremely delayed, indirect and possibly unclear feedback. Pass / fail data

Importance of Process Control

Why is Process Control so important in investment casting?

- There are many steps in the investment casting process.
- The result of each step is highly dependent on the quality from the preceding step. KOV's from preceding step may be KIV's in next step.
- Feedback from some operations can be significantly delayed and the reaction plan may be unclear.
- After the first shell layer is applied, you are not able to see the parts until knockout. Everything is hidden.
- To maintain high yields, minimize costs and achieve consistently fast deliveries, must have a system that prevents problems from occurring.

Types of Variation

Types of Variation

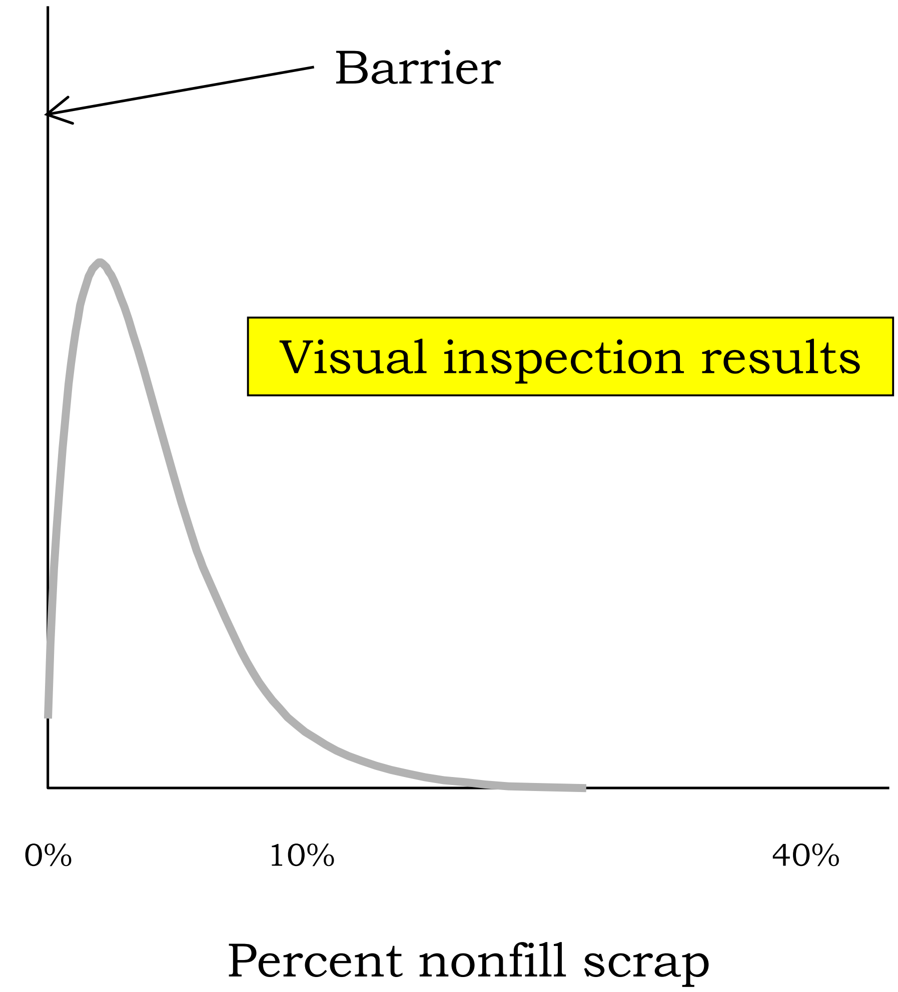
Types of Variation

You need to control two types of **variation**.

- Common Cause; Normal variation inherent to a controlled process
- Special Cause; Non-random, out of the blue result

