Integral
ENGINEERING

Corrosion Under Insulation Bayesian Network
CPT Workshops

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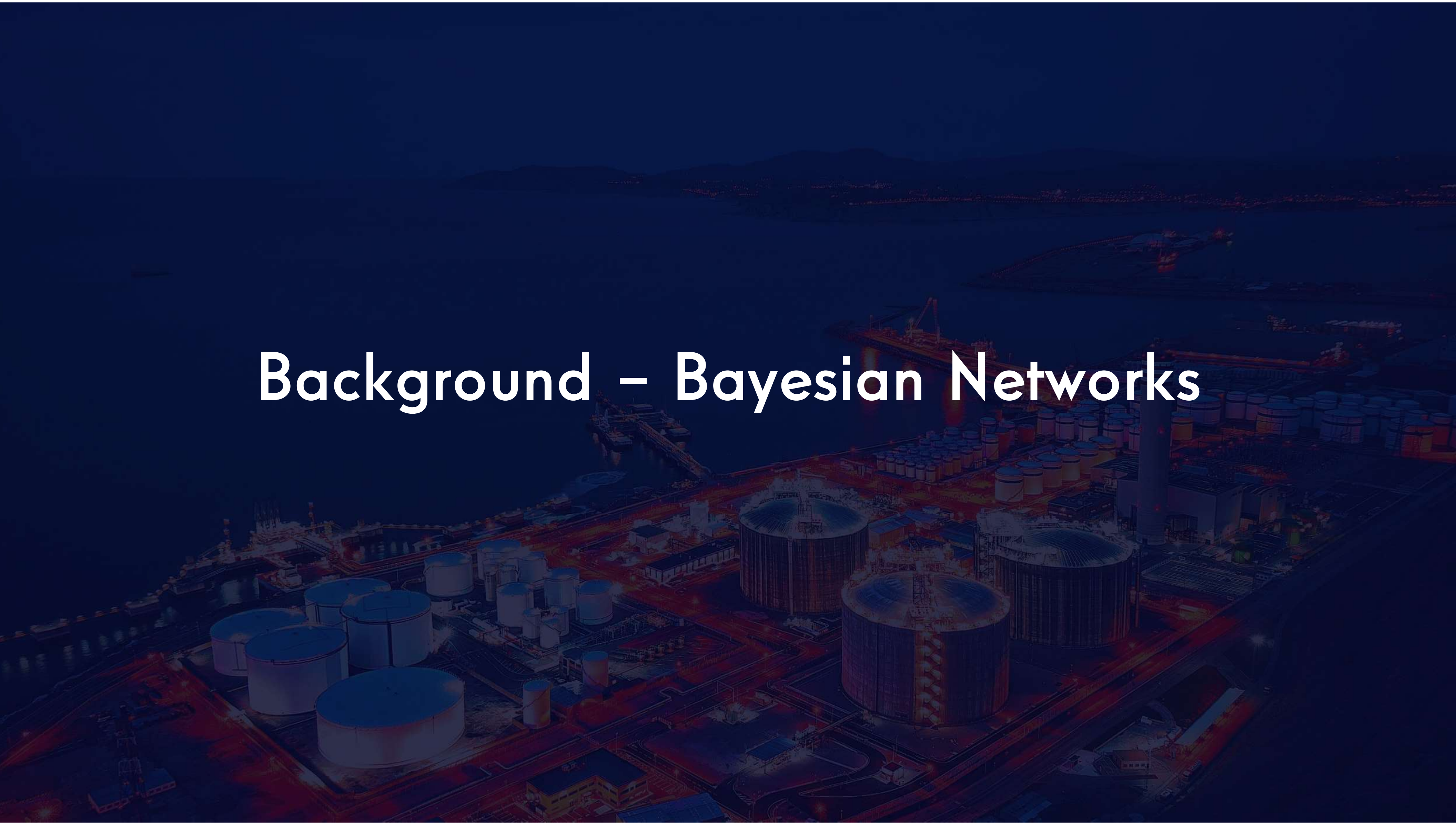
23-Jan-2020


Background – Bayesian Networks

Background - Bayesian Networks

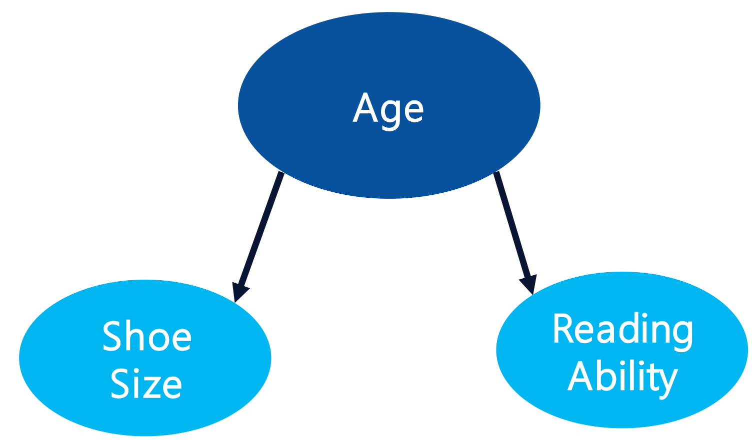
Bayesian networks are probabilistic models that define *cause-consequence relationships* between variables.

Bayesian Networks first came into prominence in the 1980s through the work of *Judea Pearl*

- He was awarded the *'Turing Award'* in 2011, the highest distinction in the computer sciences.

Common applications:

- Medicine (e.g. diagnosis of diseases)
- Finance (e.g. investment risk & return)
- Engineering (e.g. estimating the probability of equipment failure)



Background - Bayesian Networks

Advantages:

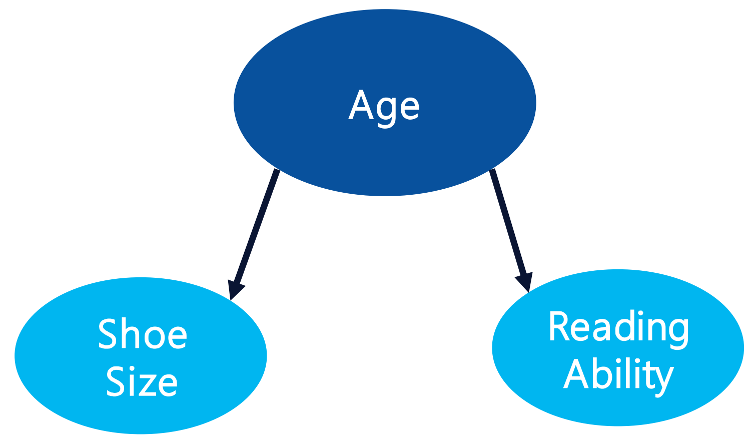
1) Combines data, subject matter expertise, and engineering models into an *interpretable* model ("clear-box")

2) Can reflect *uncertainty* in observed variables

3) Captures *cause-consequence* relationships between variables

4) Combines data, subject matter expertise, and engineering models into an *interpretable* model ("clear-box")

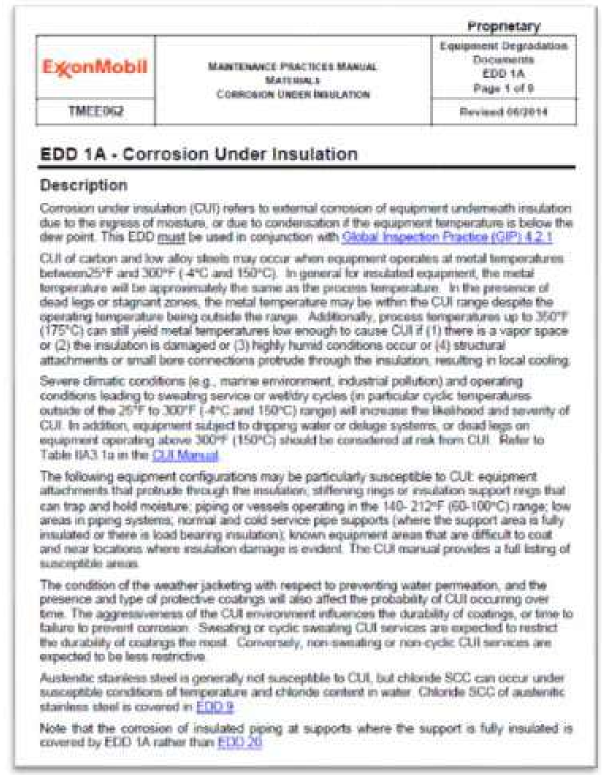
5) Can *predict* unknown values in the network using the known values (inference)



Current CUI Model: EDD1A

The current methodology for assessing the probability of failure due to *corrosion under insulation* is based on four primary factors:

1. Environmental Factors
   - Sweating Service
   - Location
   - Climate
   - Chlorides
   - SO2
2. Service Factors
   - Cyclic Service
   - Water Contact
3. Age Factors
   - Coating Type
   - Coating Age
4. Miscellaneous Factors
   - Protrusions
   - Visual Evidence



Proprietary

ExxonMobil	MAINTENANCE PRACTICES MANUAL MATERIALS CORROSION UNDER INSULATION	Equipment Degradation Documents EDD 1A Page 1 of 9
TMEE062		Revised 06/2014

EDD 1A - Corrosion Under Insulation

Description

Corrosion under insulation (CUI) refers to external corrosion of equipment underneath insulation due to the ingress of moisture, or due to condensation if the equipment temperature is below the dew point. This EDD must be used in conjunction with Global Inspection Practice (GIP) 4.2.1

CUI of carbon and low alloy steels may occur when equipment operates at metal temperatures between25°F and 300°F (-4°C and 150°C). In general for insulated equipment, the metal temperature will be approximately the same as the process temperature. In the presence of dead legs or stagnant zones, the metal temperature may be within the CUI range despite the operating temperature being outside the range. Additionally, process temperatures up to 350°F (175°C) can still yield metal temperatures low enough to cause CUI if (1) there is a vapor space or (2) the insulation is damaged or (3) highly humid conditions occur or (4) structural attachments or small bore connections protrude through the insulation, resulting in local cooling.

Severe climatic conditions (e.g., marine environment, industrial pollution) and operating conditions leading to sweating service or wet/dry cycles (in particular cyclic temperatures outside of the 25°F to 300°F (-4°C and 150°C) range) will increase the likelihood and severity of CUI. In addition, equipment subject to dripping water or deluge systems, or dead legs on equipment operating above 300°F (150°C) should be considered at risk from CUI. Refer to Table IIA3.1a in the CUI Manual

The following equipment configurations may be particularly susceptible to CUI: equipment attachments that protrude through the insulation; stiffening rings or insulation support rings that can trap and hold moisture; piping or vessels operating in the 140- 212°F (60-100°C) range; low areas in piping systems; normal and cold service pipe supports (where the support area is fully insulated or there is load bearing insulation); known equipment areas that are difficult to coat and near locations where insulation damage is evident. The CUI manual provides a full listing of susceptible areas.

The condition of the weather jacketing with respect to preventing water permeation, and the presence and type of protective coatings will also affect the probability of CUI occurring over time. The aggressiveness of the CUI environment influences the durability of coatings, or time to failure to prevent corrosion. Sweating or cyclic sweating CUI services are expected to restrict the durability of coatings the most. Conversely, non-sweating or non-cyclic CUI services are expected to be less restrictive.

Austenitic stainless steel is generally not susceptible to CUI, but chloride SCC can occur under susceptible conditions of temperature and chloride content in water. Chloride SCC of austenitic stainless steel is covered in EDD 9

Note that the corrosion of insulated piping at supports where the support is fully insulated is covered by EDD 1A rather than EDD 20

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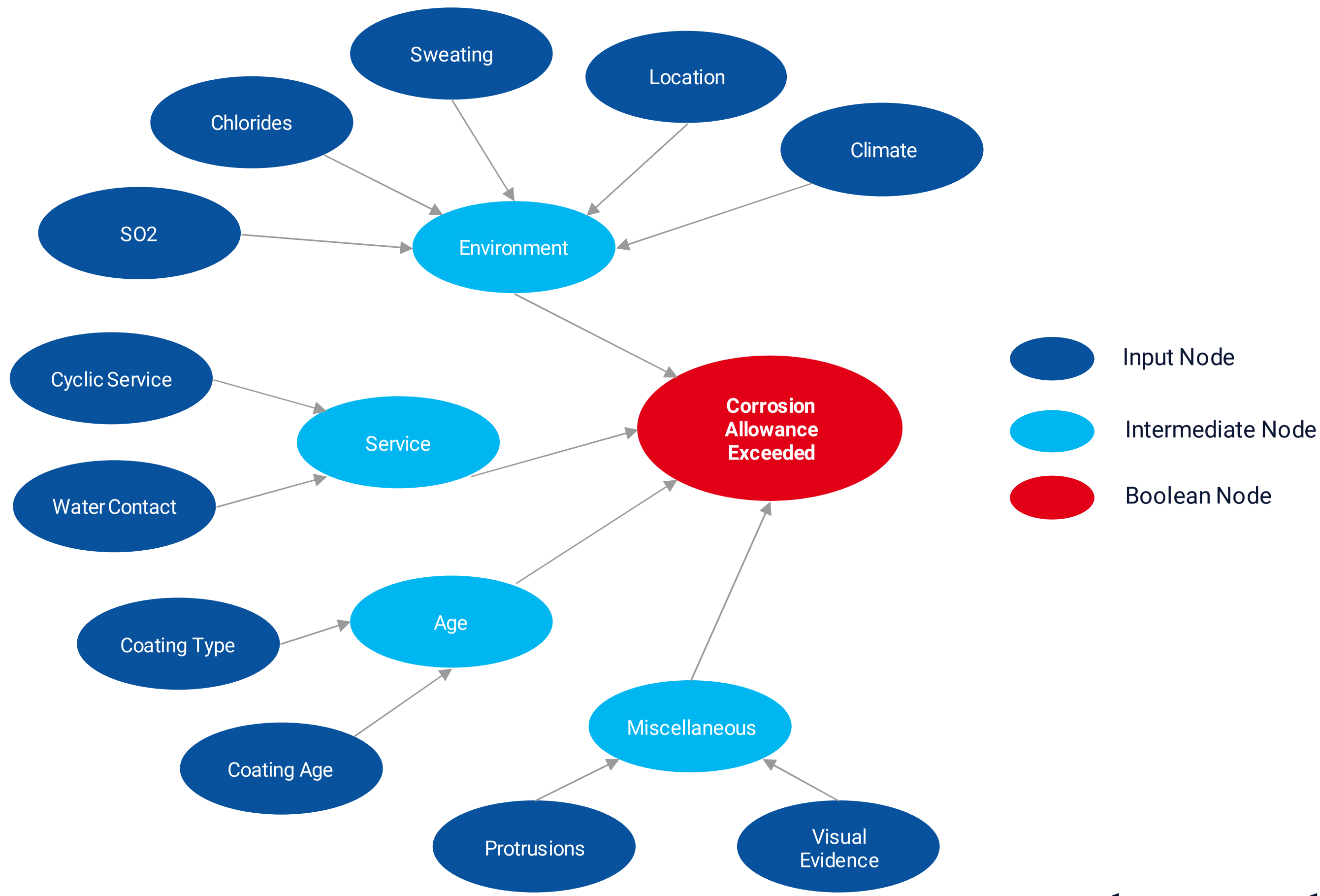
Current CUI Model: EDD1A

A *direct implementation* of the EDD1A methodology leads to the following Bayesian Network:



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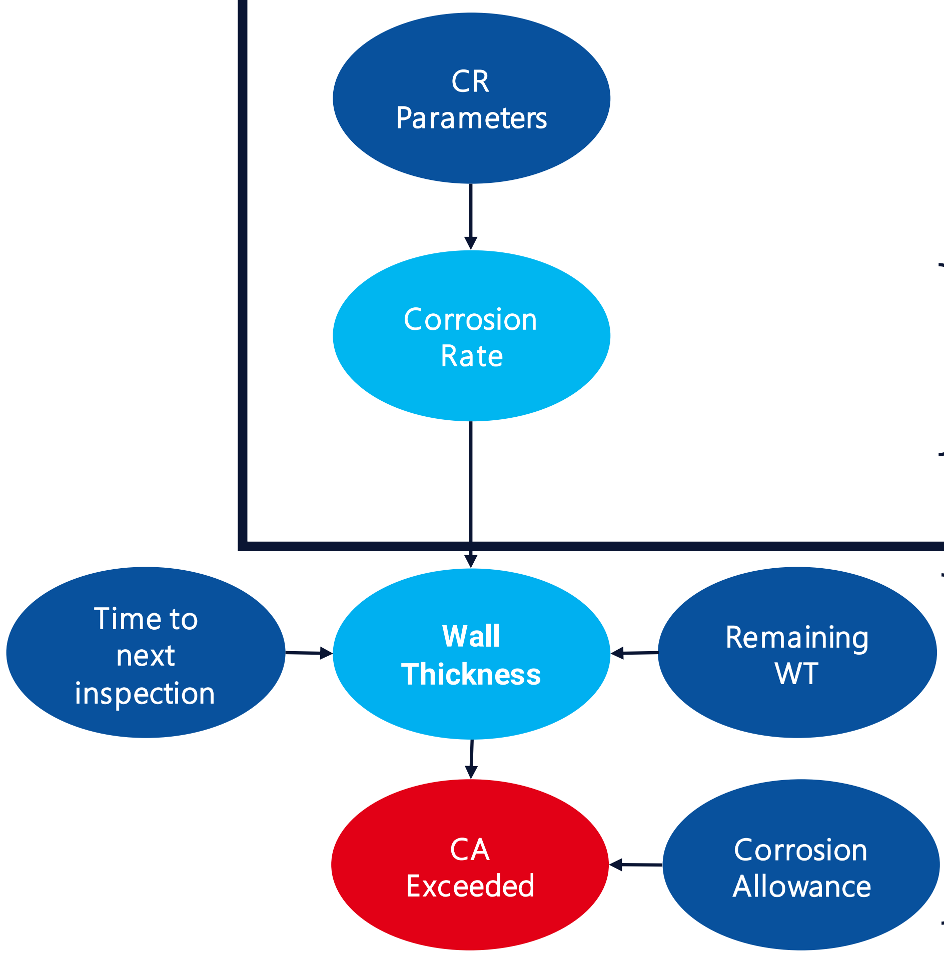
Current CUI Model: EDD1A

A direct implementation of the current CUI model into a Bayesian Network has the following limitations:

- Impact of *inspections* are not captured by the network
- Key *parameters* affecting the exceedance of corrosion allowance are missing (e.g. corrosion rate, jacketing condition)
- Direct *causal relationships* are not captured by the network – the intermediate nodes (environment, service, miscellaneous) aggregate causes into a *factor parameter*
- *Records and measurements* do not have the same format as the aggregated factor parameter (e.g. C1 to C6 categories for the environmental factor), decreasing the effectiveness of using data to update the probability model


Proposed CUI Model

Proposed Bayesian Network (High Level)



Environmental and operating conditions that affect the corrosion rate

A distribution generated from a mixture of engineering models, subject matter expertise, and data

Goal of Workshops

The corrosion rate is used to predict the likelihood that the corrosion allowance will be exceeded by the next inspection

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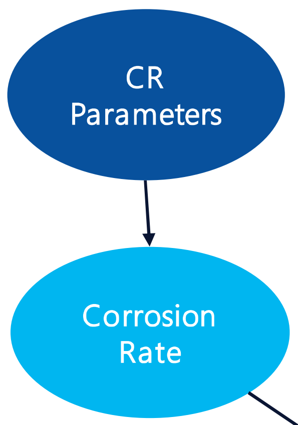
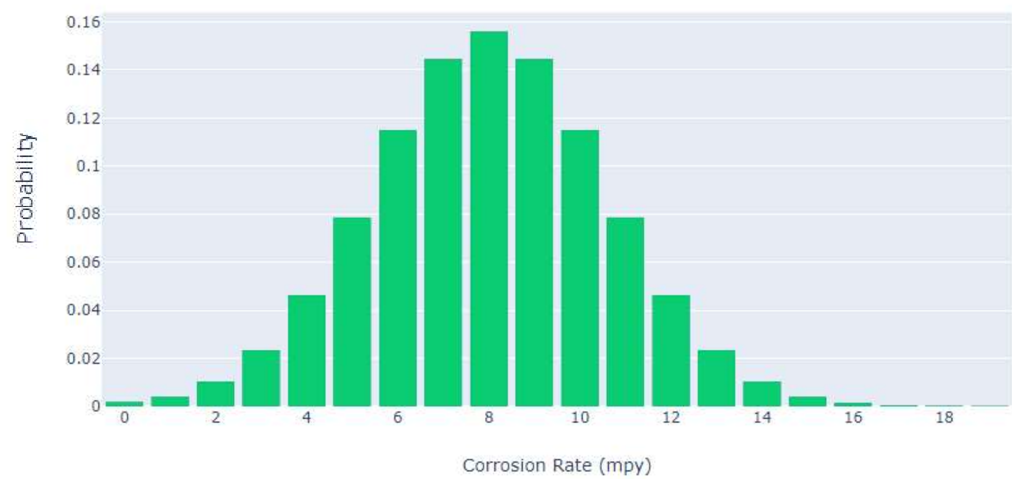
Goal of Workshops