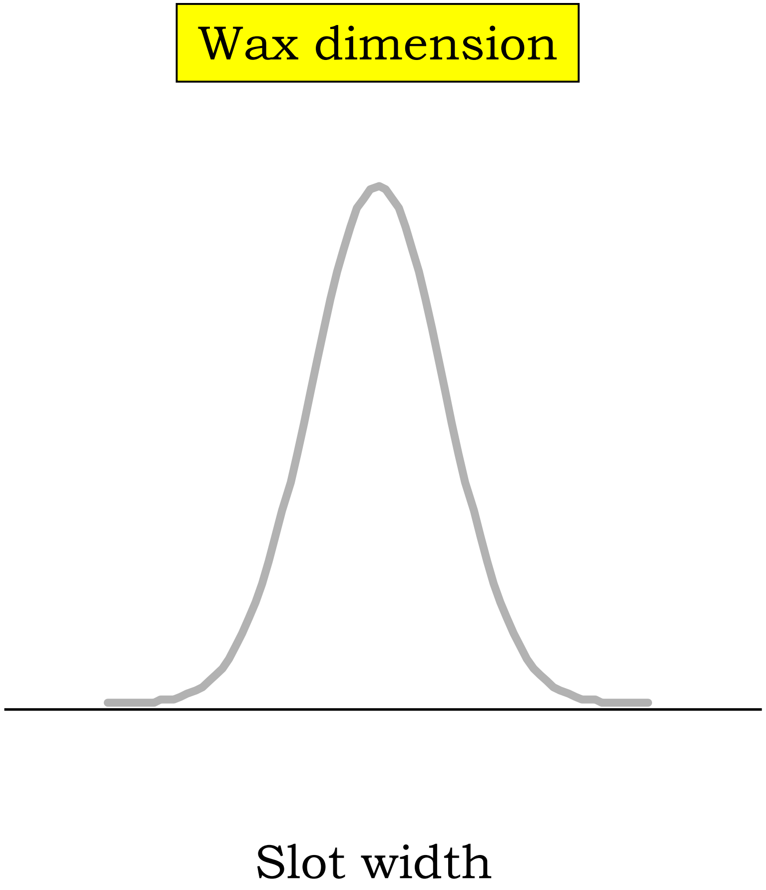
Common Cause Variation

Common Cause variation results in a steady but random distribution around the average of the data.
If there is a barrier or limit, may produce a skewed distribution.



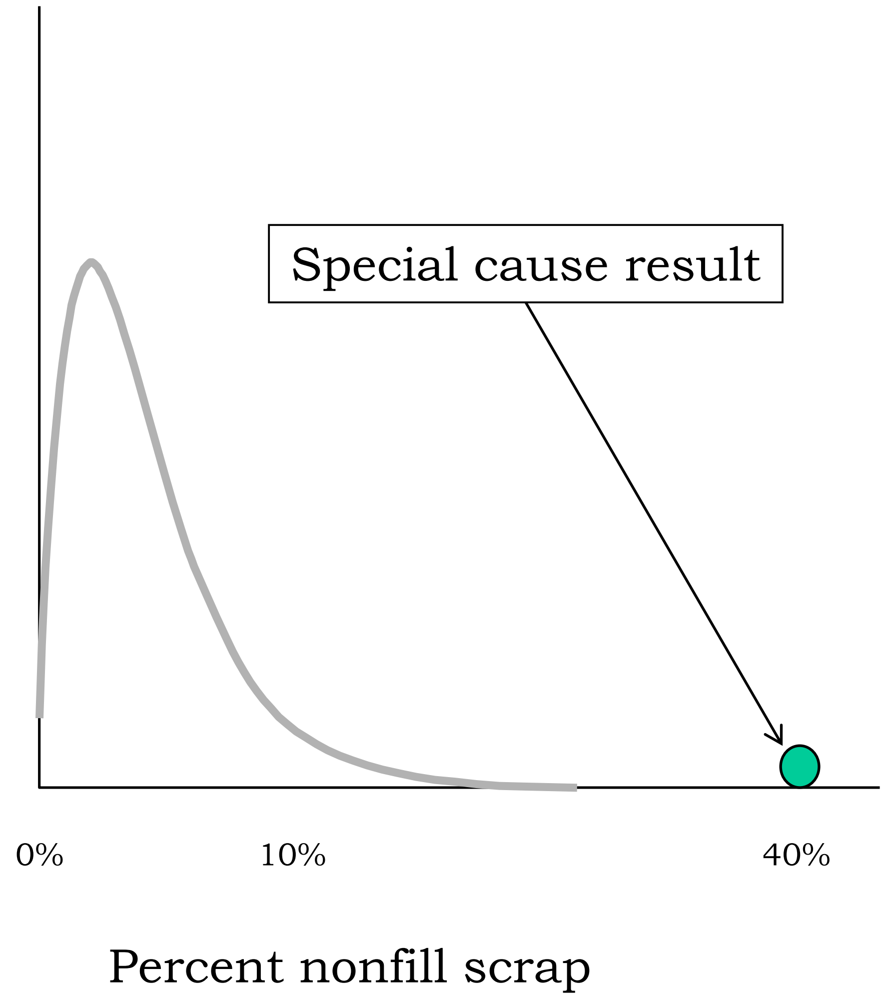
Common Cause Variation

Common Cause variation results in a steady but random distribution around the average of the data.
If no barriers, will typically produce a bell-shaped or normal distribution.