Goal:

Generate a corrosion rate distribution for a set of environmental and operating conditions

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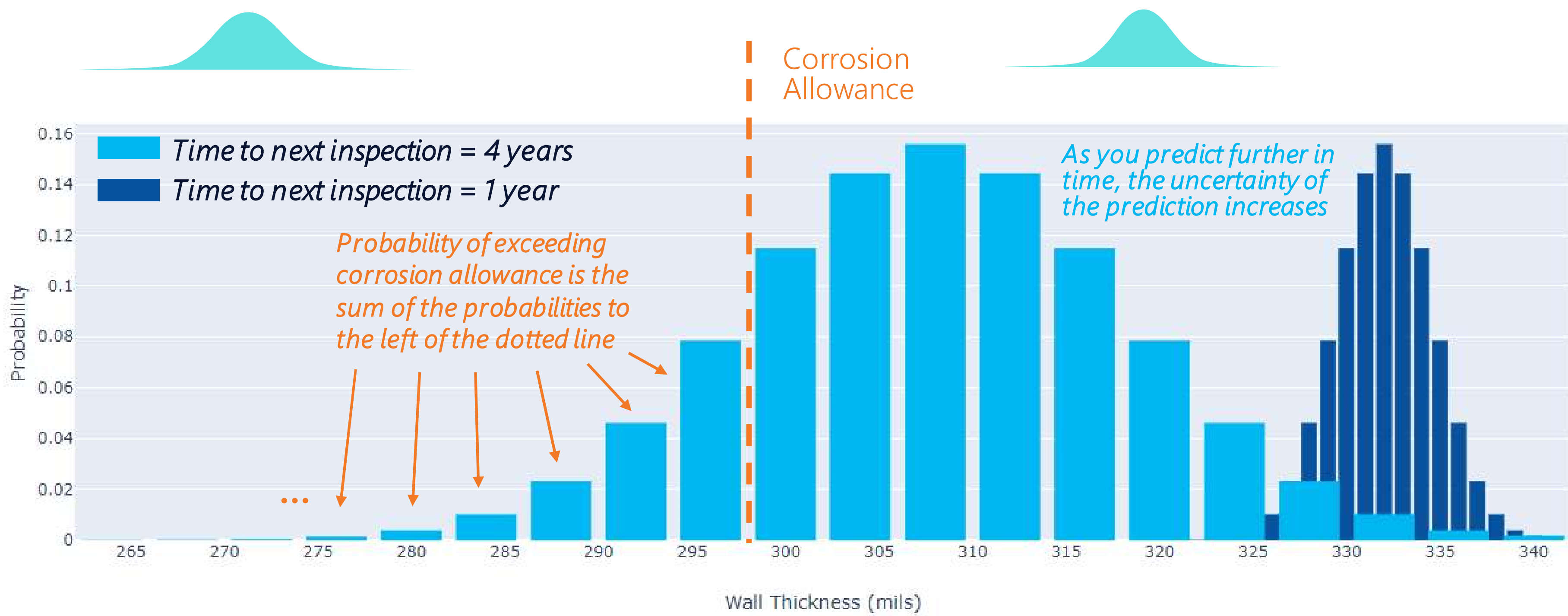
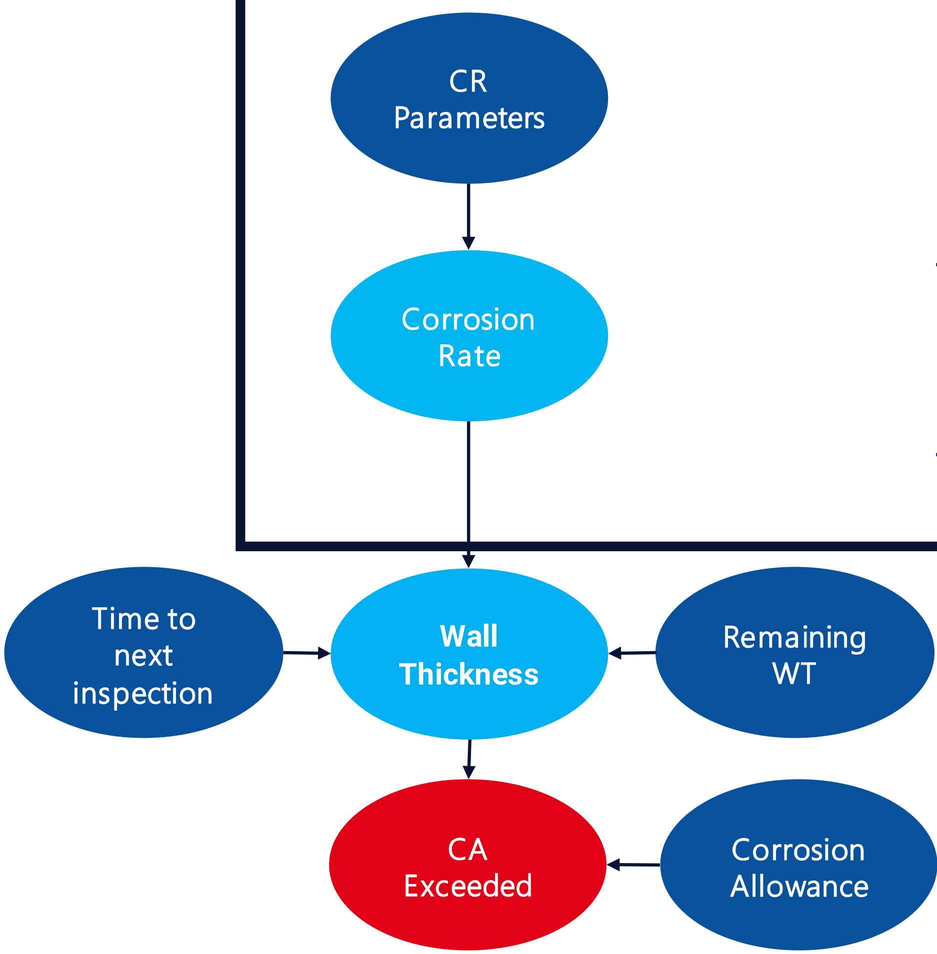
Predicting Future Wall Thickness

The corrosion rate is used to predict the wall thickness and the probability of exceeding the corrosion allowance at a given point in time:

$$Future\ Wall\ Thickness\ = Current\ Wall\ Thickness\ -\ Time\ \ x\ \ Corrosion\ Rate$$



Proposed Bayesian Network (High Level)



Environmental and operating conditions that affect the corrosion rate

A distribution generated from a mixture of engineering models, subject matter expertise, and data

Goal of Workshops

The corrosion rate is used to predict the likelihood that the corrosion allowance will be exceeded by the next inspection

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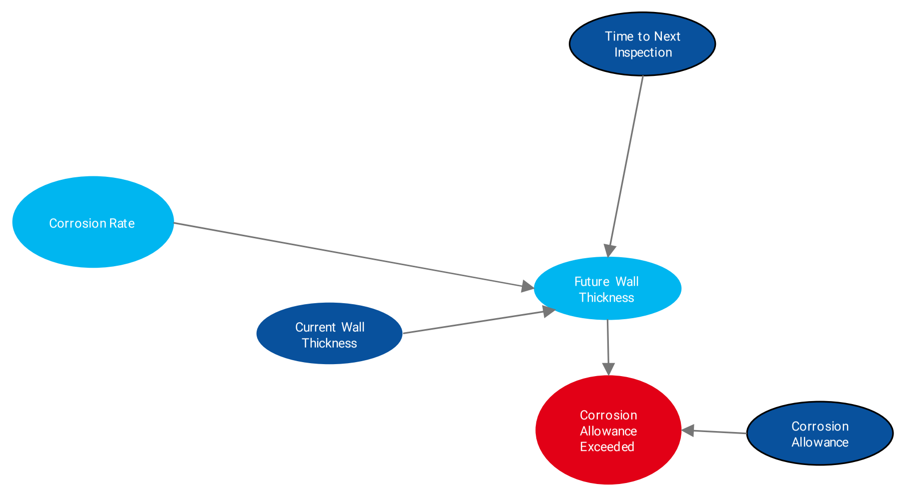
Corrosion Under Insulation
Bayesian Network

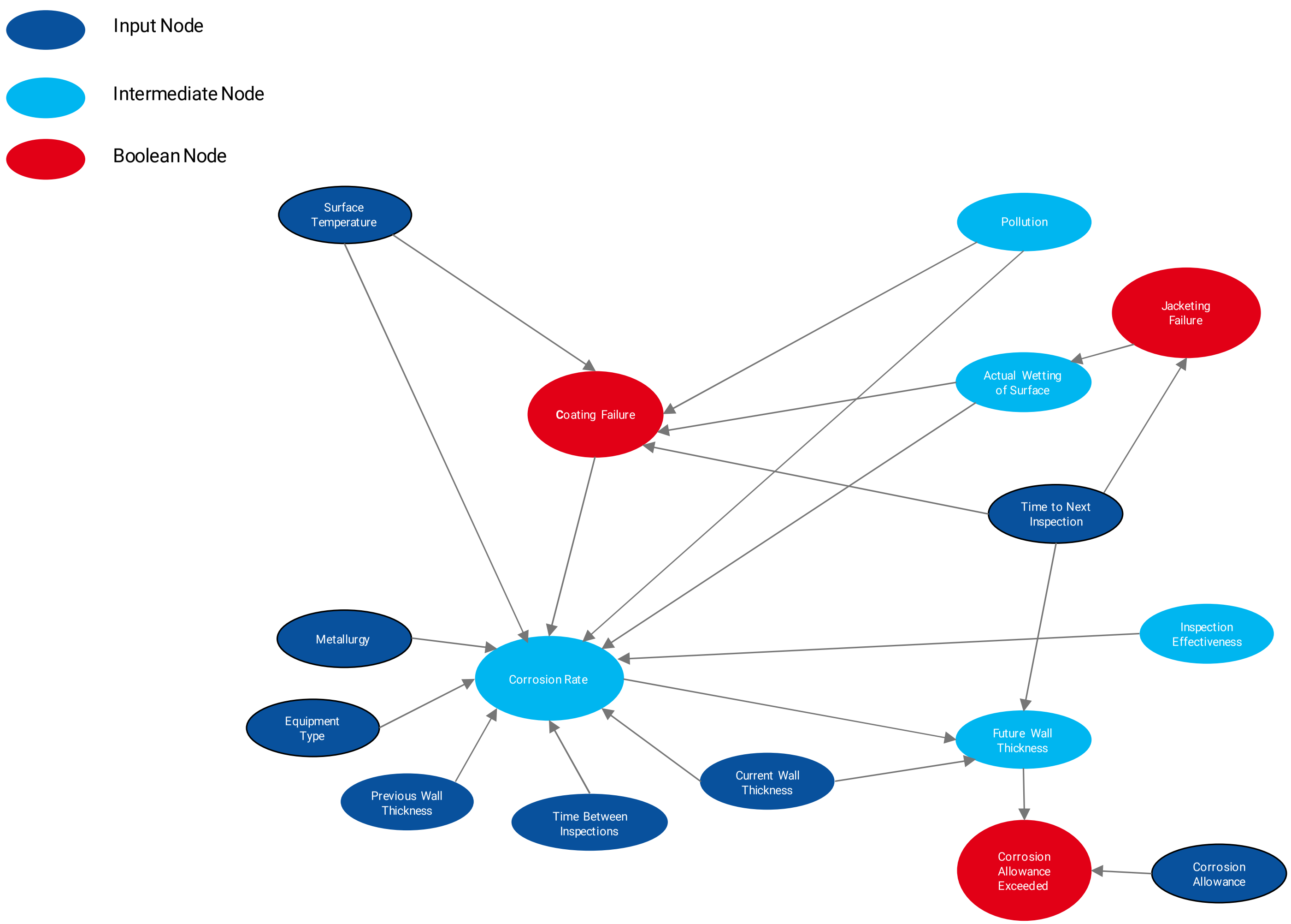
Input Node

Intermediate Node

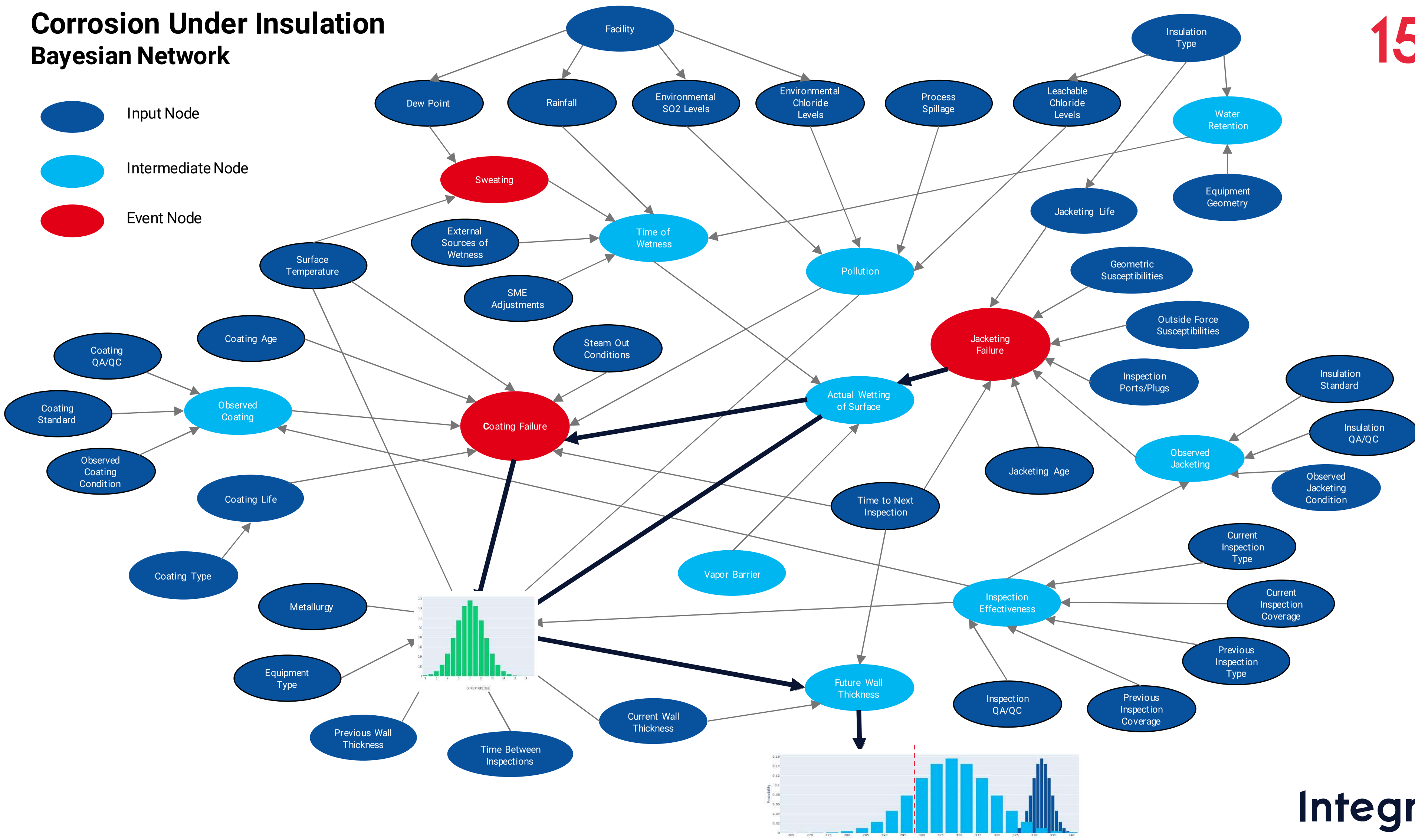
Boolean Node



Corrosion Under Insulation
Bayesian Network



Corrosion Under Insulation
Bayesian Network



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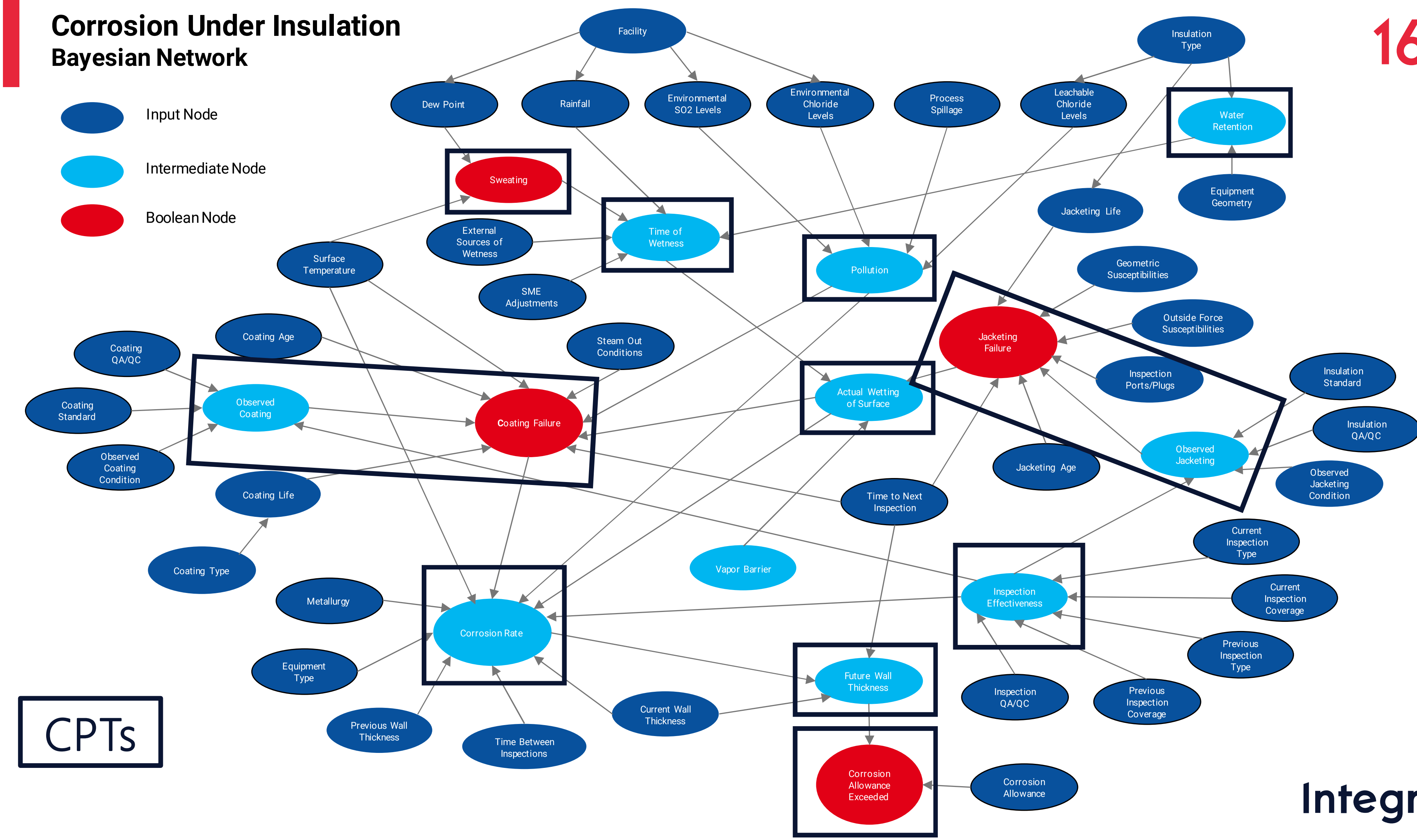
Corrosion Under Insulation
Bayesian Network