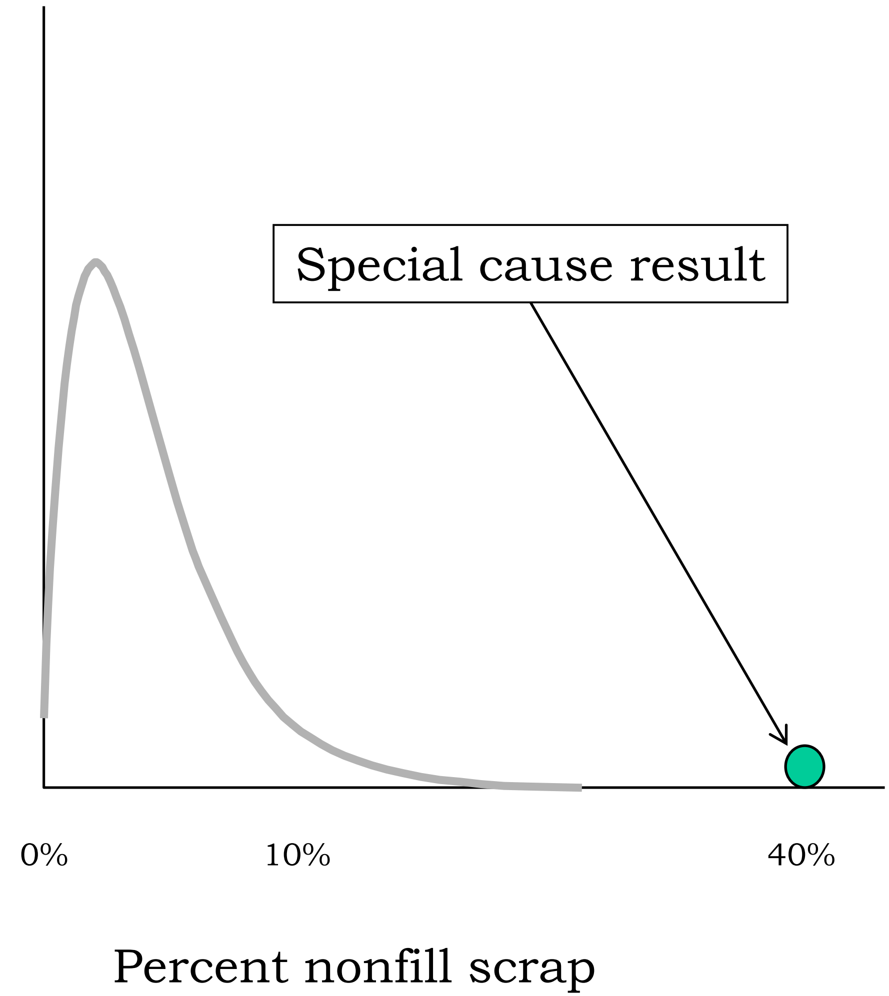
Special Cause Variation

Special Cause variation is created by a non-random event leading to an **unexpected change** in the process output.



Special Cause Variation

Example
Investigation into the cause of the high nonfill percentage revealed the oven never reached temperature.



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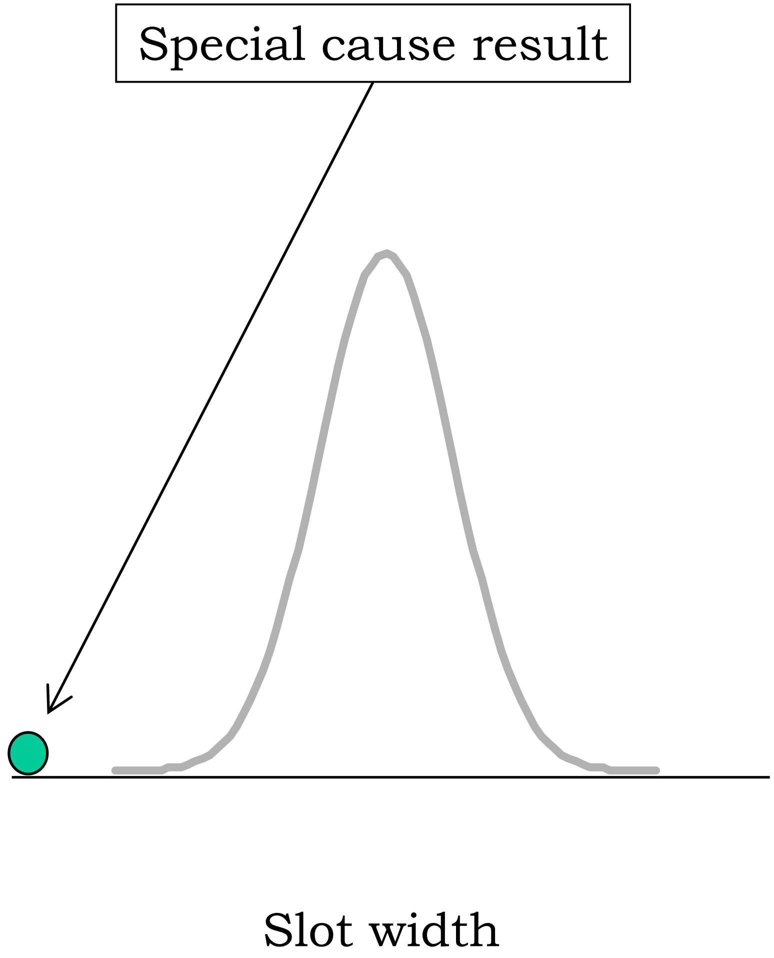
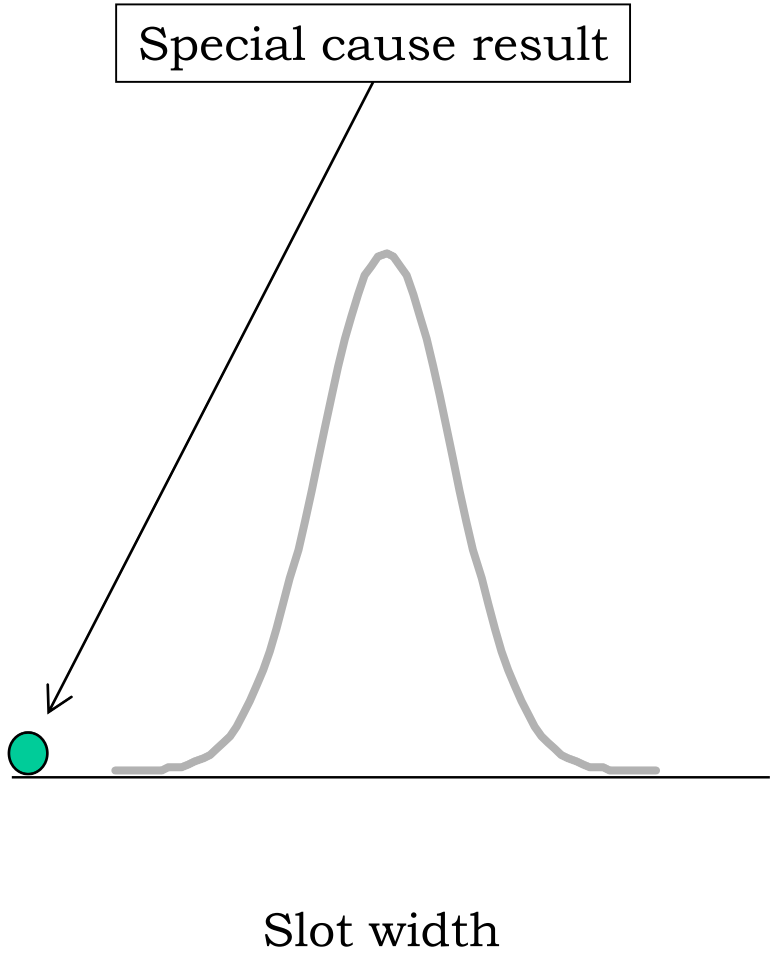