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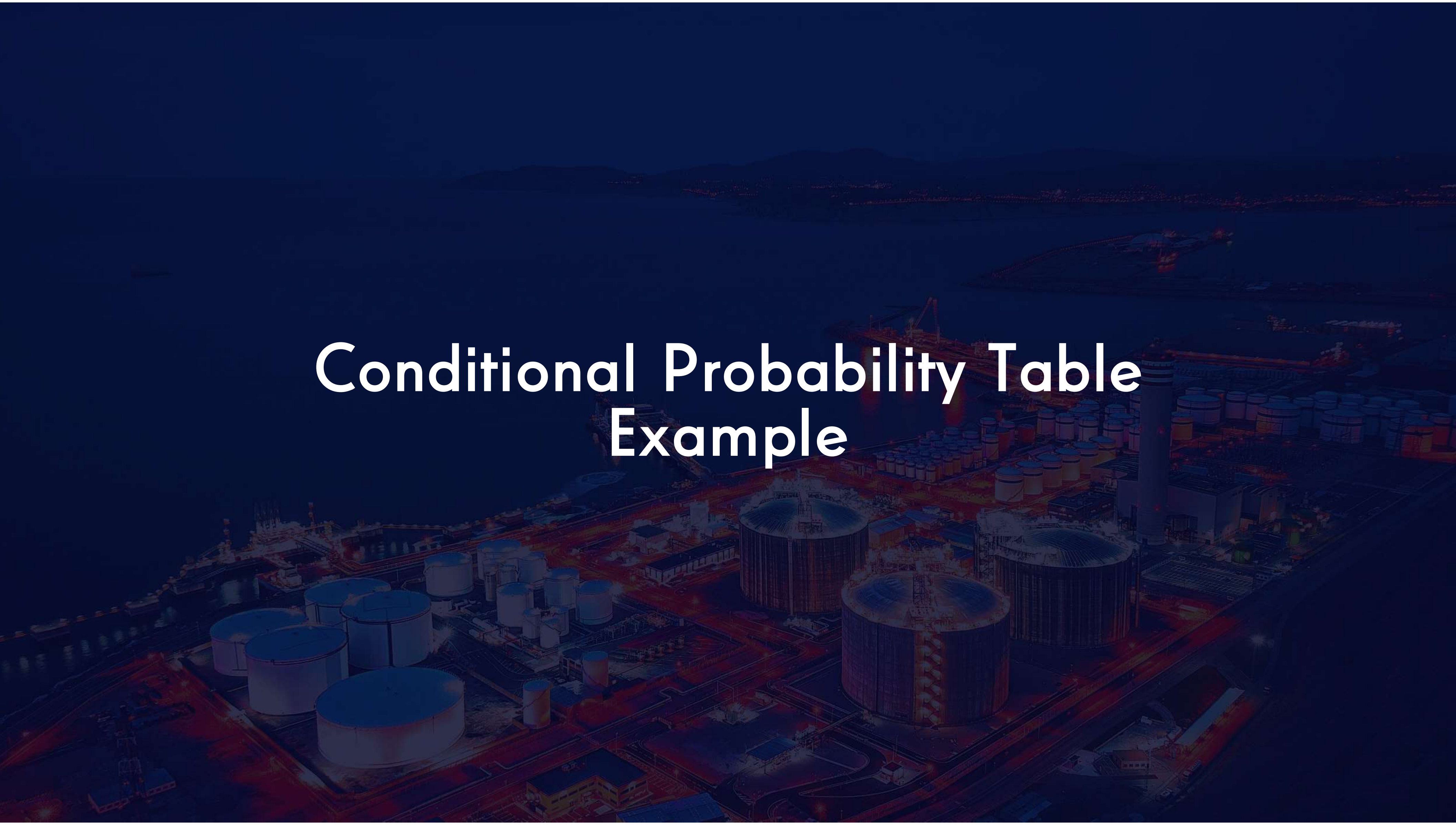
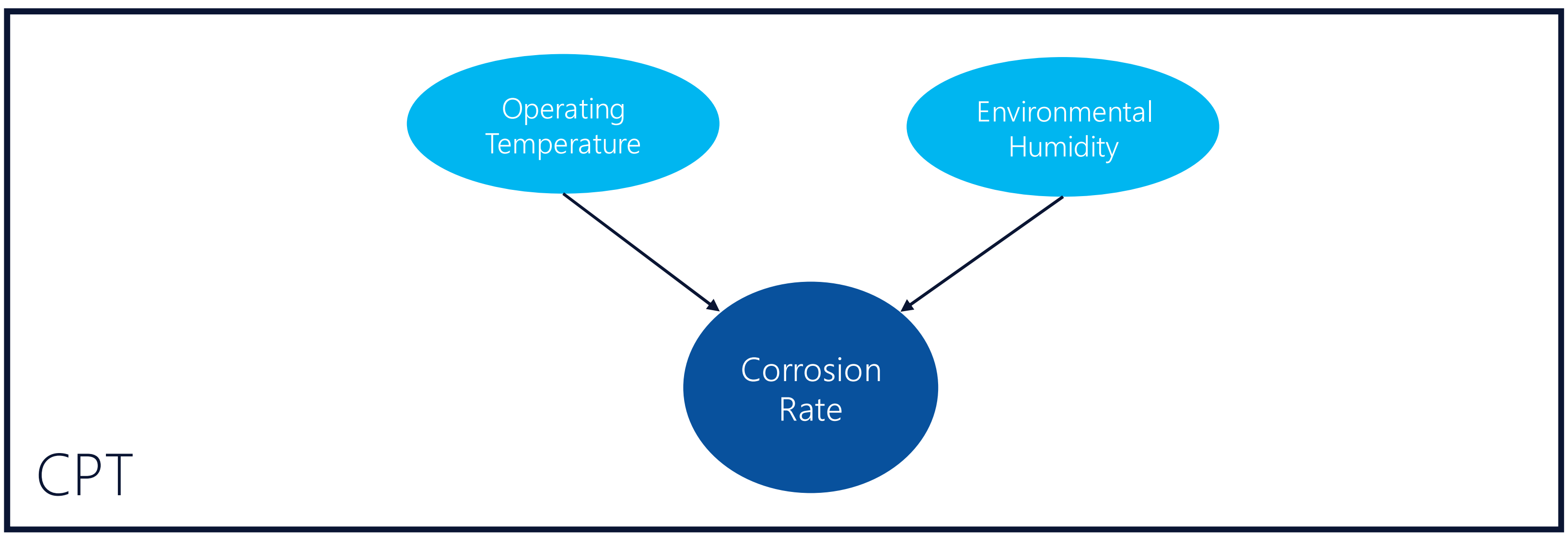


Conditional Probability Table Example

Conditional Probability Tables (CPTs)

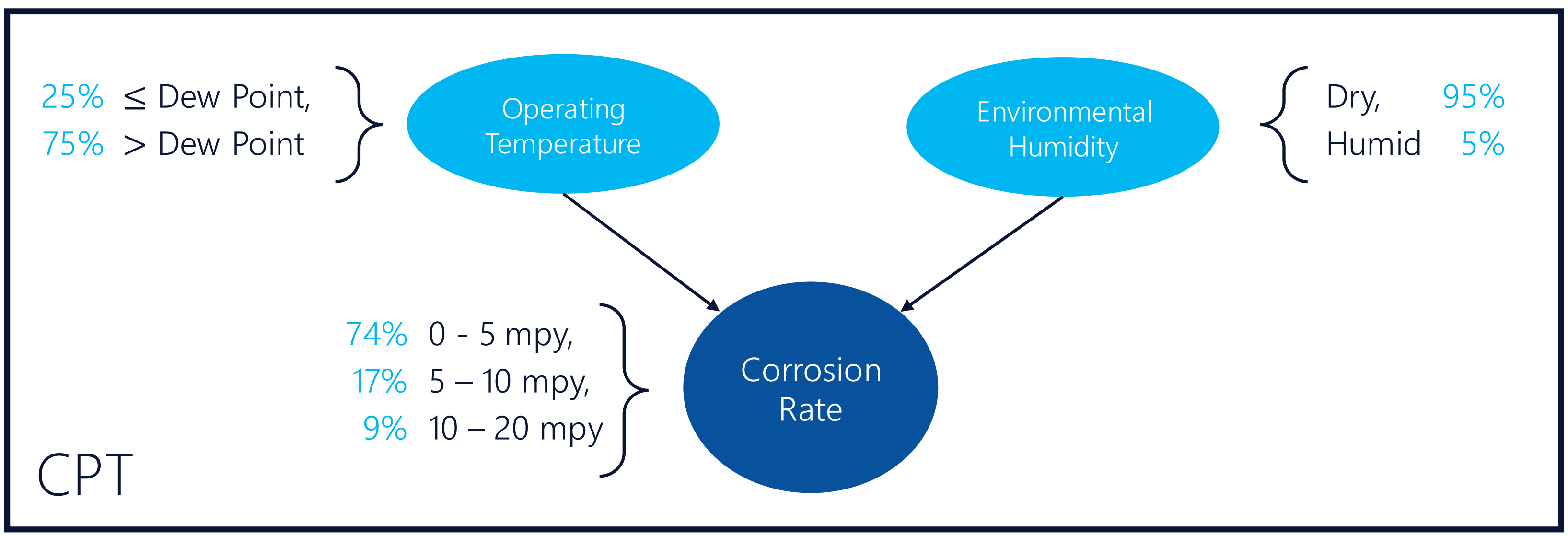
A conditional probability table (CPT) captures the cause-consequence relationships between a set of inputs and an output



Conditional Probability Tables (CPTs)

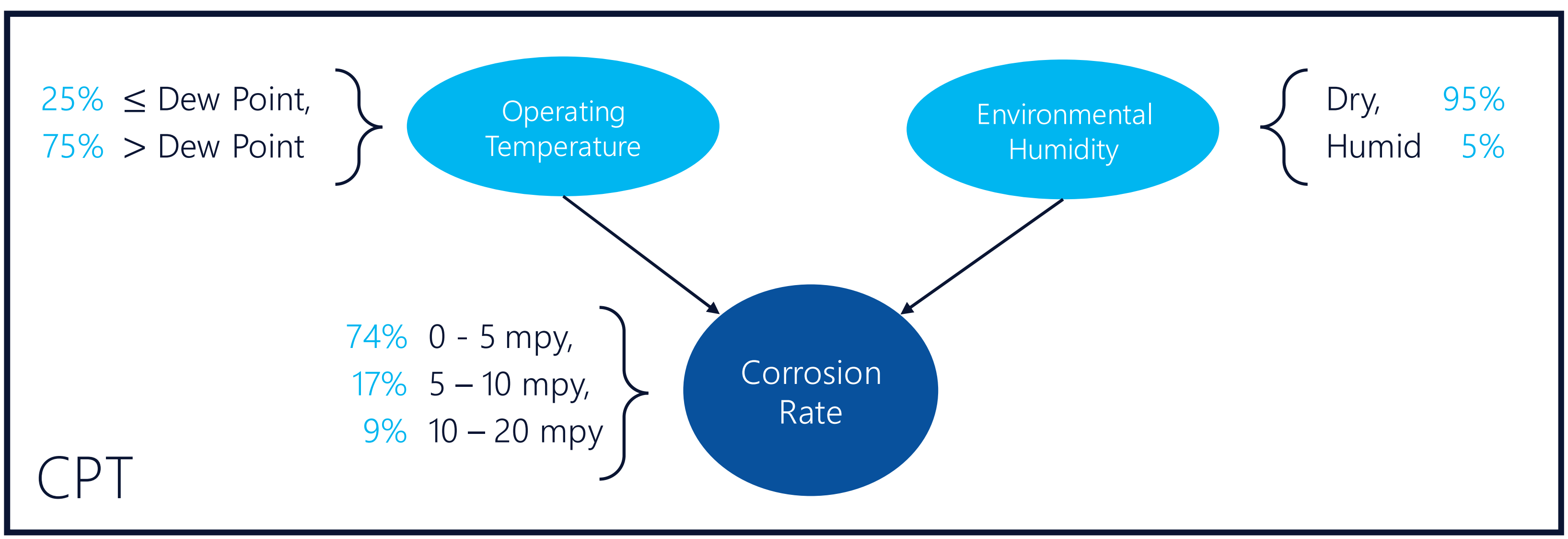
The inputs and output of a CPT are typically discrete categories.

- Each category has a probability
- The probabilities in a category add to 100%.
- A large number of sub-categories has more resolution but increases computation time



Conditional Probability Tables (CPTs)

The output of a CPT is the input to a subsequent node



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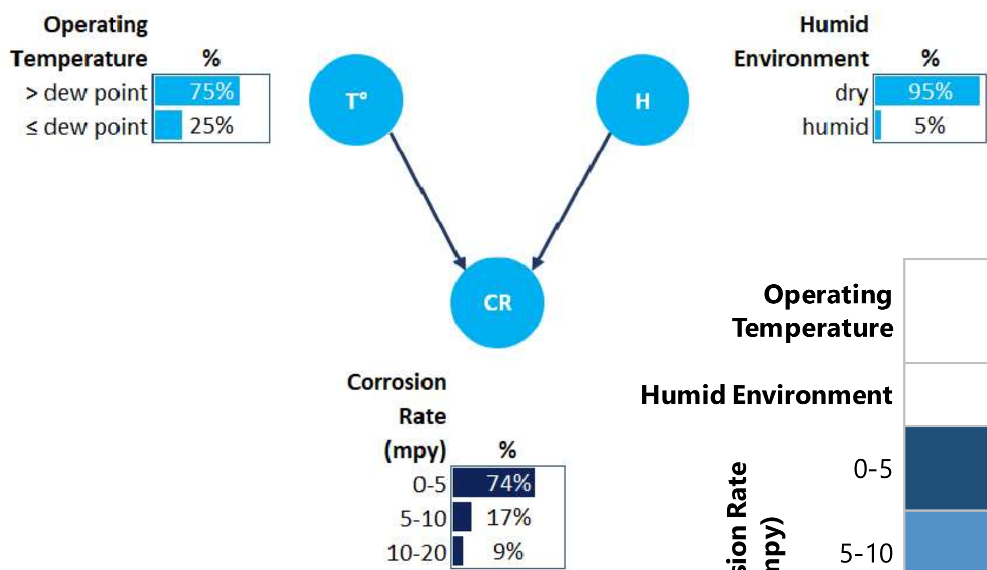
Conditional Probability Tables (CPTs)

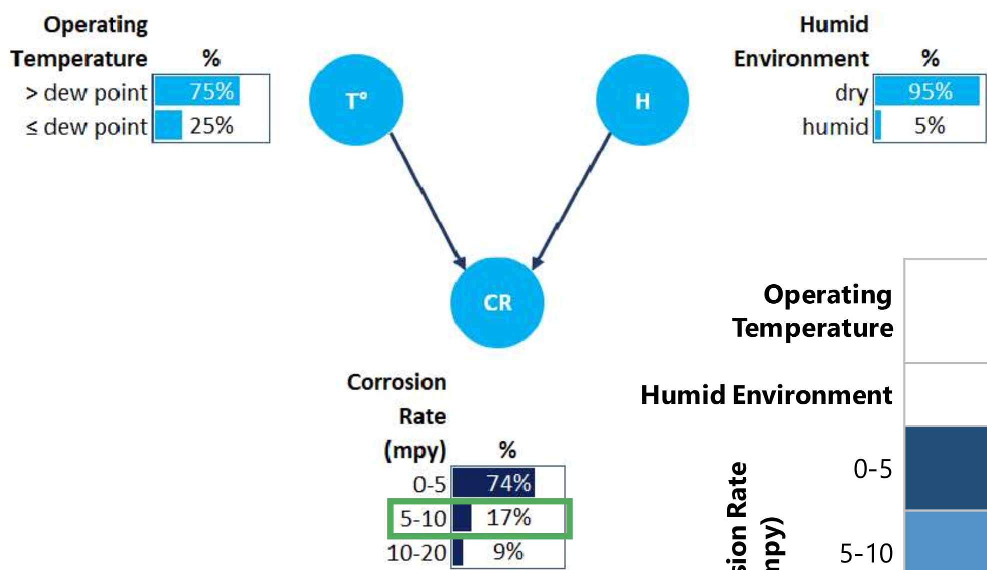
Example CPT: Simple Corrosion Rate Node



Operating Temperature		> dew point		≤ dew point	
Humid Environment		dry	humid	dry	humid
Corrosion Rate (mpy)	0-5	80%	70%	60%	40%
	5-10	15%	20%	20%	30%
	10-20	5%	10%	20%	30%

Conditional Probability Tables (CPTs)

Example CPT: Simple Corrosion Rate Node



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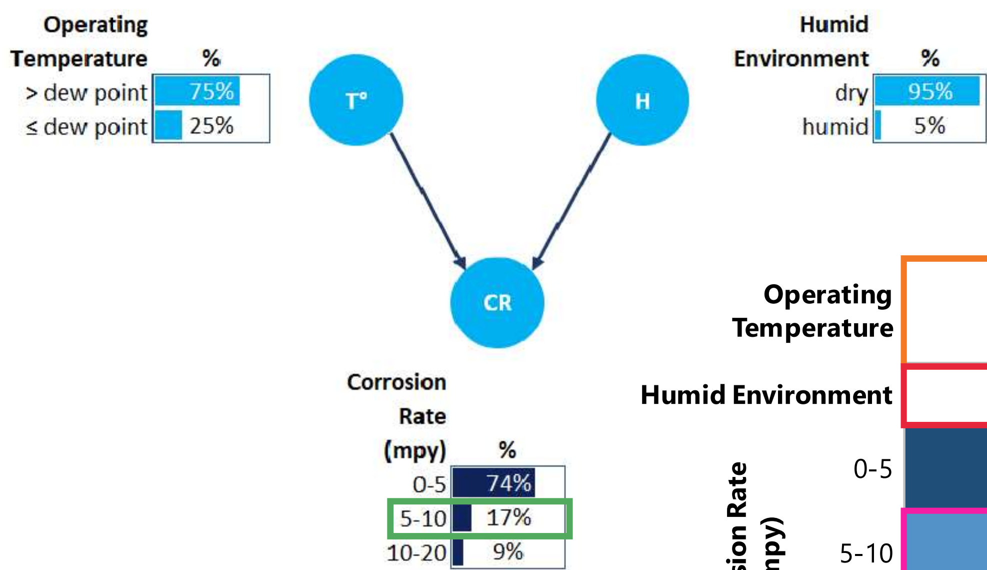
Corrosion Rate (mpy)	0-5	80%	70%	60%	40%
	5-10	15%	20%	20%	30%
	10-20	5%	10%	20%	30%
	Total:	100%	100%	100%	100%

$$P_{5-10} = P_I + P_{II} + P_{III} + P_{IV} = 17\%$$

Conditional Probability Tables (CPTs)

Example CPT: Simple Corrosion Rate Node



$P_I = 75\% \times 95\% \times 15\% = 10.7\%$

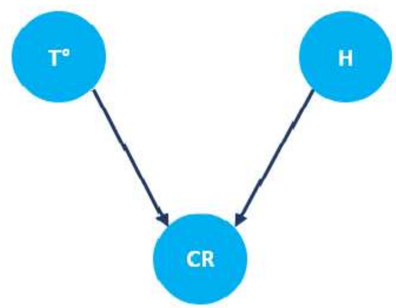
Operating Temperature	> dew point		≤ dew point	
Humid Environment	dry	humid	dry	humid
Corrosion Rate (mpy) 0-5	80%	70%	60%	40%
5-10	15%	20%	20%	30%
10-20	5%	10%	20%	30%
Total:	100%	100%	100%	100%

$P_{5-10} = P_I + P_{II} + P_{III} + P_{IV} = 17\%$

Conditional Probability Tables (CPTs)

Example CPT: Simple Corrosion Rate Node

Operating Temperature	%
> dew point	75%
≤ dew point	25%



Humid Environment	%
dry	95%
humid	5%

Corrosion Rate (mpy)	%
0-5	74%
5-10	17%
10-20	9%

$$P_{II} = 75\% \times 5\% \times 20\% = 0.8\%$$

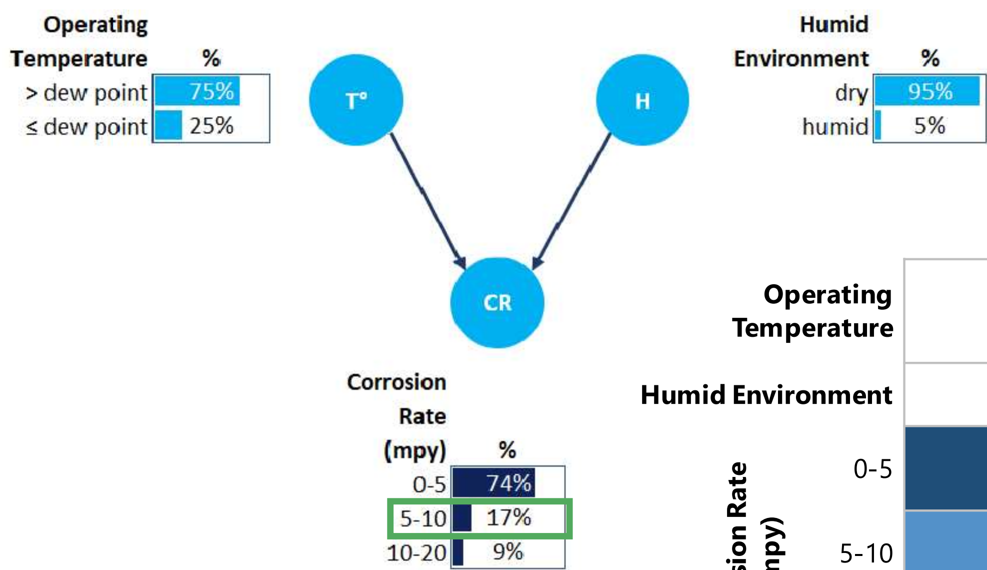
Operating Temperature		> dew point		≤ dew point	
Humid Environment		dry	humid	dry	humid
Corrosion Rate (mpy)	0-5	80%	70%	60%	40%
	5-10	15%	20%	20%	30%
	10-20	5%	10%	20%	30%
	Total:	100%	100%	100%	100%

$$P_{5-10} = 10.7\% + P_{II} + P_{III} + P_{IV} = 17\%$$

Integral

Conditional Probability Tables (CPTs)

Example CPT: Simple Corrosion Rate Node



$$P_{III} = 25\% \times 95\% \times 20\% = 4.8\%$$

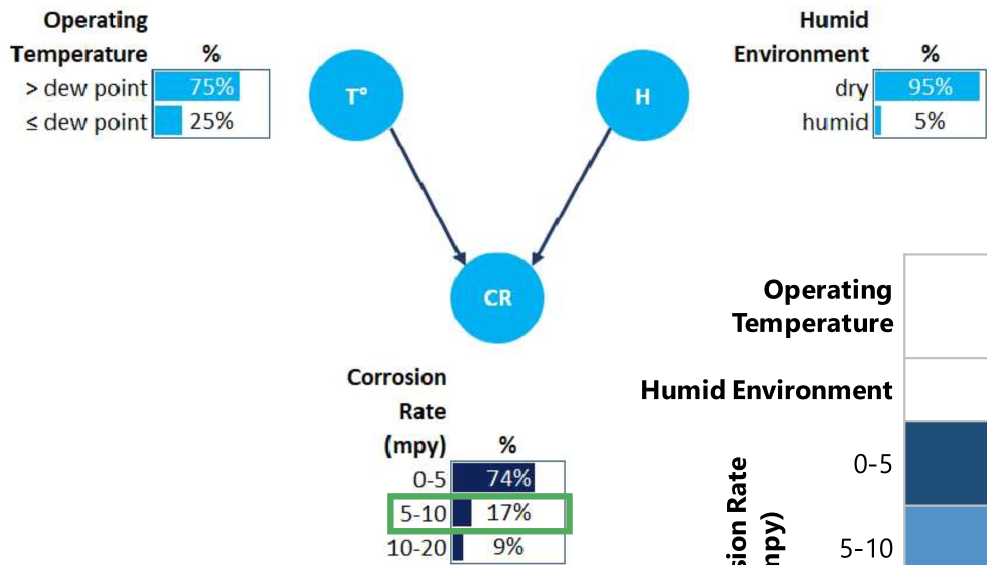
Operating Temperature	> dew point		≤ dew point	
Humid Environment	dry	humid	dry	humid
Corrosion Rate (mpy) 0-5	80%	70%	60%	40%
5-10	15%	20%	20%	30%
10-20	5%	10%	20%	30%
Total:	100%	100%	100%	100%

$$P_{5-10} = 10.7\% + 0.8\% + P_{III} + P_{IV} = 17\%$$

Integral

Conditional Probability Tables (CPTs)

Example CPT: Simple Corrosion Rate Node



$P_{IV} = 25\% \times 5\% \times 30\% = 0.4\%$

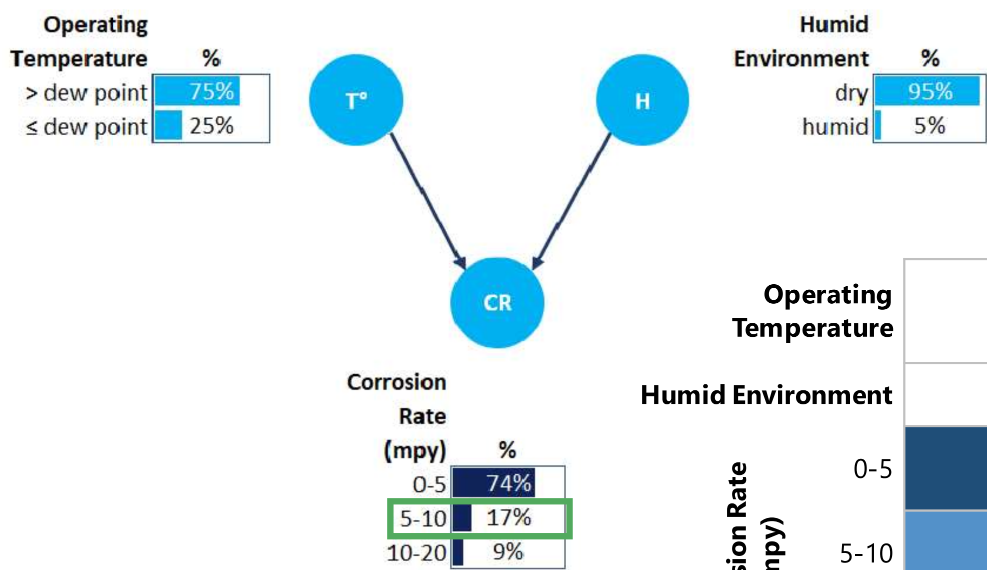
Operating Temperature	> dew point		≤ dew point	
Humid Environment	dry	humid	dry	humid
Corrosion Rate (mpy) 0-5	80%	70%	60%	40%
5-10	15%	20%	20%	30%
10-20	5%	10%	20%	30%
Total:	100%	100%	100%	100%

$P_{5-10} = 10.7\% + 0.8\% + 4.8\% + P_{IV} = 17\%$

Integral

Conditional Probability Tables (CPTs)

Example CPT: Simple Corrosion Rate Node

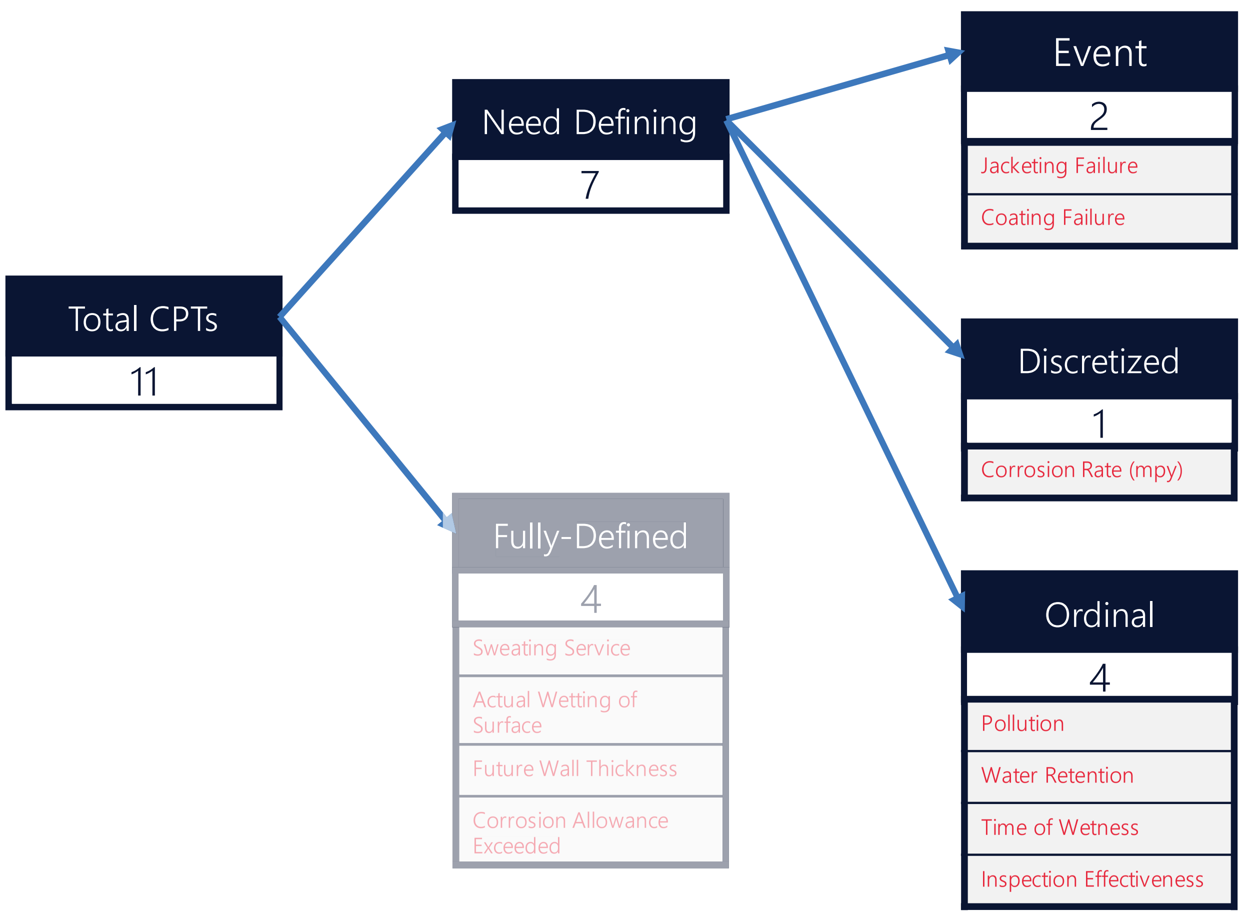


Operating Temperature		> dew point		≤ dew point	
Humid Environment		dry	humid	dry	humid
Corrosion Rate (mpy)	0-5	80%	70%	60%	40%
	5-10	15%	20%	20%	30%
	10-20	5%	10%	20%	30%
	Total:	100%	100%	100%	100%

$$P_{5-10} = 10.7\% + 0.8\% + 4.8\% + 0.4\% = 16.7\%$$

Conditional Probability Tables for CUI Model

Conditional Probability Tables (CPTs)



Event: this type of CPT has a binary output. The output describes the probability of an event occurring (e.g. coating intact, coating not intact).

Discretized: a discrete output defined over a range. The output describes the probability of each bin in the range occuring (e.g. 1 mpy, 2 mpy, …etc.).

Ordinal: a ranked order output (e.g. high, medium, low). Often fitted to a truncated normal distribution.

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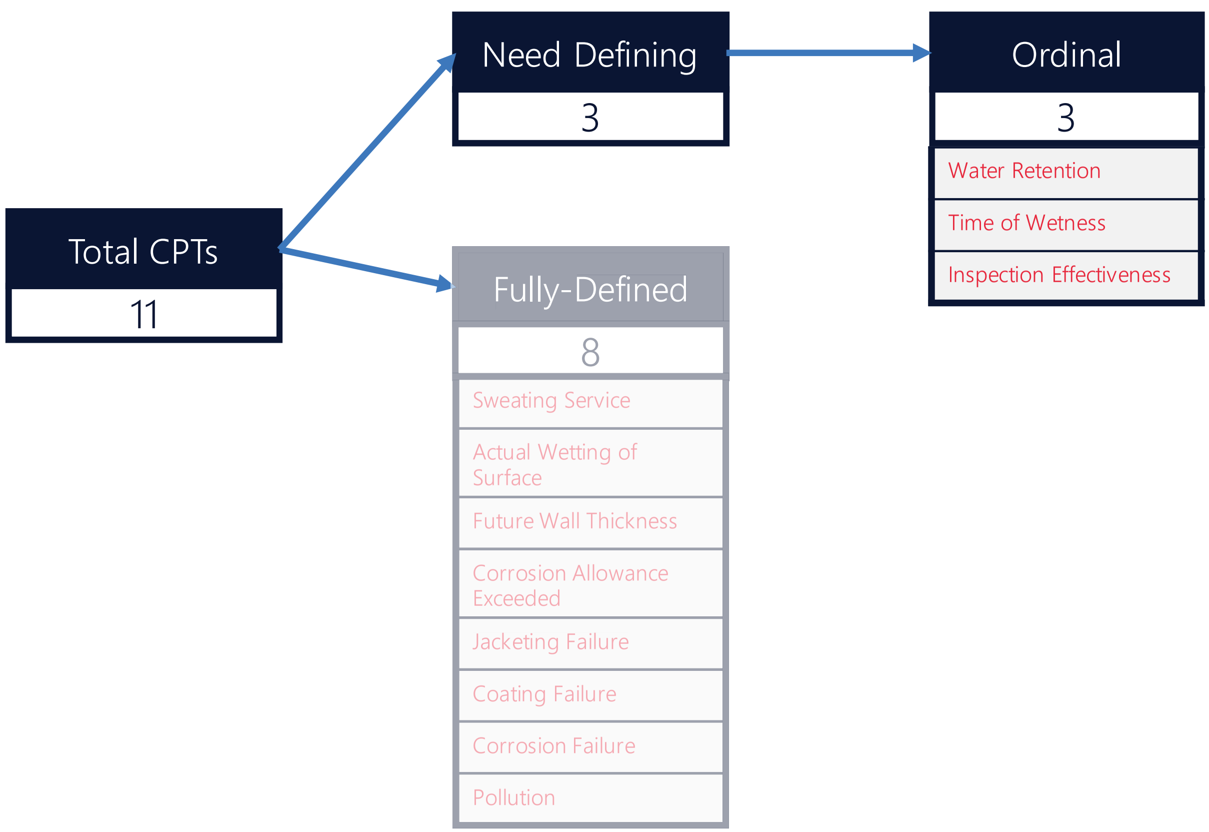
Conditional Probability Tables (CPTs)



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Ordinal: a ranked order output (e.g. high, medium, low). Often fitted to a truncated normal distribution.

Conditional Probability Tables (CPTs)

Node	Inputs	CPT	Outputs
Sweating Service	✓	✓	✓
Future Wall Thickness	✓	✓	✓
Corrosion Allowance Exceeded	✓	✓	✓
Actual Wetting of Surface	✓	✓	✓
Jacketing Failure			✓
Coating Failure			✓
Corrosion Rate			✓
Pollution			
Water Retention			
Time of Wetness			
Inspection Effectiveness			

Conditional Probability Tables (CPTs)

Node	Inputs	CPT	Outputs
Sweating Service	✓	✓	✓
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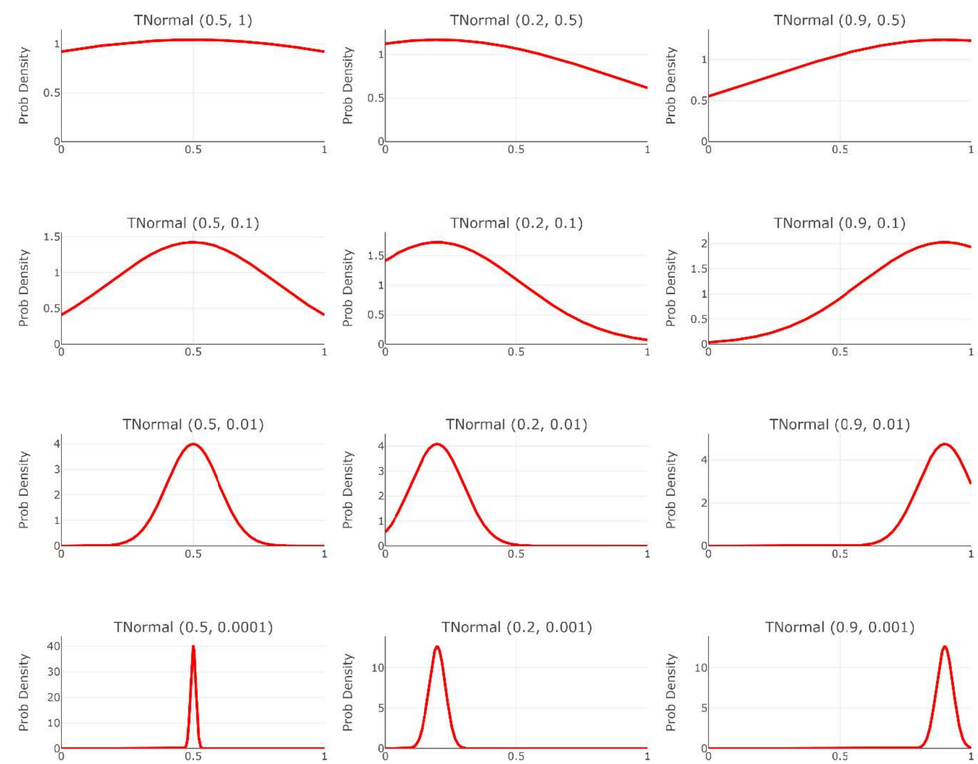
Actual Wetting of Surface	✓	✓	✓
Jacketing Failure	✓	✓	✓
Coating Failure	✓	✓	✓
Corrosion Rate	✓	✓	✓
Pollution	✓	✓	✓
Water Retention			
Time of Wetness			
Inspection Effectiveness			

Fitting to Truncated Normal

- Ordinal CPTs can be populated by fitting to a truncated normal distribution.
- Uncertainty is captured by the width of the distribution
- The mean is based on how the input variables interact:
  - Weighted Average
  - Weighted Maximum Value
  - Weighted Minimum Value
  - Additive



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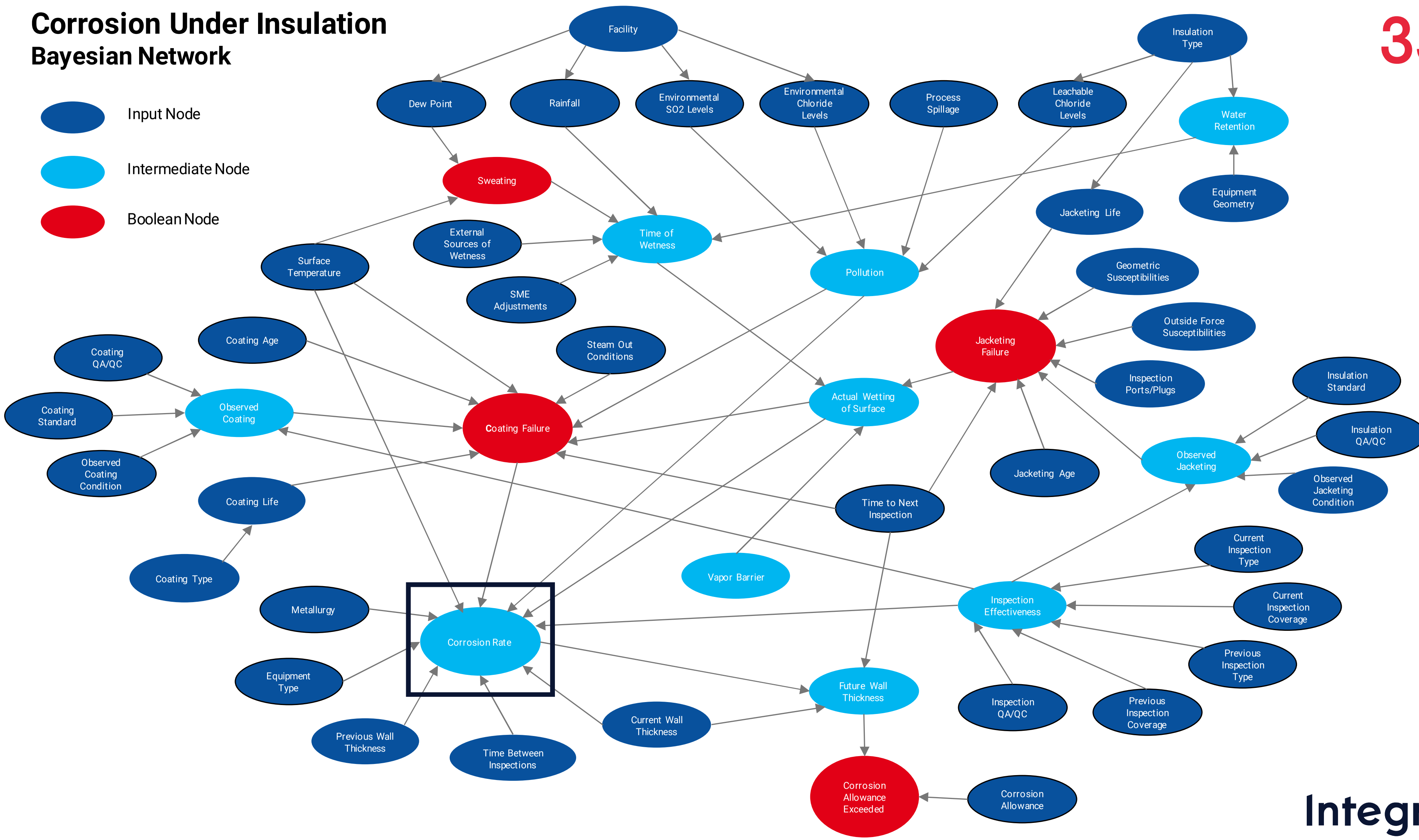
Corrosion Rate CPT