Special Cause Variation

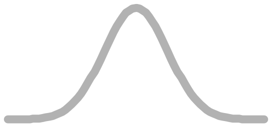
Example
Investigation into the cause of the small slot width revealed the operator never placed the pattern in a wax setter.



Normal Variation

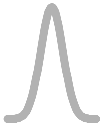
Example; Variation in gate length after fixtured cutoff operation

Variation between **operators**



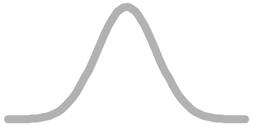
Assembly operator, cutoff operator

Variation caused by **equipment**



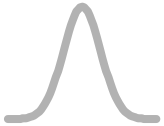
Cutoff saw table wear and spindle runout, fixture wear

Variation caused by differences in **methods**



Adjustment of cutoff fixture, changing blade

Variation caused by **material**



Differences between cutoff blade manufactures

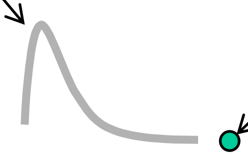
Special Cause Variation

Example; Nonfill defects

Normal nonfill amount

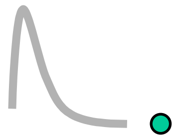
Special cause result

Variation in **measurement**



Untrained inspector over-inspects, scraps good parts

Variation caused by **methods**

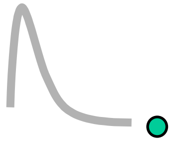


Wrong shell code selected resulting in 1 less layer being applied to the molds

Variation caused by differences in **operator**

Untrained operator assembles patterns upside down.

Variation caused by **equipment**



Preheat oven never reaches required temperature

Variation Reduction

What **Type** of Variation Are You Trying To Reduce?

- Improve overall capability – predictable results but need improvement (Common Cause)
- Eliminate bad, unpredictable results (Special Cause)

Different control tools are used for different types of variation.