Corrosion Under Insulation
Bayesian Network



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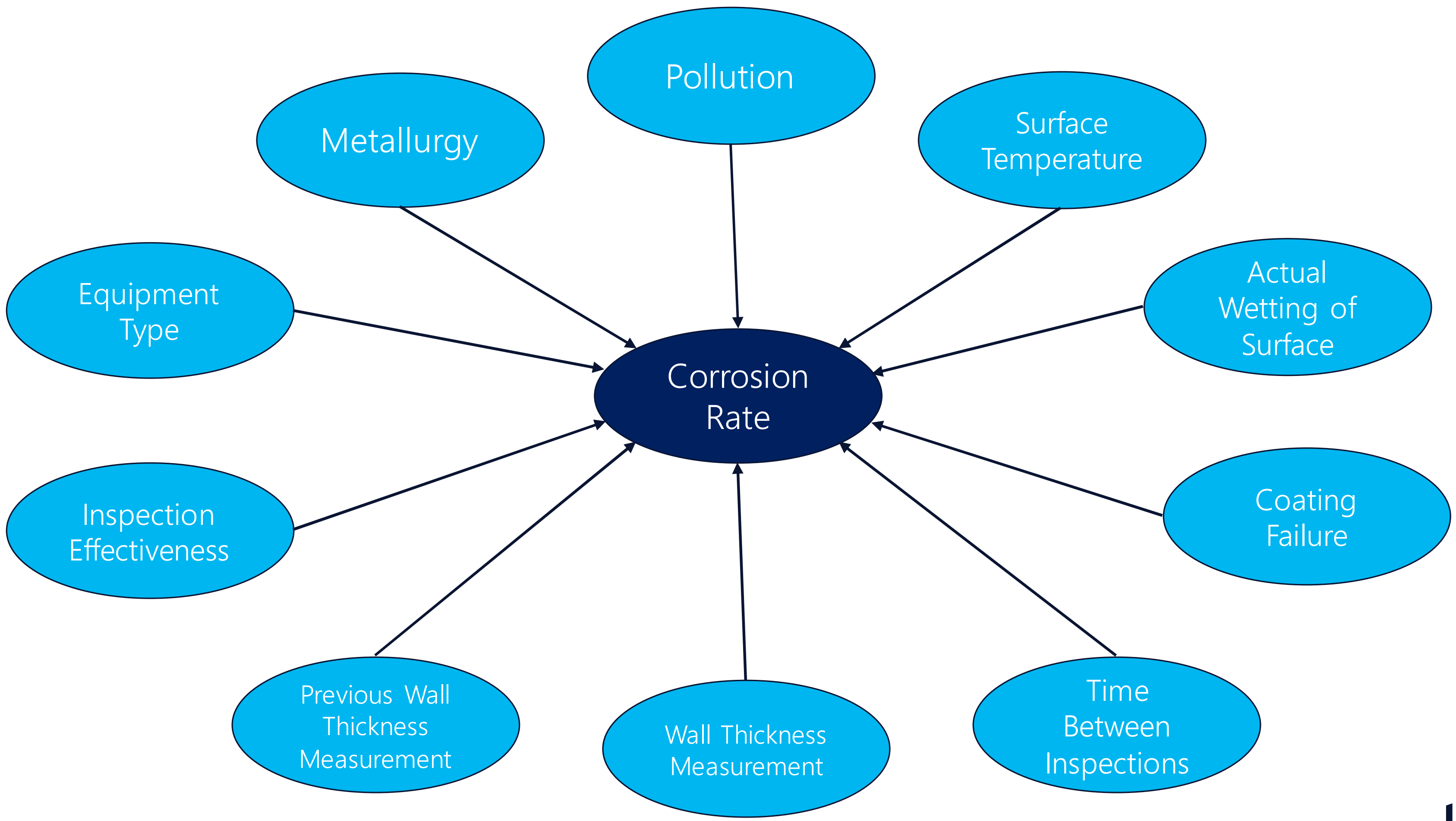
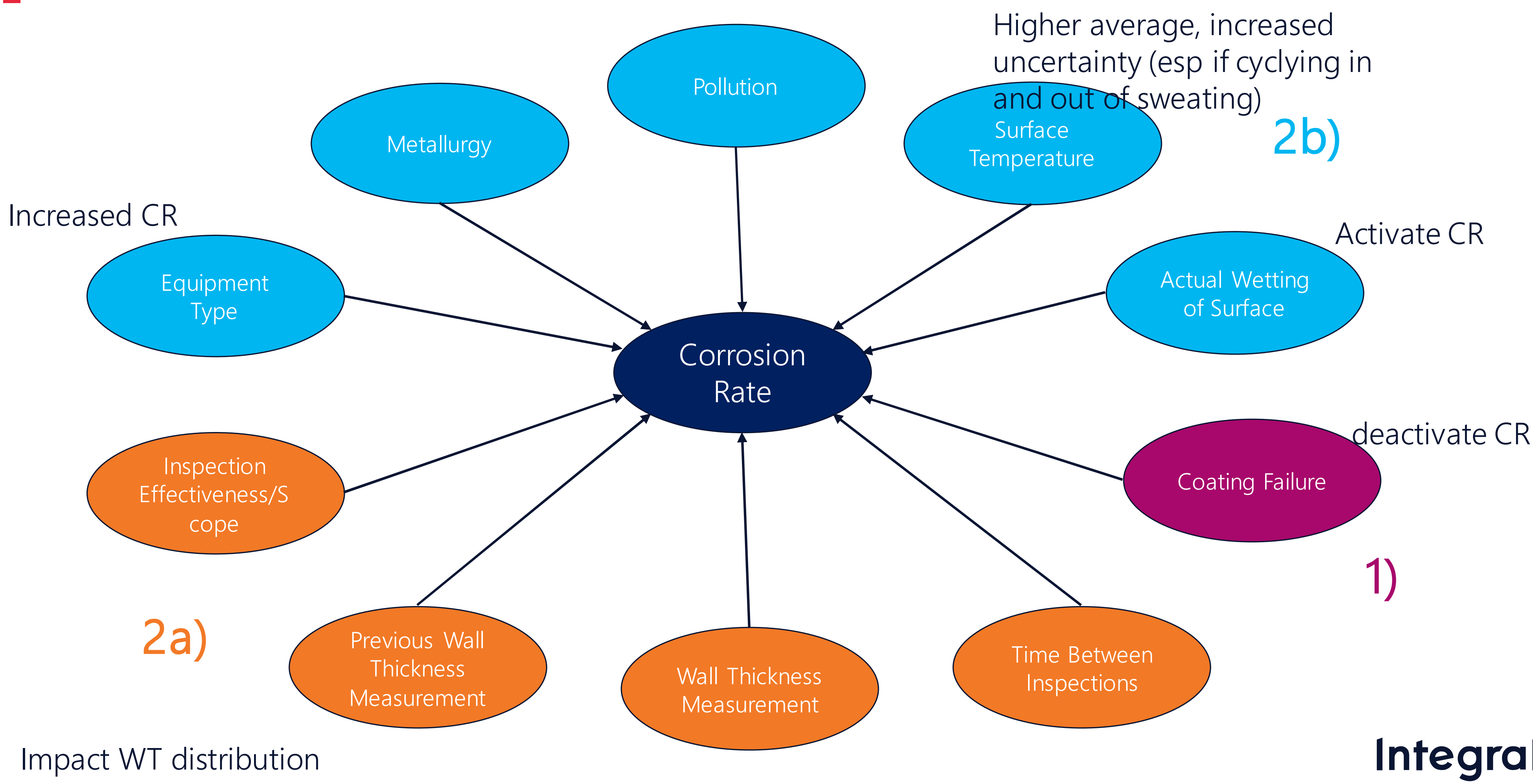
Corrosion Rate CPT



Corrosion Rate CPT



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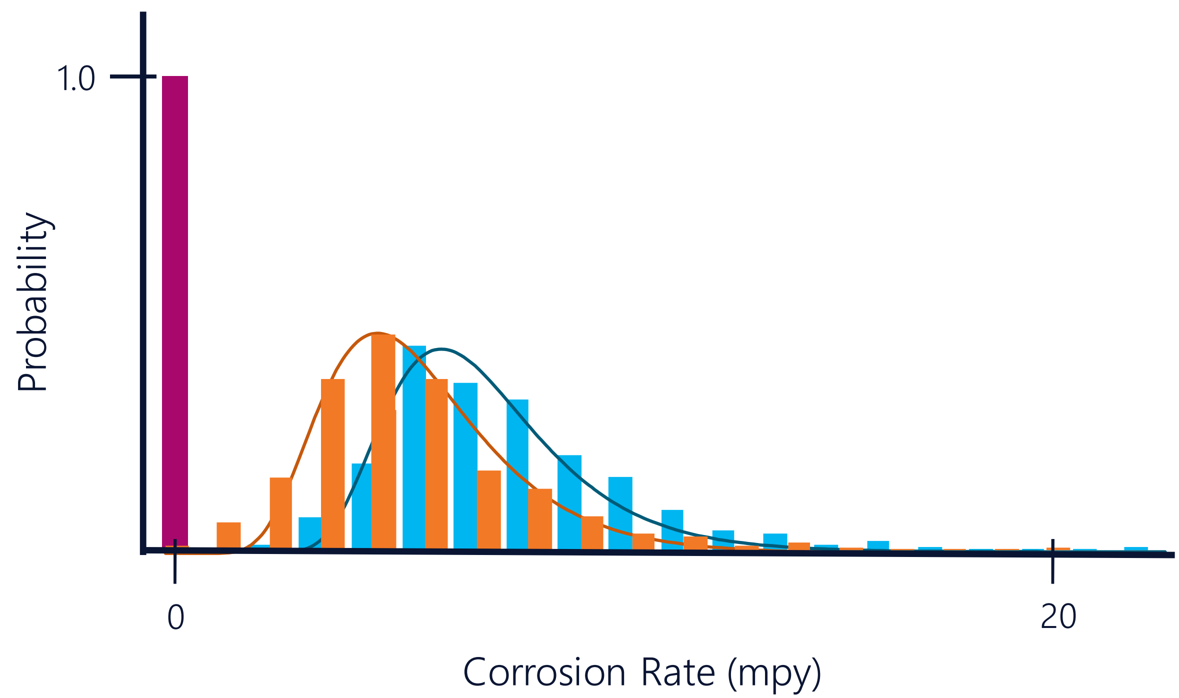
Corrosion Rate CPT



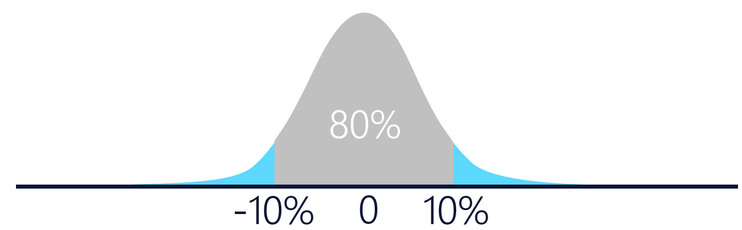
1): If the coating is intact, the corrosion rate is 0 mpy

2a): If the coating is not intact and inspection data is available, a corrosion rate distribution is generated using the inspection measurements

2b): If the coating is not intact and there is no inspection data available, a default distribution is used and shifted according to the environmental and operating conditions that the equipment is subjected to

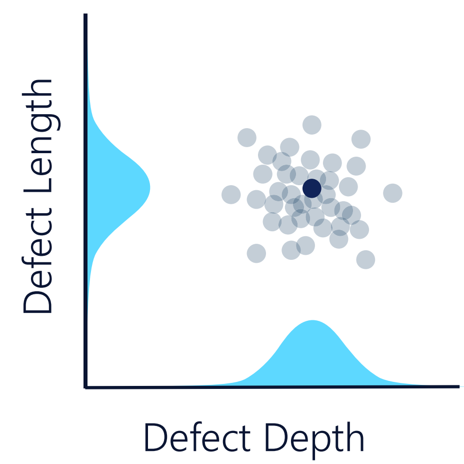
Corrosion Rate Based on Inspection Measurements

$$Corrosion\ Rate = \frac{d_2 - d_1}{\Delta t_{insp}}$$



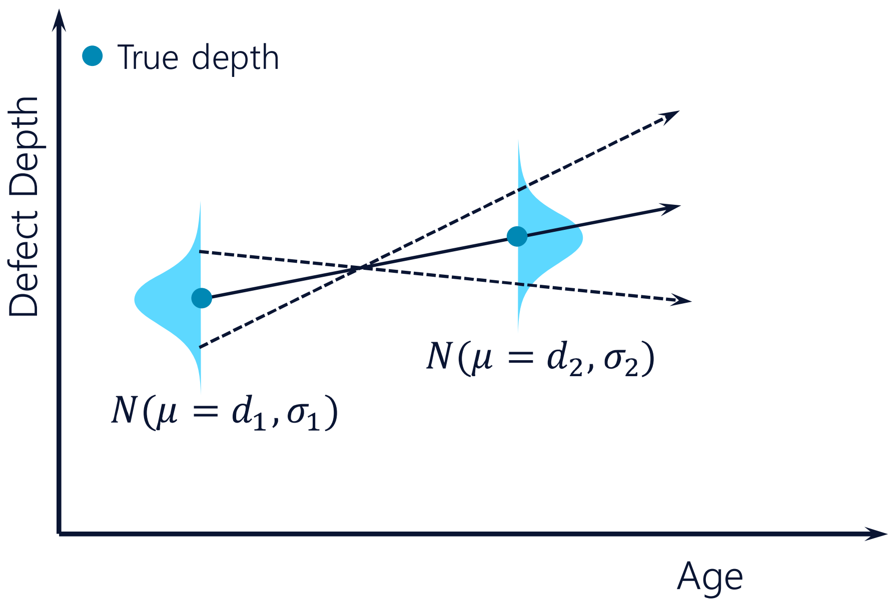
Effect of Measurement Error:

- An inspection tool reports a defect to be a specific depth and a specific length
- Typical depth measurement error specification:
  - ±10% at 80% certainty
- In 10% of cases the true depth is > 10% deeper



Corrosion Rate Based on Inspection Measurements

For Repeated Inspections:



- The corrosion rate is given by

$$CR = \frac{d_2 - d_1}{\Delta t_{insp}}$$

- Now, account for the variability due to measurement error

$$CR = \frac{N(d_2, \sigma_2) - N(d_1, \sigma_1)}{\Delta t_{insp}}$$

$$= \frac{N\left(d_2 - d_1, \sqrt{\sigma_1^2 + \sigma_2^2}\right)}{\Delta t_{insp}}$$

- Hence, the corrosion rate can be *represented as a distribution* based on repeated measurements

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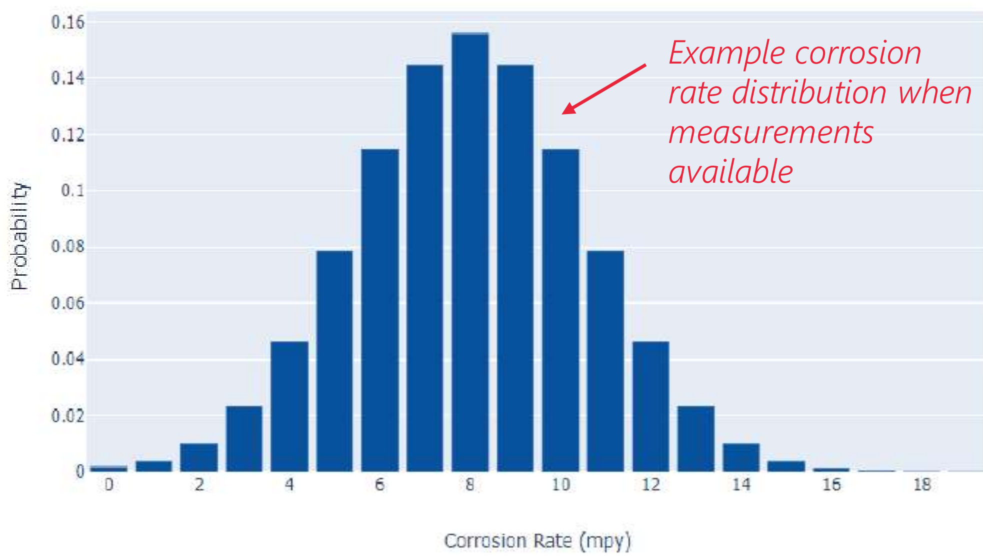
Corrosion Rate Based on Inspection Measurements

Information from *two previous inspections* is used to generate the corrosion rate distribution:



Mean is based on measurements (i.e. the recorded measurements)

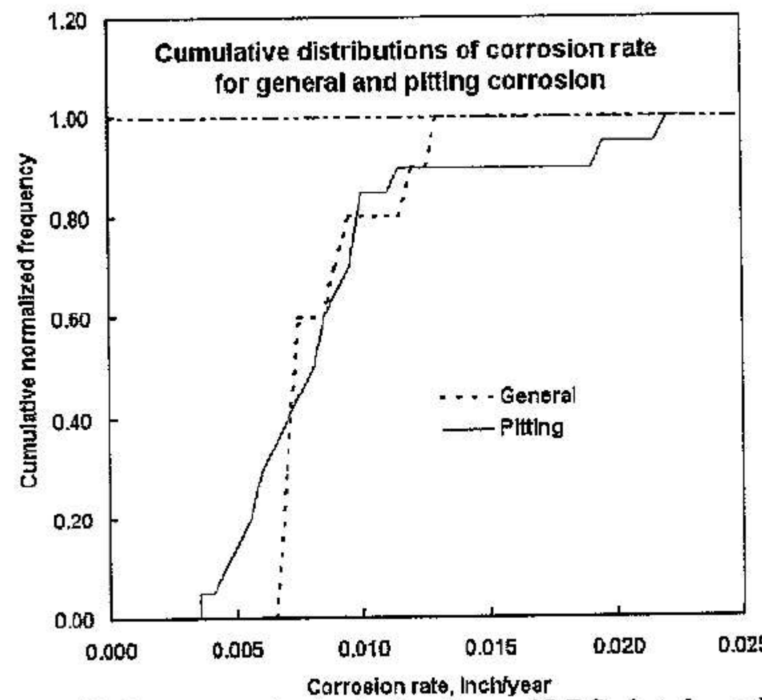
Standard deviation (i.e. the error associated with the measurements) is based on inspection effectiveness:

Inspection Effectiveness	Error for a Single Measurement (+/- mils)
Acceptable	
Effective	
Very Effective	

Corrosion Rate when no Measurements Available

If no wall thickness measurements are available, a default corrosion rate can be used:

- **Example - GRI-00/0230:**
    - Outlines a cumulative corrosion growth rate distribution for pitting on pipelines with an average of 9 mpy, and a 90th percentile of 12 mpy
    - ASME B31.8S refers to GRI-00/0230 for guidance in making assumptions about the growth rate of time dependent conditions.



b) bare, protected pipelines (OPS database)

Corrosion Rate when no Measurements Available

If no wall thickness measurements are available, a default corrosion rate can be used:

- **Example - GRI-00/0230:**
  - Outlines a cumulative corrosion growth rate distribution for pitting on pipelines with an average of 9 mpy, and a 90th percentile of 12 mpy
  - ASME B31.8S refers to GRI-00/0230 for guidance in making assumptions about the growth rate of time dependent conditions.
- **API-581:**
  - Provides deterministic CUI rates based on climate and operating temperature
  - Ranges from 0 – 20 mpy

Table 17.3 – Corrosion Rates for Calculation of the Damage Factor – CUI

Operating Temperature (°F)	Corrosion Rate as a Function of Driver (1) (mpy)			
	Marine / Cooling Tower Drift Area	Temperate	Arid / Dry	Severe
10	0	0	0	0
18	1	0	0	3
43	5	3	1	10
90	5	3	1	10
160	10	5	2	20
225	5	1	1	10
275	2	1	0	10
325	1	0	0	5
350	0	0	0	0

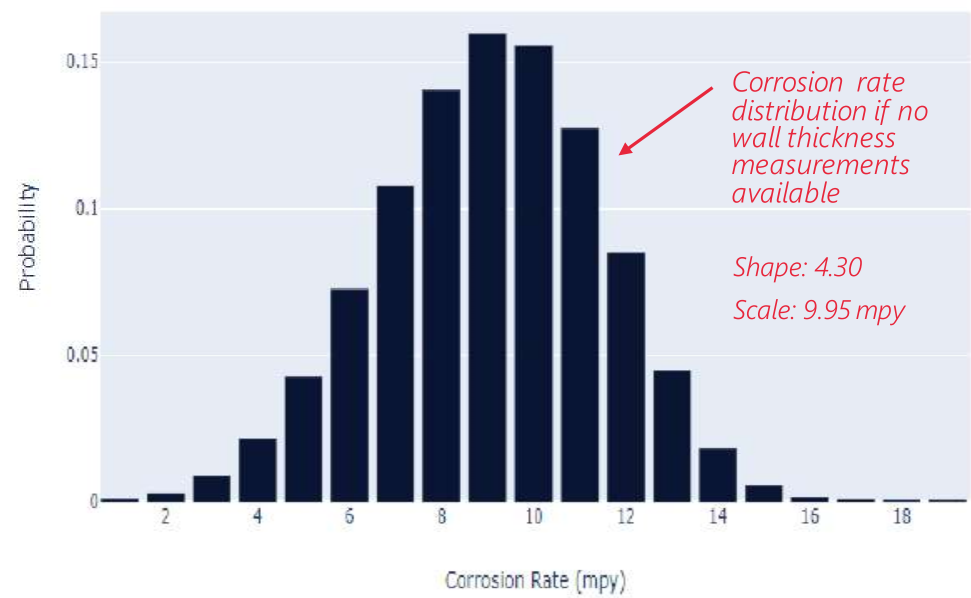
Note:
1. Driver is defined as the atmospheric condition causing the corrosion rate.
2. Interpolation may be used for intermediate values of temperature.

Corrosion Rate when no Measurements Available

If no wall thickness measurements are available, a default corrosion rate can be used:

- **Example - GRI-00/0230:**
  - Outlines a cumulative corrosion growth rate distribution for pitting on pipelines with an average of 9 mpy, and a 90th percentile of 12 mpy
  - ASME B31.8S refers to GRI-00/0230 for guidance in making assumptions about the growth rate of time dependent conditions.
- **API-581:**
  - Provides deterministic CUI rates based on climate and operating temperature
  - Ranges from 0 – 20 mpy
- **Laycock et al, 1990; Caleyo, 2008:**
  - Show that corrosion growth rates can be modeled using extreme value distributions, such as a Weibull distribution

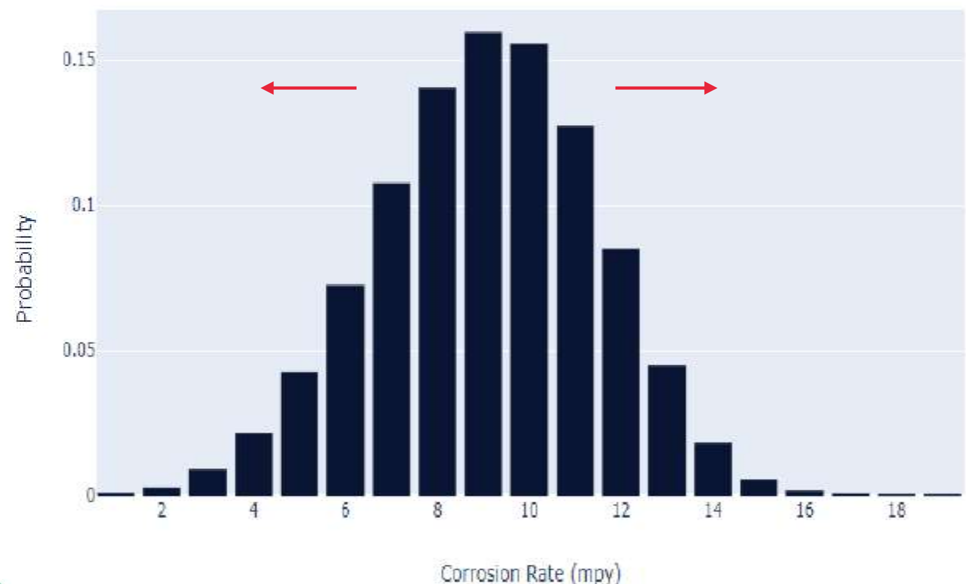
Fitting a Weibull distribution to the GRI data results in the following distribution, which has comparable growth rates to API-581:



Integral

Corrosion Rate when no Measurements Available

The default corrosion rate distribution is shifted (left or right) based on the equipment attributes and environmental & operating conditions:



		Shift (mpy)
Pollution	Low Pollution	
	Medium Pollution	
	High Pollution	

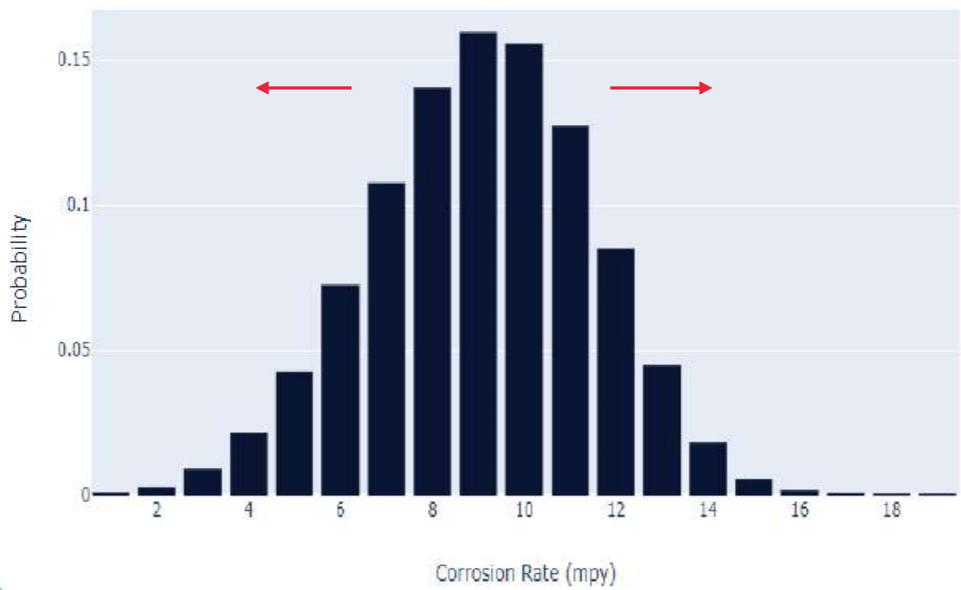
		Shift (mpy)
Actual Wetting of Surface	Low Wetness	
	Medium Wetness	
	High Wetness	

		Shift (mpy)
Equipment Type	Pipe	
	Vessel	
	Deadleg	
	Elbow	

Integral

Corrosion Rate when no Measurements Available

The default corrosion rate distribution is shifted (left or right) based on the equipment attributes and environmental & operating conditions:



		Shift (mpy)
Surface Temperature	Below -4 Celsius	
	Between -4 and 60 Celsius	
	Between 60 and 100 Celsius	
	Between 100 and 150 Celsius	
	Greater than 150 Celsius	

		Shift (mpy)
Metallurgy		

Information Required for Model Development

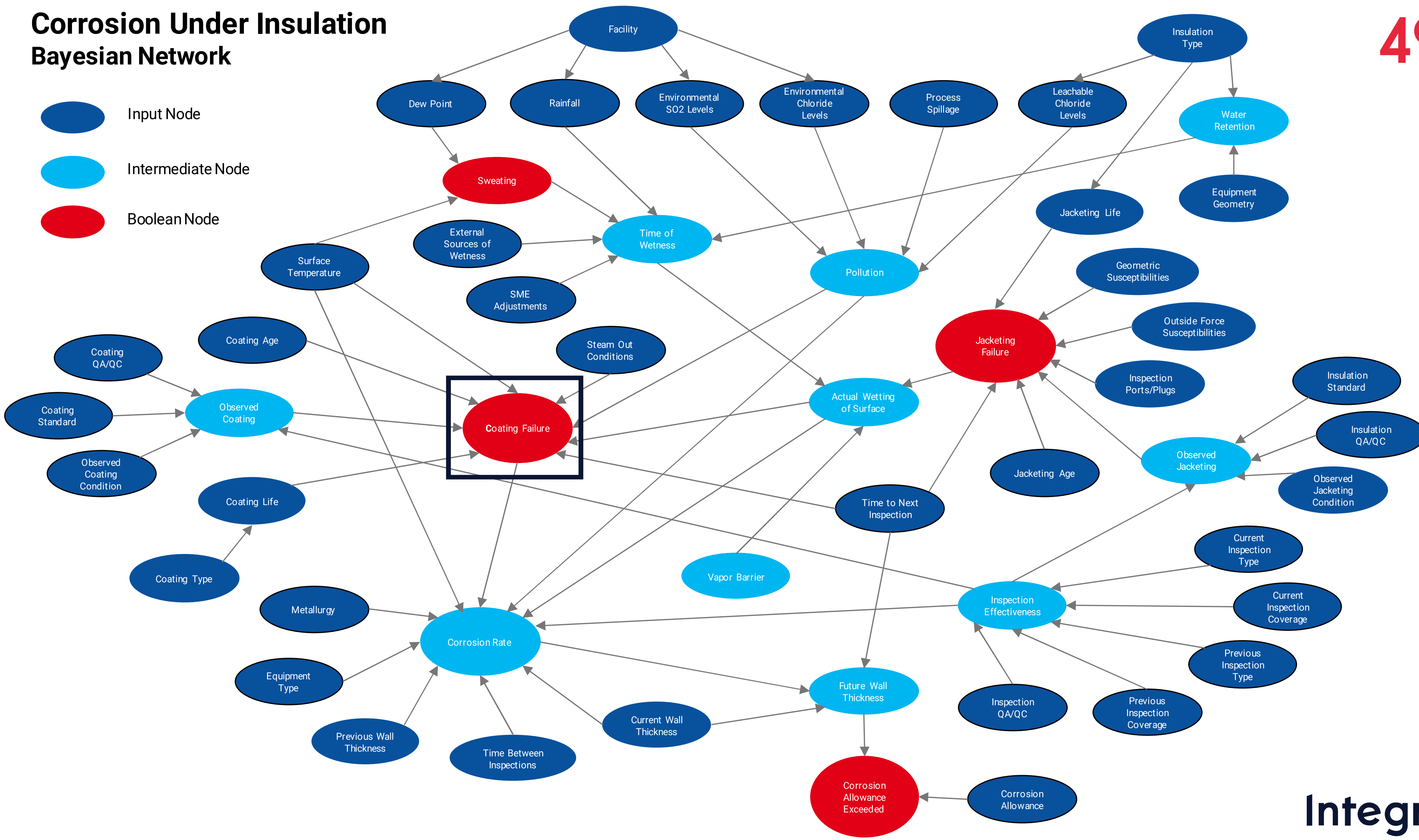
Default Corrosion Rates:

In cases where wall thickness measurements are not available, a 'default' corrosion rate will be used depending on the type of equipment

Equipment Type	Distribution Type	Distribution Param 1 - Name	Distribution Param 1 - Value	Distribution Param 2 - Name	Distribution Param 2 - Value
Pipe	Weibull	Shape	4.30 mpy	Scale	9.95 mpy
Vessel	Weibull	Shape	4.30 mpy	Scale	9.95 mpy
Deadleg	Weibull	Shape	4.30 mpy	Scale	9.95 mpy
Elbow	Weibull	Shape	4.30 mpy	Scale	9.95 mpy
starship	*Normal*	*Mean*	*4 mpy*	*Std*	*2 mpy*
jetpack	*Weibull*	*Shape*	*4.3*	*Scale*	*10 mpy*

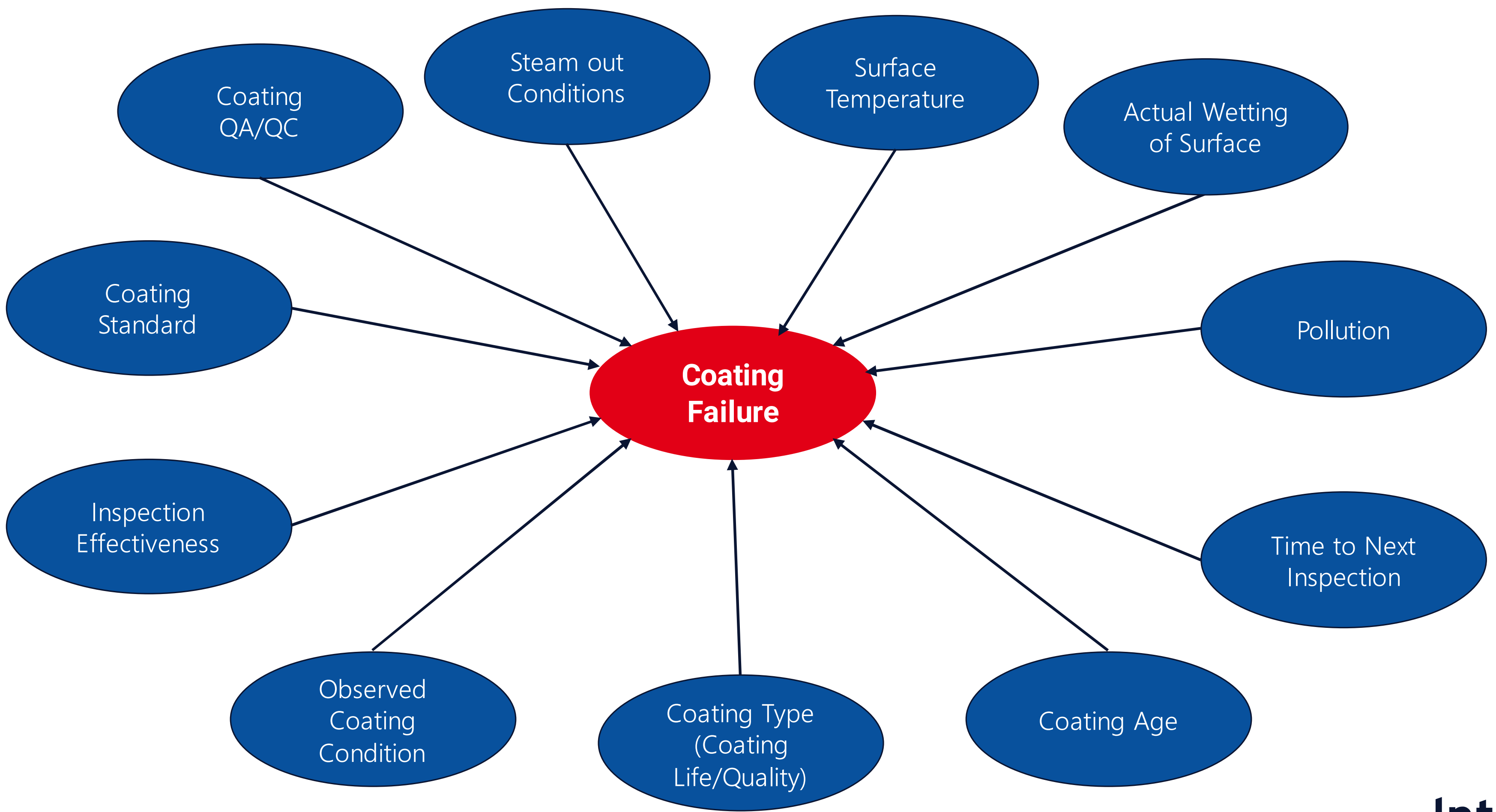

Coating Failure CPT

Corrosion Under Insulation
Bayesian Network

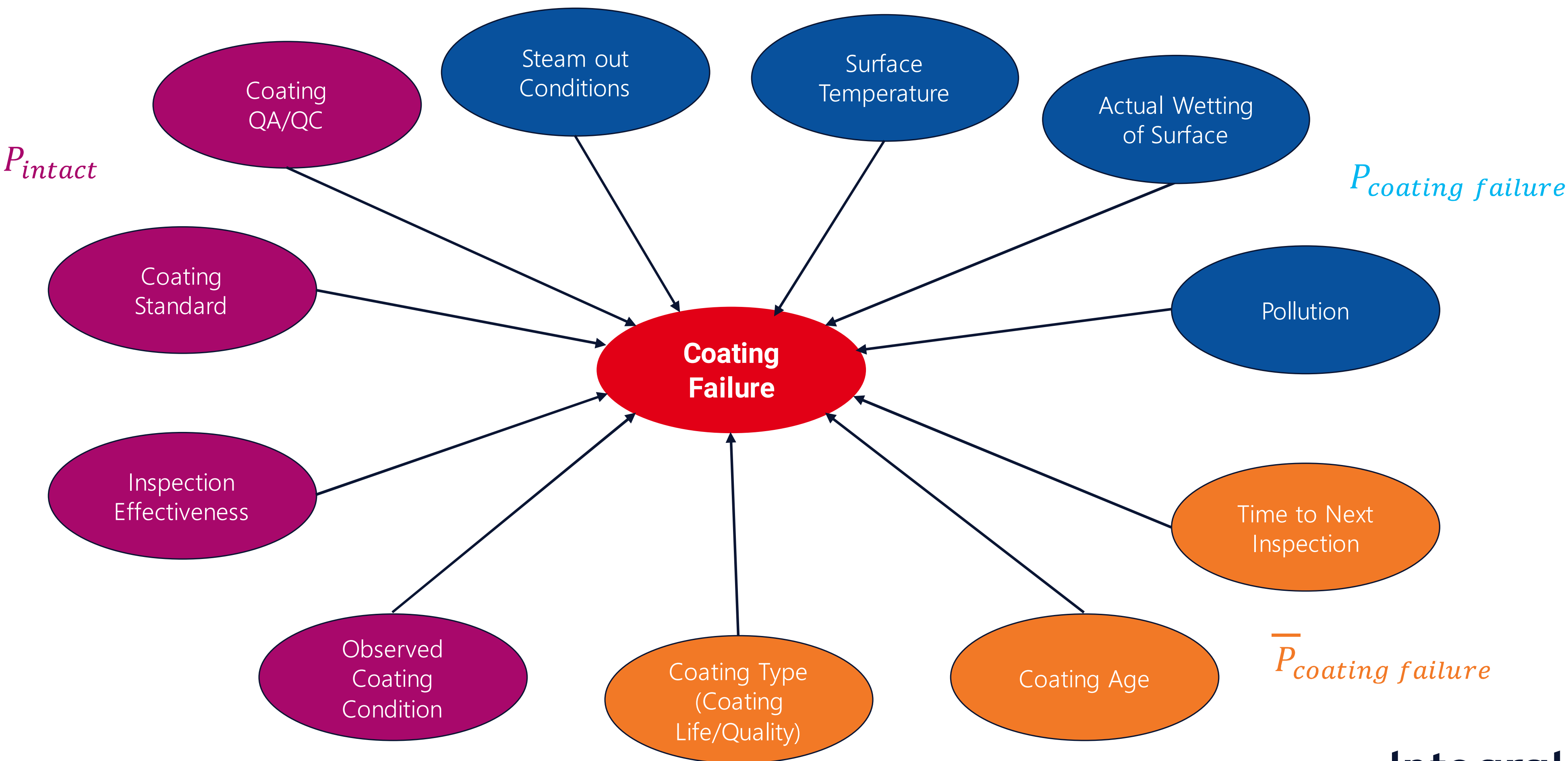


Integral

Coating Failure CPT



Coating Failure CPT



Integral

Coating Failure CPT

Goal: Estimate the probability that the coating will not be intact at the next inspection

CPT Logic:

Was the coating intact at the last inspection?