The Process of Process Control

The Process of Process Control

What is the process for process control improvement? Process Control encompasses three main areas of activity:

1. Controlling known KIV's within desired limits.
2. Uncovering hidden KIV's.
3. KIV targeting and limits.

Controlling KIV's

Controlling KIV's

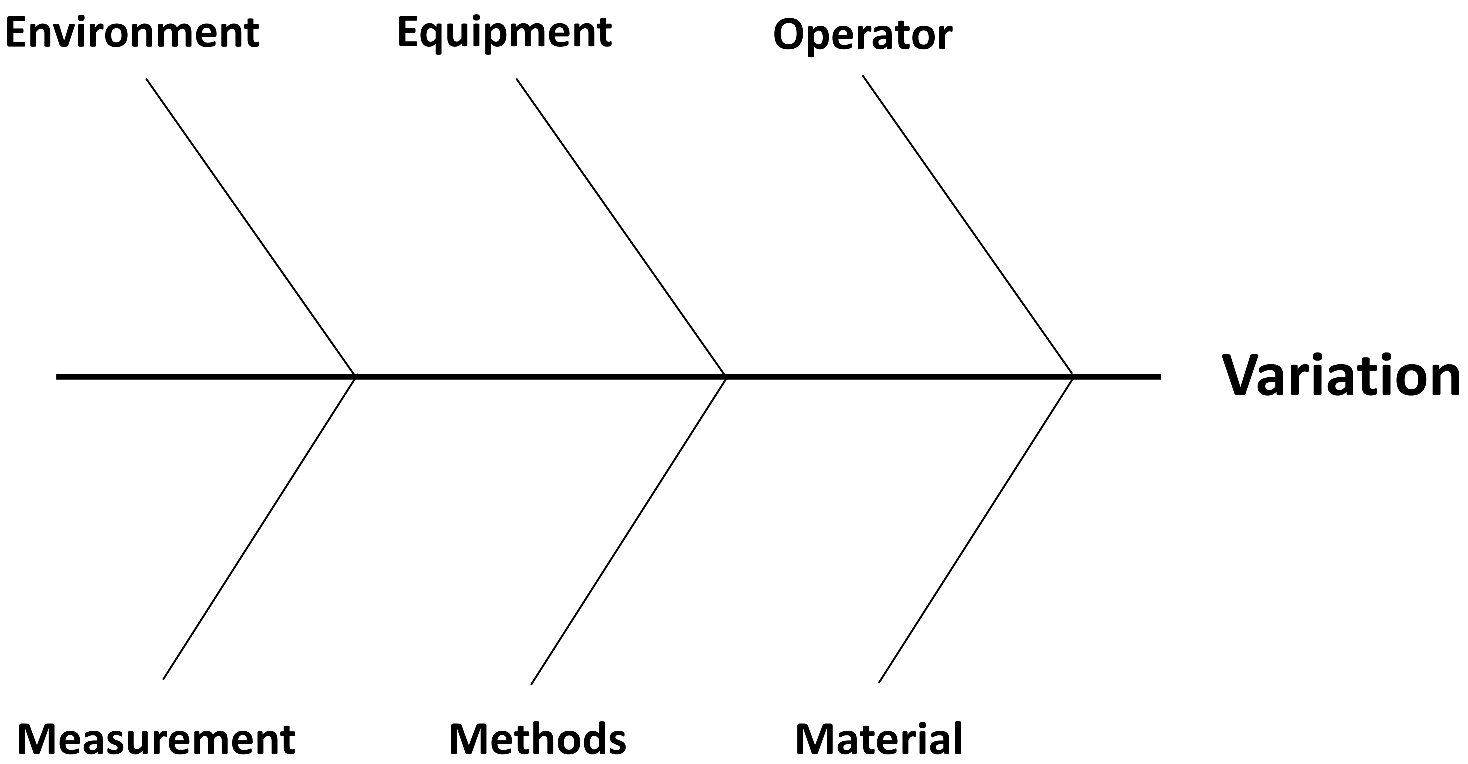
All processes have **variation**. We expect variation. But, we need to control it to a level that is does not negatively impact KOV's. What are all of the sources of variation?

What is a **Process**?

"Unique combination of machines, materials, methods, measurement, environment and people engaged in producing a measurable output."