P_{intact}

Yes

Calculate nominal probability that the coating will not be intact at the next inspection

$\overline{P}_{coating\ failure}$

Adjust nominal probability based on environmental and operational factors

$P_{coating\ failure}$

No

$P_{coating\ failure} = 1.0$

Coating Failure CPT

1) Was the coating intact at the last inspection?

$$P_{intact} = \left\{ \begin{array}{ll} 0, & observed\ coating\ not\ intact \\ 1, & observed\ coating\ intact \end{array} \right\} \times likelihood\ that\ observation\ is\ correct$$

Example) When the best inspection practices are performed, the probability that the observed coating condition is correct is 0.9:

$$P_{intact} = \left\{ \begin{array}{ll} 0, & observed\ coating\ not\ intact \\ 1, & observed\ coating\ intact \end{array} \right\} \times 0.9 = \left\{ \begin{array}{l} 0.0 \\ 0.9 \end{array} \right\}$$

Integral

Coating Failure CPT

1) Was the coating intact at the last inspection?

$$P_{intact} = \left\{ \begin{array}{ll} 0, & observed\ coating\ not\ intact \\ 1, & observed\ coating\ intact \end{array} \right\} \times \underbrace{likelihood\ that\ observation\ is\ correct}_{= F_{inspection} \times F_{standards} \times F_{QA/QC}}$$

Uncertainty factors

Coating Failure CPT

1) Was the coating intact at the last inspection?

$$P_{intact} = \begin{Bmatrix} 0, & observed\ coating\ not\ intact \\ 1, & observed\ coating\ intact \end{Bmatrix} \times F_{inspection} \times F_{standards} \times F_{QA/QC}$$

Coating QA/QC		Factor
	Yes	
	No	

Coating Standard		Factor
	No Standard Used	
	Site-Specific	
	CINI	

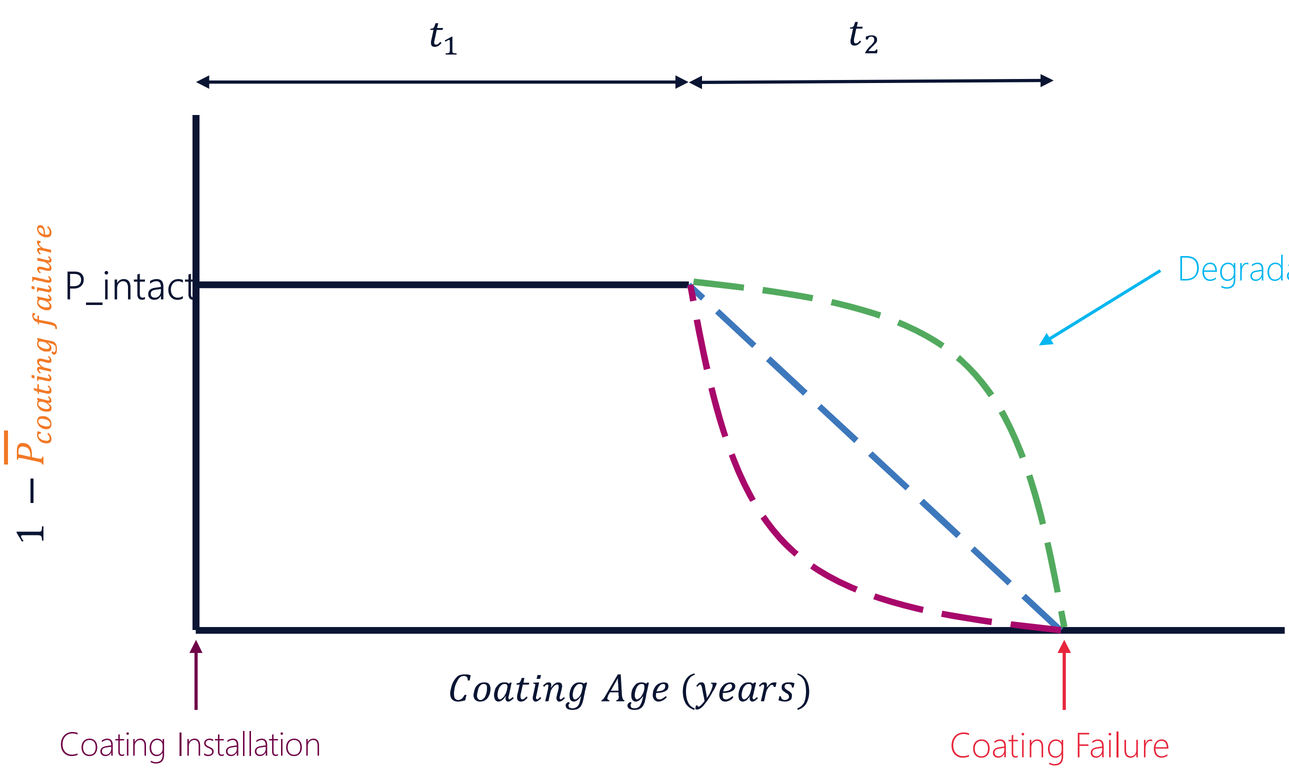
Inspection Effectiveness		Factor
	Acceptable	
	Effective	
	Very Effective	
	No Inspection	

Spreadsheet

Integral

Coating Failure CPT

2) Calculate the nominal probability that the coating will not be intact at the next inspection

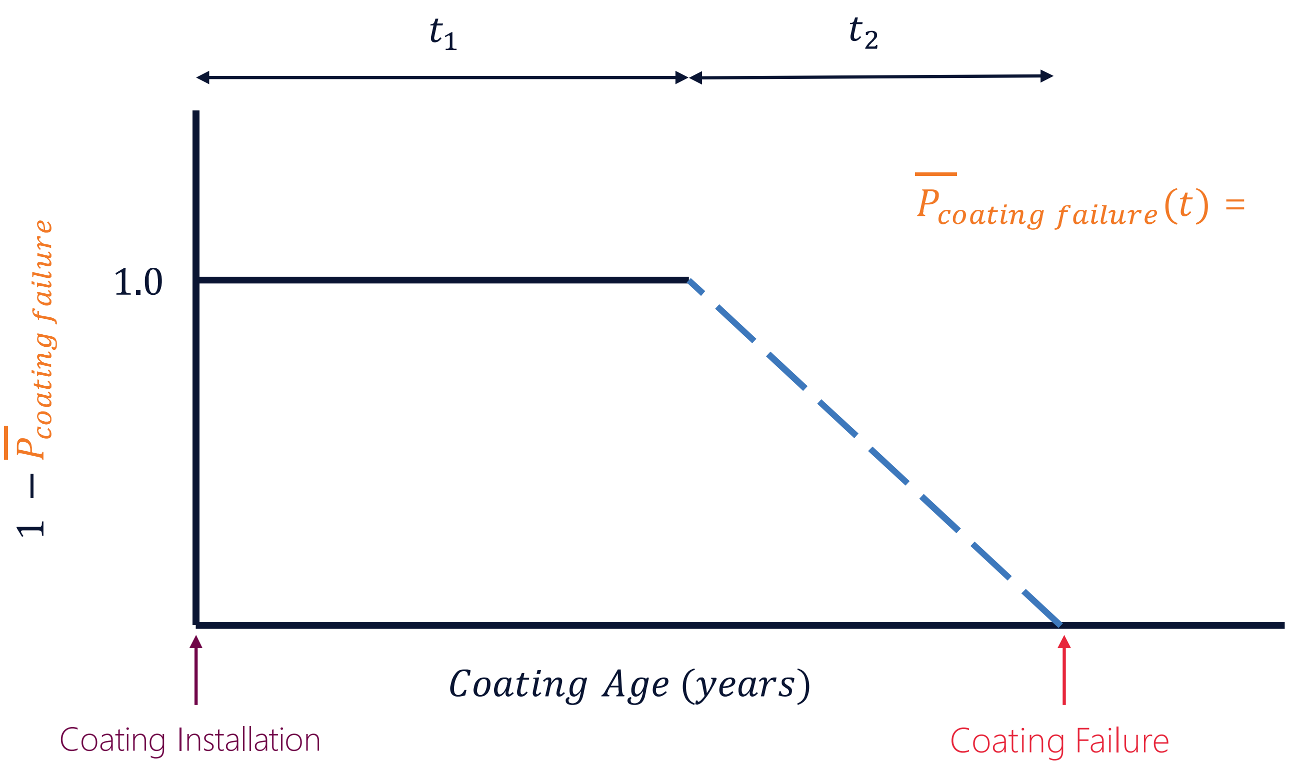


The nominal probability is a function of the coating age at the next inspection

Integral

Coating Failure CPT

2) Calculate the nominal probability that the coating will not be intact at the next inspection

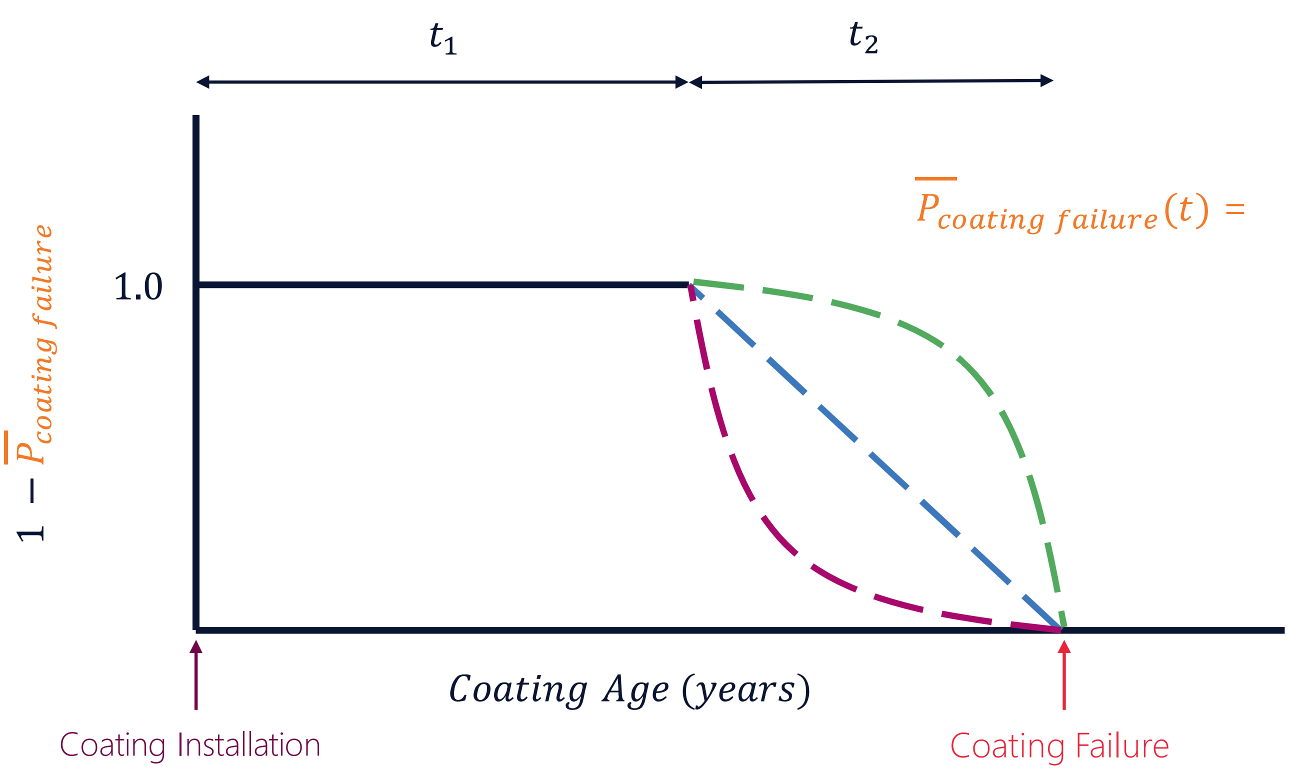


$$\overline{P}_{coating\ failure}(t) = \begin{cases} 0, & t < t_1 \\ \dfrac{t - t_1}{t_2}, & t_1 < t < (t_1 + t_2) \\ 1, & t > (t_1 + t_2) \end{cases}$$

Integral

Coating Failure CPT

2) Calculate the nominal probability that the coating will not be intact at the next inspection



$$\overline{P}_{coating\ failure}(t) = \begin{cases} 0, & t < t_1 \\ d(t), & t_1 < t < (t_1 + t_2) \\ 1, & t > (t_1 + t_2) \end{cases}$$

Integral

Coating Failure CPT

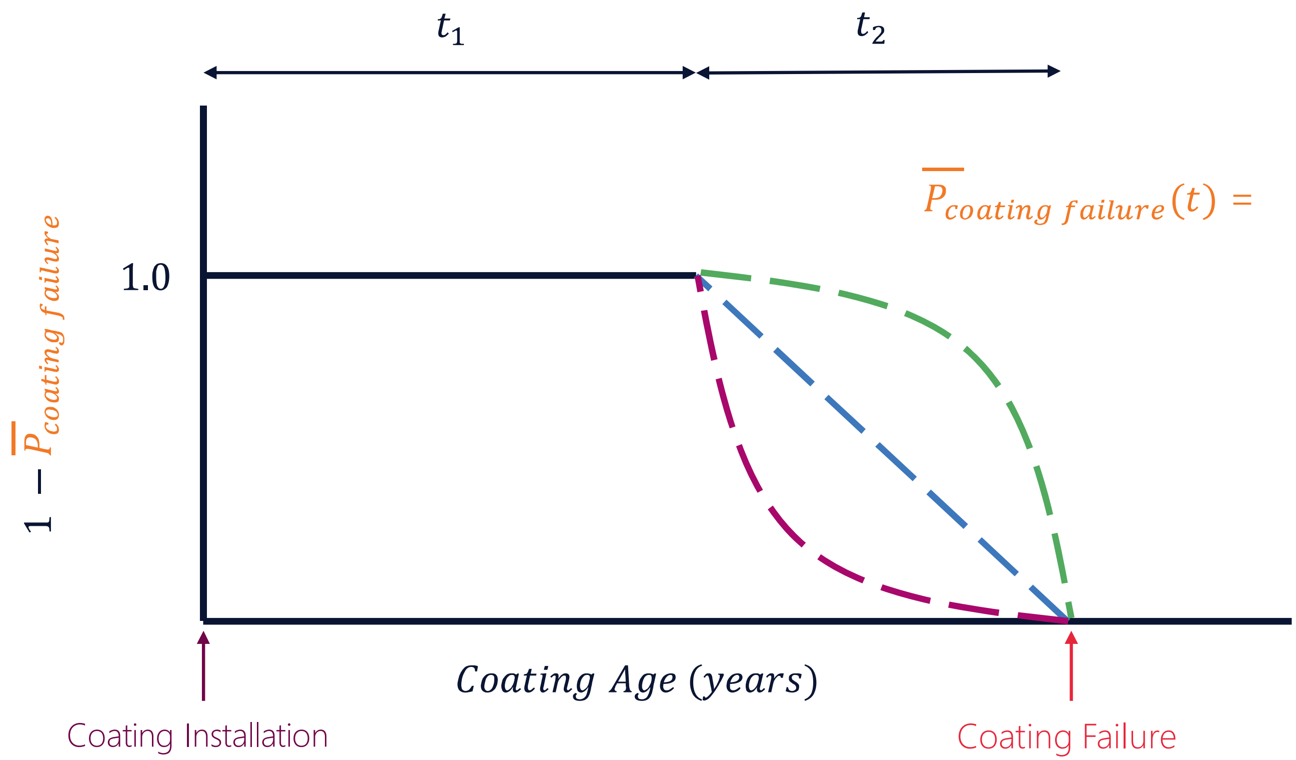
General Coating data:

Coating Type	Time Before Degradation, t_1 (Years)	Degradation Time, t_2 (Years)	Degradation Over Time, $d(t)$ (linear, exponential decay, etc.)	Time of wetness effect
Bare	0	0		1, 1, 1
Immersion Grade (rec)	8 +/- 2	7 +/- 2	linear	1, 0.9, 0.8
Non-Immersion	2 +/- 2	2 +/- 2	linear	1, 0.8, 0.7
TSA	10 +/- 2	15 +/- 2	linear	1, 0.95, 0.9
Lead paint?				
Coal Tar Epoxy?				
Immersion (not rec)?	5 +/- 3	5 +/- 3	linear	1, 0.9, 0.8
kryptonite	*10 years*	*5 years*	*Degrades linearly over time*	

egral

Coating Failure CPT

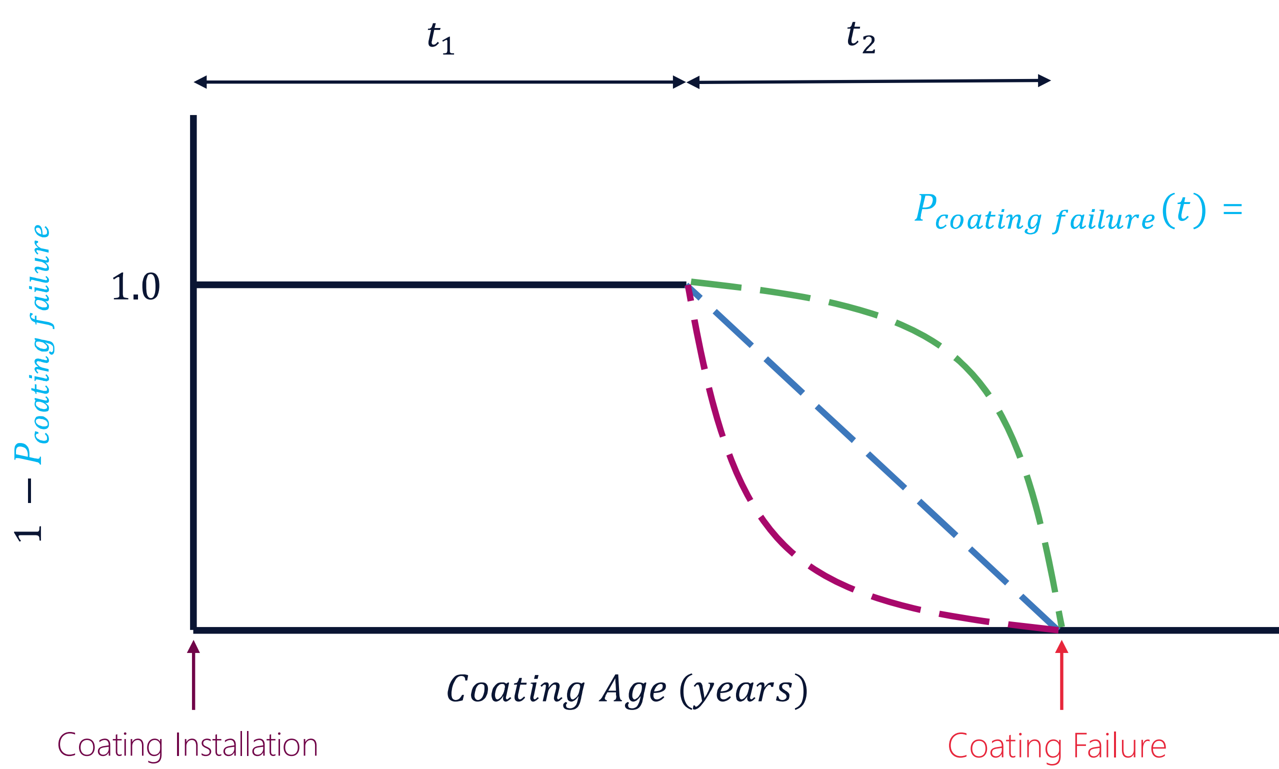
3) Adjust nominal probability based on environmental and operational factors



$$\overline{P}_{coating\ failure}(t) = \begin{cases} 0, & t < t_1 \\ d(t), & t_1 < t < (t_1 + t_2) \\ 1, & t > (t_1 + t_2) \end{cases}$$

Coating Failure CPT

3) Adjust nominal probability based on environmental and operational factors



$$P_{coating\ failure}(t) = \begin{cases} 0, & t < \frac{t_1}{F} \\ \min(1, d(t) \times F), & t > \frac{t_1}{F} \end{cases}$$

Integral

Coating Failure CPT

3) Adjust nominal probability based on environmental and operational factors

$$P_{coating\ failure}(t) = \begin{cases} 0, & t < \frac{t_1}{F} \\ \min(1, d(t) \times F), & t > \frac{t_1}{F} \end{cases}$$

Spreadsheet

$$F = F_{surface\ temp} \times F_{pollution} \times F_{wetting} \times F_{steam\ out}$$

Coating Failure CPT

Degradation factors:

$$F = F_{surface\ temp} \times F_{pollution} \times F_{wetting} \times F_{steam\ out}$$

Steam out Conditions	Factor
No	
Yes	

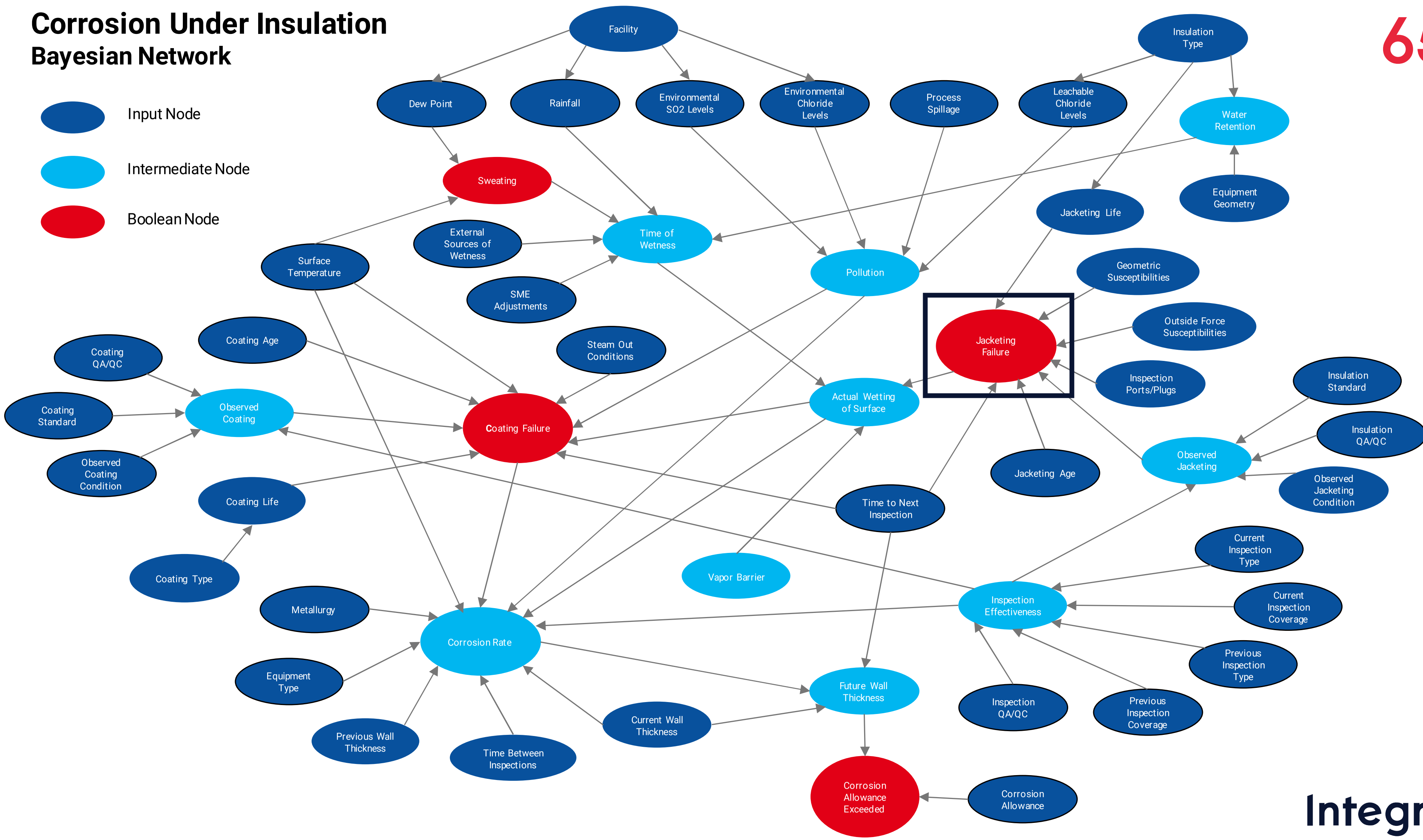
Actual Wetting of Surface	Factor
Low Wetness	
Medium Wetness	
High Wetness	