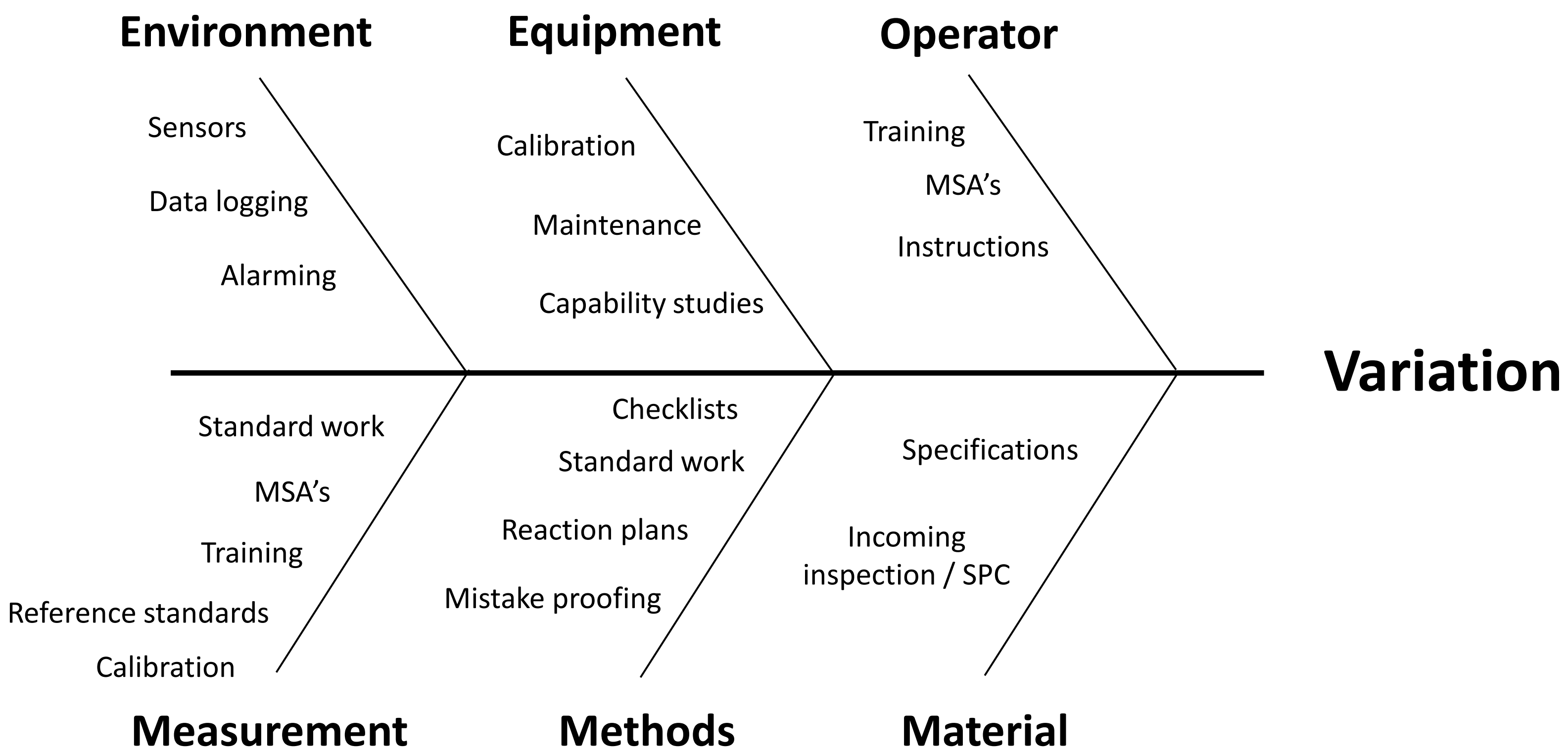
Sounds like all of the fishbones in a Ishikawa diagram.

Sources of Variation



An Ishikawa or **Fishbone Diagram**

Sources of Variation



These are some of the tools that can be used for each source of variation.

Sources of Variation

There is no one best method for controlling KIV's. The control method is dependent on the type of variation:

1. **Operator** variation
2. **Methods** variation
3. **Equipment** variation
4. **Material** variation
5. **Measurement** variation
6. **Environment** variation

And, once you have established the controls, use auditing to prevent long term degradation.

Operator Variation

Differences between ***operators*** significantly affecting the output

- Assembly spacing, bond strength
- Dipping and draining technique
- Metal pouring speed and height
- Blending
- Weld repair
- Straightening

Training

MSA's

Instructions

Guides, fixtures

Methods Variation

Differences in **method** significantly affecting the output

- Adjusting slurry viscosity
- Adjusting wax injection press settings to eliminate defects
- Adjusting cutoff fixture
- Adjusting for tooling wear on a machining center
- Equipment startup and shutdown

Reaction Plans

Checklists

Standard Work

Mistake proofing

Equipment Variation

Differences in ***equipment*** significantly affecting the output

- Mold temperature variation by oven
- Pattern quality by wax injection press
- Mold quality by shell robot line

Can be differences between machines or degradation over time

- Calibration
- Preventive maintenance
- Alarming
- SPC

Material Variation

Differences caused by variation in the ***material***

- Differences in remelt quality
- Differences in as-mixed slurry viscosity
- Differences in stucco sizes
- Differences in mold strength and perm (flour size variation)
- Differences between cutting tool vendors

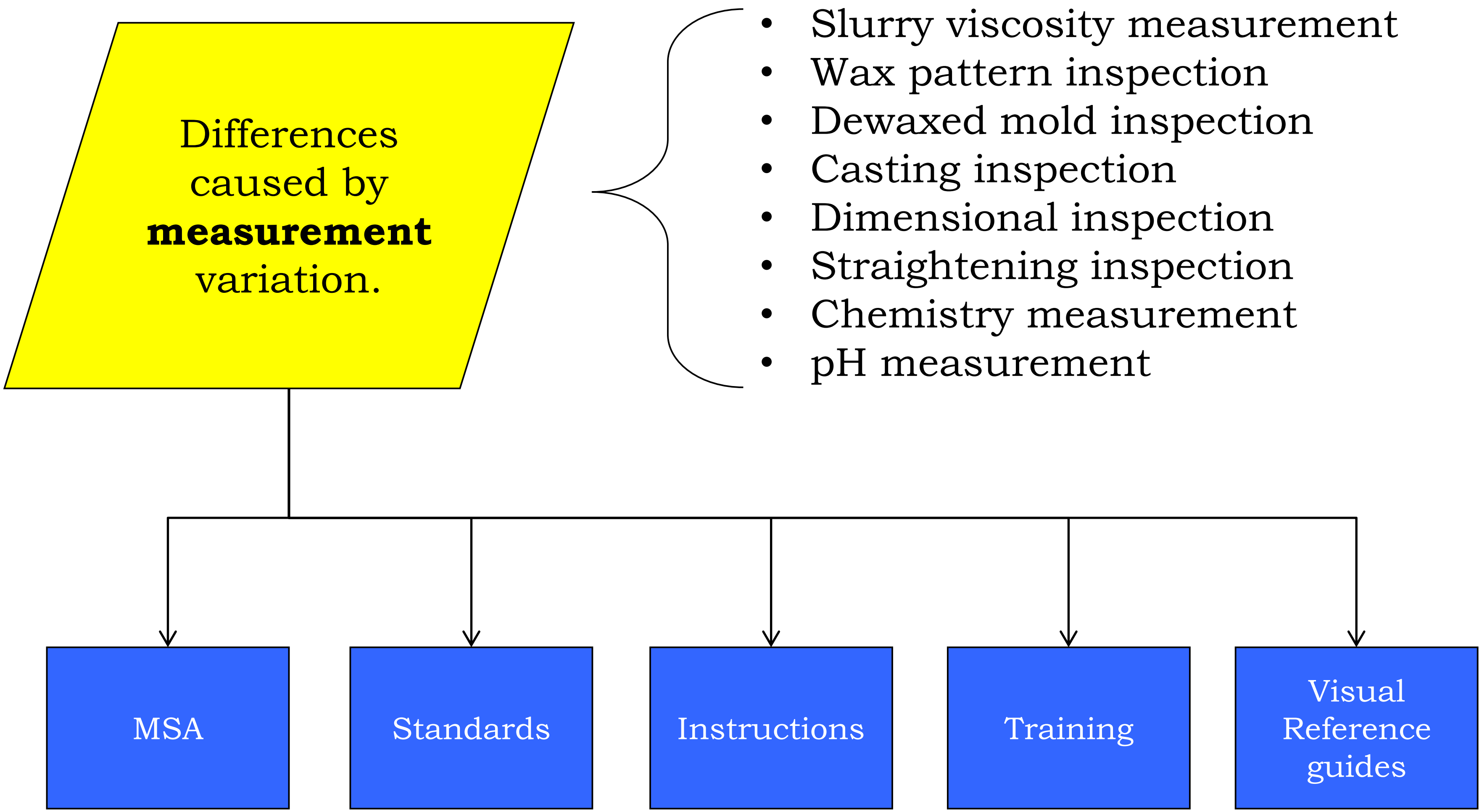
The material can be recycled internally or from an outside supplier

Material specification

Incoming inspection / SPC

Vendor audit / SPC

Measurement Variation



Uncovering Hidden KIV’s

Uncovering Hidden KIV's

We probably have not identified all of the KIV's for every process.

What methods can be used to uncover hidden KIV's?

1. Research
2. PFMEA's
3. Root Cause Analysis
4. Families of Variation Analysis
5. Data Mining

Research

There are many sources of technical information. They may reveal hidden potential KIV's.

- Experts and consultants
- Material vendors
- Equipment manufacturers
- Books and technical papers
- Atlas of Casting Defects
- Industry training
- Best Practices

PFMEA

Process ***F***ailure ***M***ode ***E***ffects ***A***nalysis

"A PFMEA is a structured analytical tool used to identify and evaluate the potential failures of a process. PFMEA evaluates each process step and assigns a score on a scale of 1 to 10 for the following variables:"

Occurrence - chance of failure happening

Detection - chance of the failure being detected

Severity – impact of failure mode

RPN – risk priority number; O x D x S

Source: A Guide to Process Failure Mode Effects Analysis, Process Excellence Network.com

Root Cause Investigation

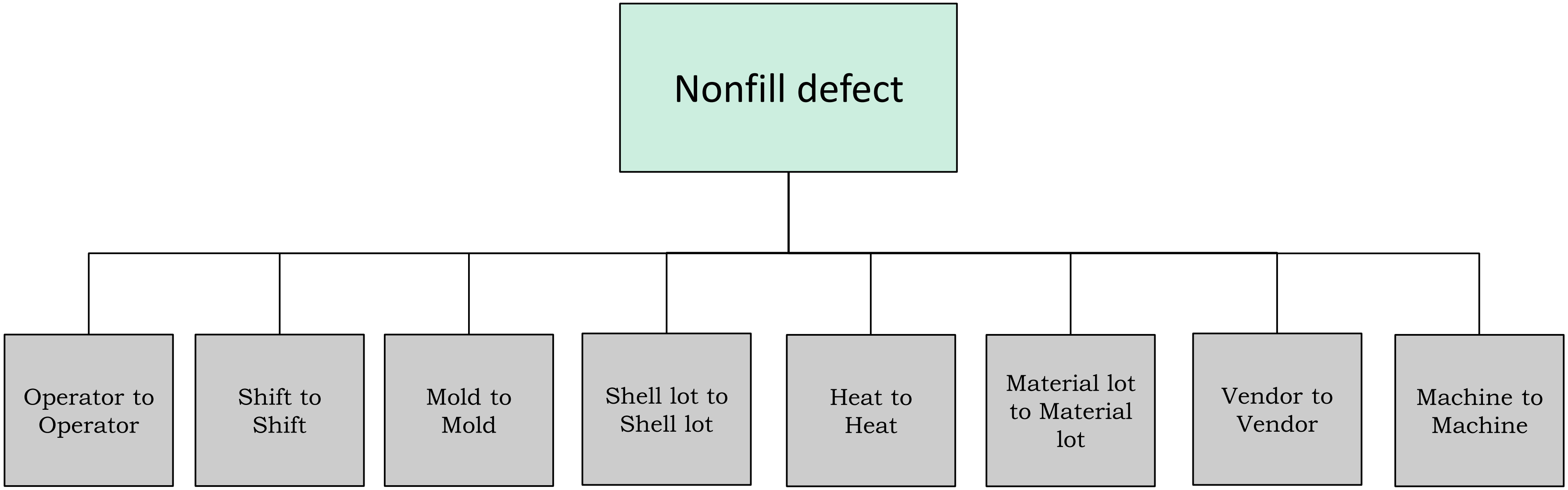
When you have an ***unexpected outcome*** from a process, figure out what happened and modify the controls to prevent a re-occurrence.

- Did we identify all of the KIV's?
- Did we target the KIV's properly?
- Are we controlling the KIV's?
- Is our training system effective?

Perform a ***root cause investigation*** in order to find the failure mode.

Families of Variation

A common method of analyzing data is to look at **Families of Variation**. In this approach we sort KOV results into different rational sub-groups (families) in order to reveal any hidden sources of variation.



Families of Variation

If a significant difference is revealed within a family, further investigation is required in that area to find the source of that variation.

Data Mining

Data mining is the process of examining large data sets to find new relationships between a response (KOV) and many predictors (inputs).

This can be done through regression analysis using statistical software.

Data Mining

"Significant" predictors discovered during data mining SHOULD NOT be treated as fact, only items that may warrant further investigation.

Predictors should only be considered significant after they have been verified through well-controlled experimentation.

Testing

These various methods will uncover a large number of ***Potential*** *Key Input Variables.* We need to determine the statistical significance between these factors and the Key Output Variables.

Using screening DOE's we can quickly and efficiently separate the **"trivial many** from the **vital few"**. This is typically done using a 2-level factorial design.

KIV Targeting and Limits

KIV Targeting and Limits

Once a factor (KIV) is found to be significant, how do we determine where it should be targeted and the amount of variation that can be tolerated?

Optimization Testing

Optimization testing is a type of experimentation in which more than 2 levels are used on some or all of the continuous factors in order to determine the ideal settings. This can be done using either a 2-level factorial design with center points or with a General full factorial design.

KIV Targeting and Limits

Example – Determine the ideal wax injection parameters

- 3 factors; wax temperature, wax flow and injection time (**KIV's**).
- 3 levels for each factor.
- Each pattern inspected for surface quality and dimensions (**KOV's**).
- Results analyzed using statistical software. Response Optimizer and Composite Desirability function used to find the ideal conditions for both dimensions and surface quality.

Wax temp	Wax flow	Injection time
132	10	20
132	10	30
132	10	40
132	20	20
132	20	30
132	20	40
132	30	20
132	30	30
132	30	40
136	10	20
136	10	30
136	10	40
136	20	20
136	20	30
136	20	40
136	30	20
136	30	30
136	30	40
140	10	20
140	10	30
140	10	40
140	20	20
140	20	30
140	20	40
140	30	20
140	30	30
140	30	40

Process Control Summary

Process Control Summary

Effective process control in investment casting is achieved by identifying and controlling the KIV's.

Effective process control requires the use of many tools.

Process Control Tools

PFMEA	Calibration	Instructions
Reaction plans	Control plans	Purchasing specifications
Control charts and SPC	Research	Standard operating procedures
MSA’s	Process flow diagrams	Design of Experiments
Standard work	Guides	Families of Variation
Root cause analysis	Reference standards	Data mining
Vendor Corrective Action	Capability studies	Analysis of Variance
Training and verification	Mistake-proofing	Audits
Preventative maintenance	Alarming	Data logging
Vendor audits	Checklists	

Questions?