Surface Temperature	Factor
Below -4 Celsius	
Between -4 and 60 Celsius	
Between 60 and 100 Celsius	
Between 100 and 150 Celsius	
Greater than 150 Celsius	

Pollution	Factor
Low Pollution	
Medium Pollution	
High Pollution	

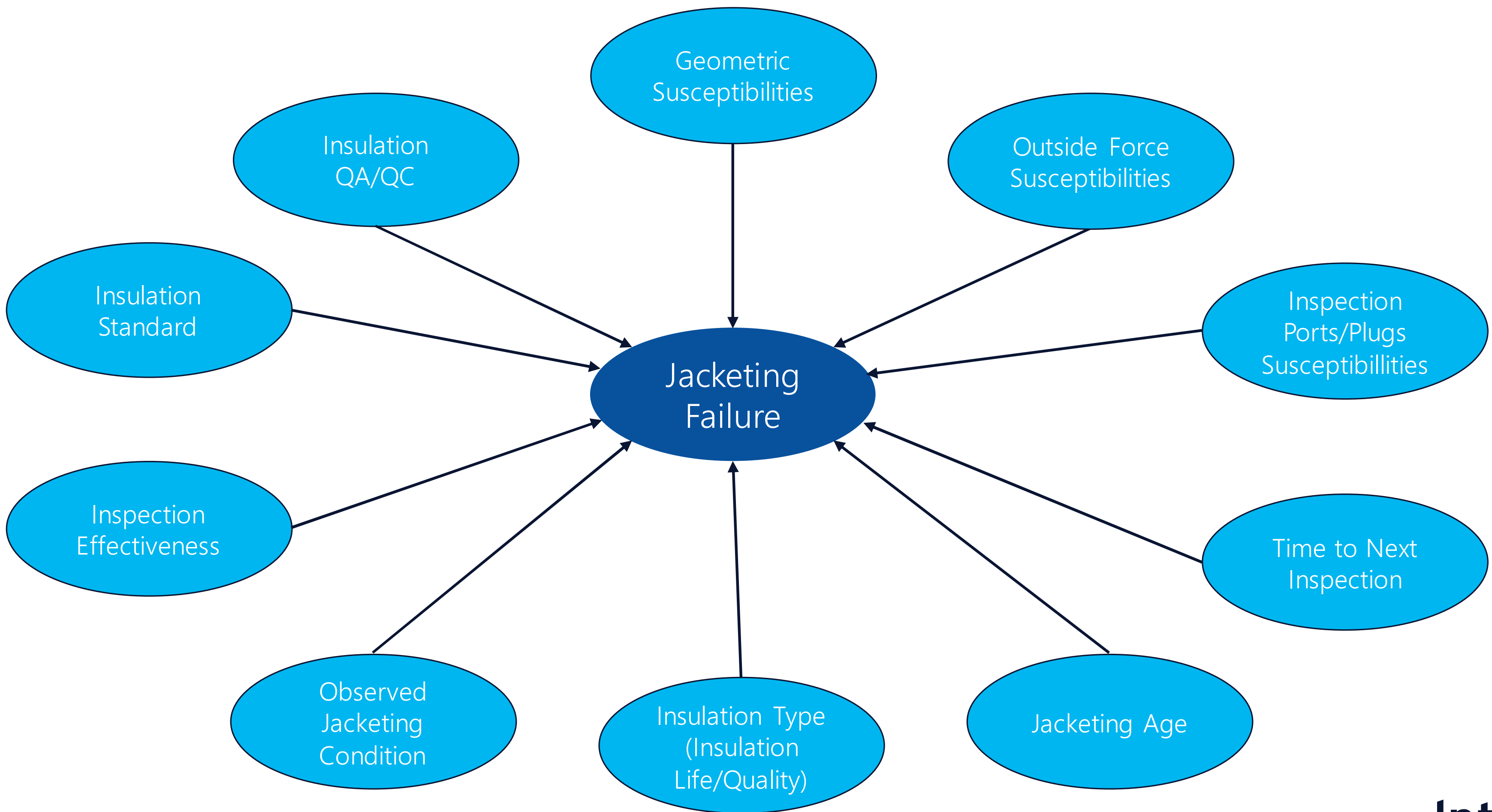
Jacketing Failure CPT

Corrosion Under Insulation
Bayesian Network



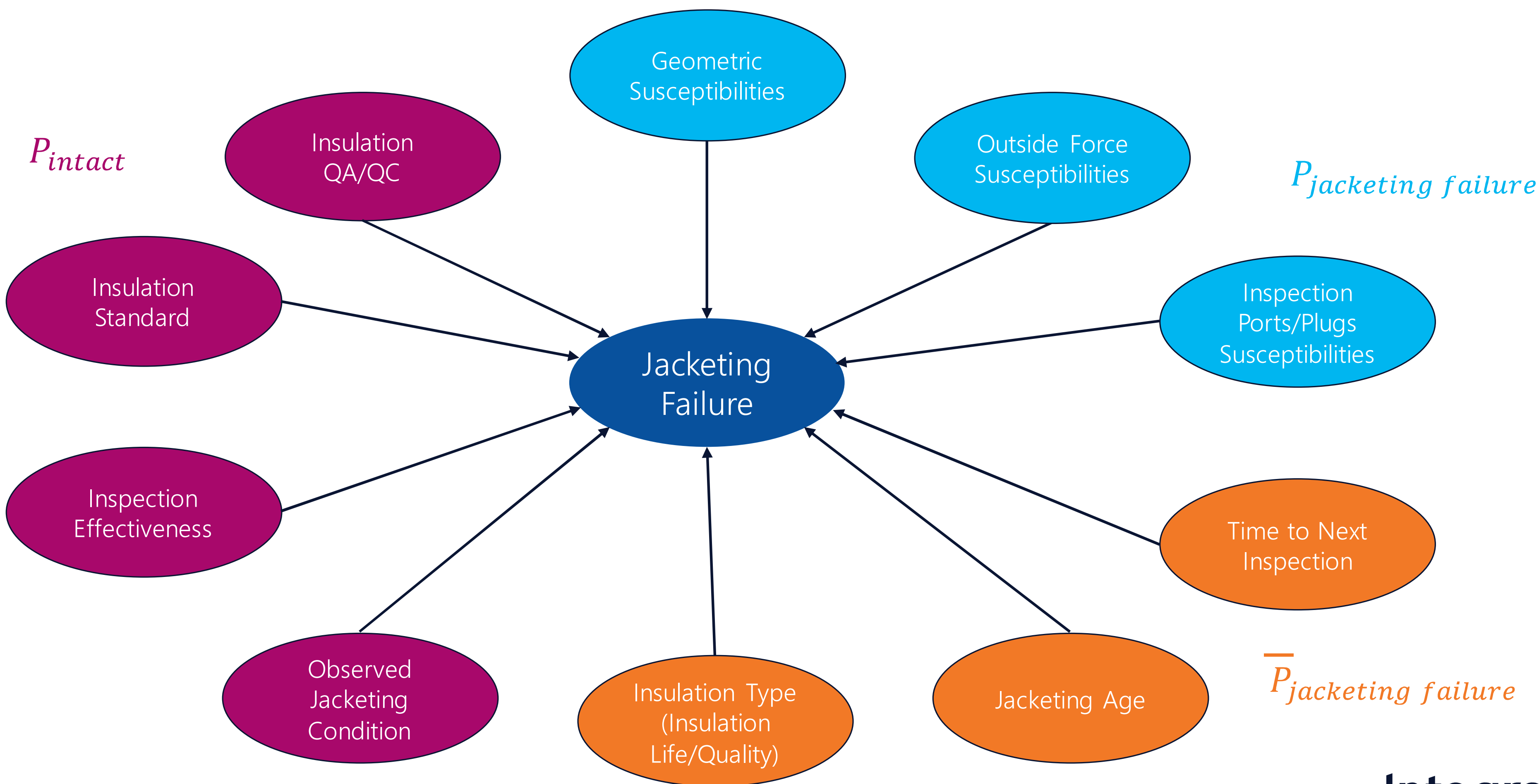
Integral

Jacketing Failure CPT



Integral

Jacketing Failure CPT



Integral

Jacketing Failure CPT

Goal: Estimate the probability that the jacketing will not be intact at the next inspection

CPT Logic:

Was the jacketing intact at the installation date?

P_{intact} (based on QA/QC,

Yes

Calculate nominal probability that the jacketing will not be intact at the next inspection

$\overline{P}_{jacketing\ failure}$

Adjust nominal probability based on environmental and operational factors

$P_{jacketing\ failure}$

Jacketing Failure CPT

1) Was the jacketing intact at the last inspection?

$$P_{intact} = \left\{ \begin{array}{ll} 0, & observed\ jacketing\ not\ intact \\ 1, & observed\ jacketing\ intact \end{array} \right\} \times likelihood\ that\ observation\ is\ correct$$

Example) When the best inspection practices are performed, the probability that the observed jacketing condition is correct is 0.9:

$$P_{intact} = \left\{ \begin{array}{ll} 0, & observed\ jacketing\ not\ intact \\ 1, & observed\ jacketing\ intact \end{array} \right\} \times 0.9 = \left\{ \begin{array}{c} 0.0 \\ 0.9 \end{array} \right\}$$

Jacketing Failure CPT

1) Was the jacketing intact at the last inspection?

$$P_{intact} = \left\{ \begin{array}{ll} 0, & observed\ jacketing\ not\ intact \\ 1, & observed\ jacketing\ intact \end{array} \right\} \times \underbrace{likelihood\ that\ observation\ is\ correct}_{= F_{inspection} \times F_{standards} \times F_{QA/QC}}$$

Uncertainty factors

Integral

Jacketing Failure CPT

1) Was the jacketing intact at the last inspection?

$$P_{intact} = \left\{ \begin{array}{ll} 0, & observed\ jacketing\ not\ intact \\ 1, & observed\ jacketing\ intact \end{array} \right\} \times F_{inspection} \times F_{standards} \times F_{QA/QC}$$

Jacketing QA/QC		Factor
	Yes	
	No	

Jacketing Standard		Factor

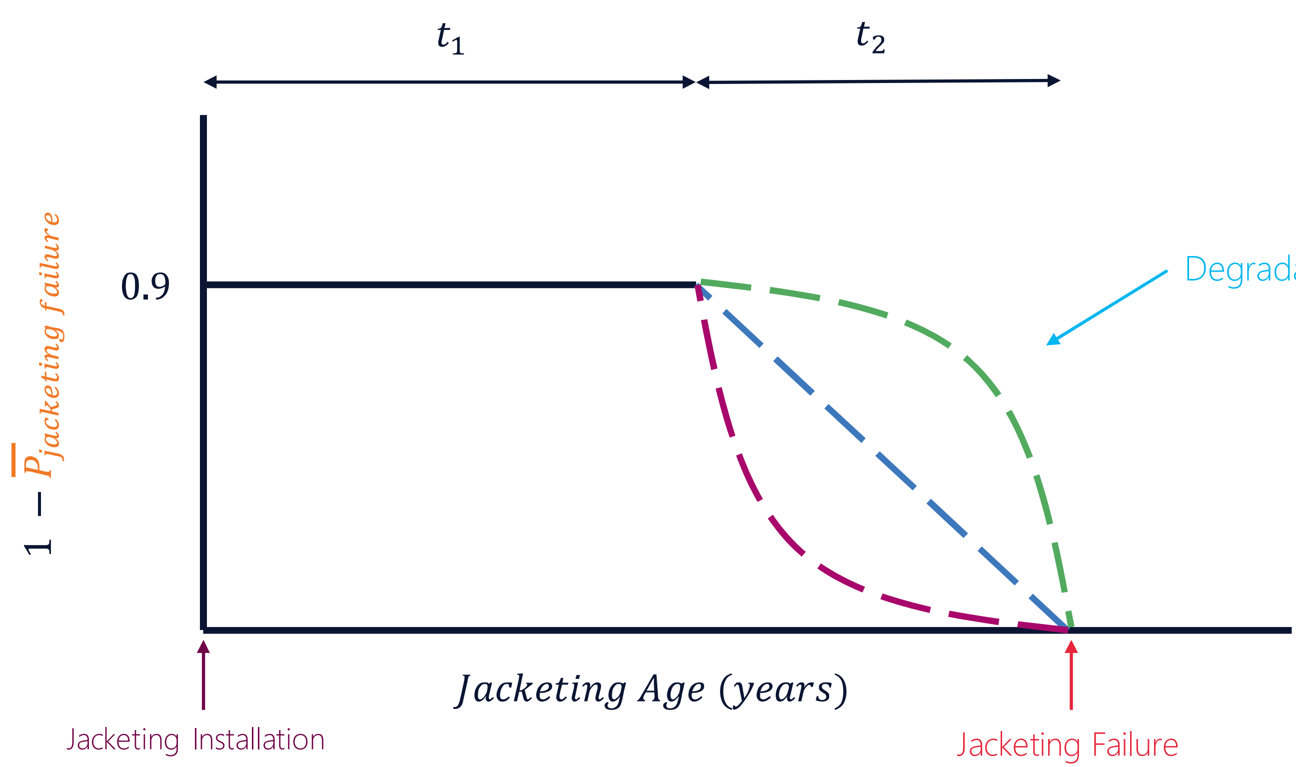
Inspection Effectiveness		Factor
	Acceptable	
	Effective	
	Very Effective	
	No Inspection	

Spreadsheet

Integral

Jacketing Failure CPT

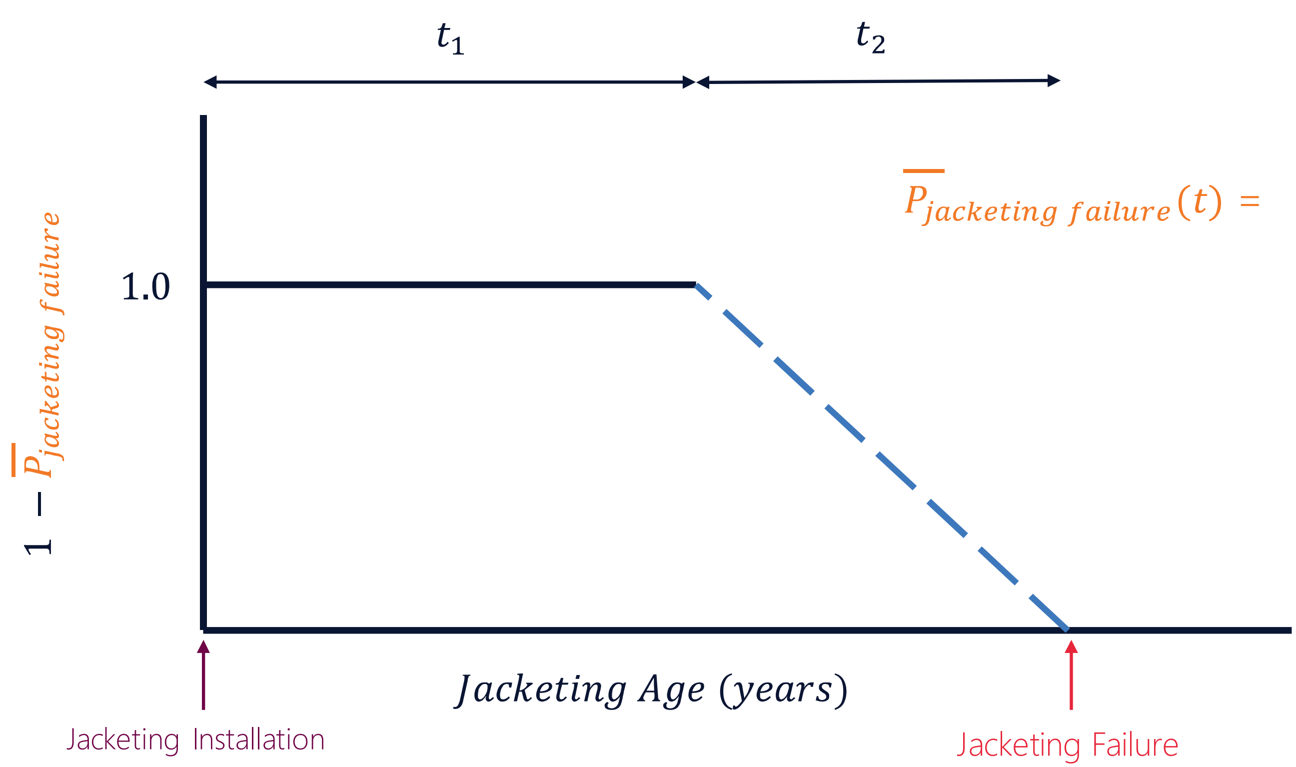
2) Calculate the nominal probability that the jacketing will not be intact at the next inspection



The nominal probability is a function of the jacketing age at the next inspection

Jacketing Failure CPT

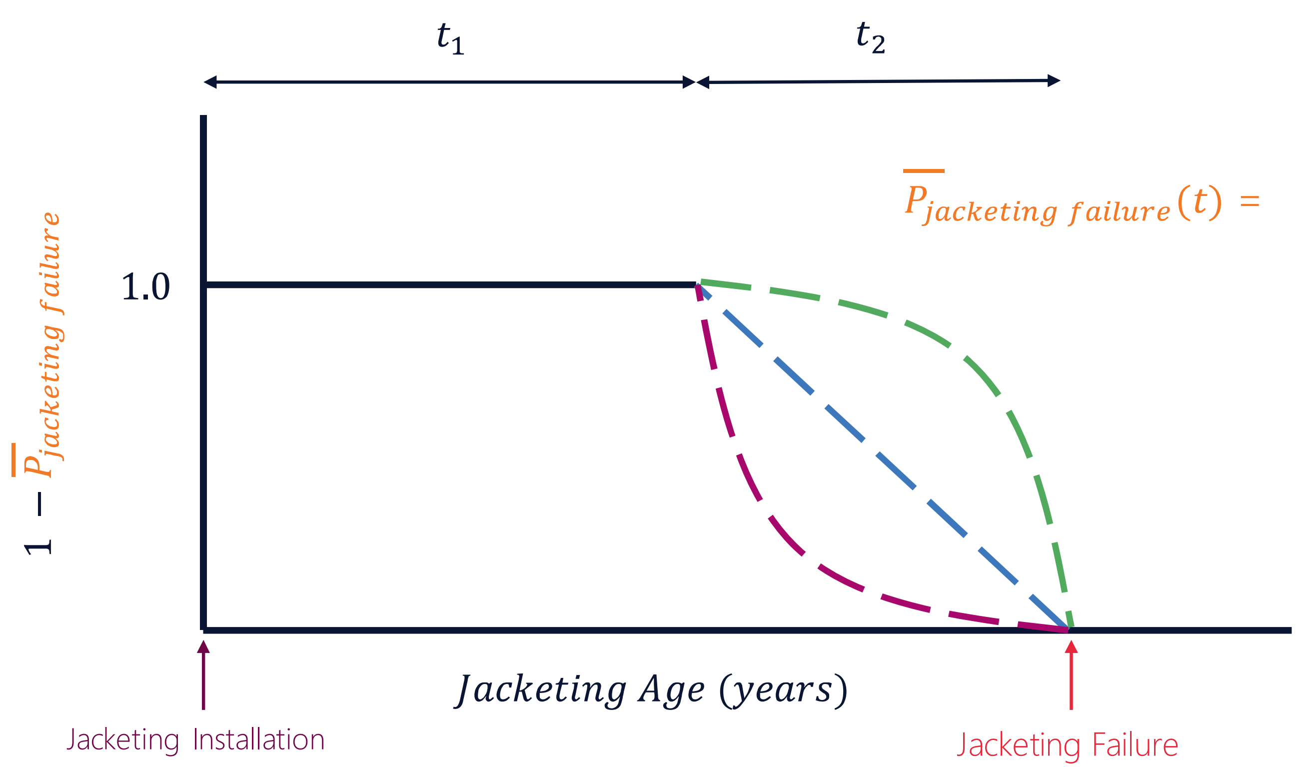
2) Calculate the nominal probability that the jacketing will not be intact at the next inspection



$$\overline{P}_{jacketing\ failure}(t) = \begin{cases} 0, & t < t_1 \\ \dfrac{t - t_1}{t_2}, & t_1 < t < (t_1 + t_2) \\ 1, & t > (t_1 + t_2) \end{cases}$$

Jacketing Failure CPT

2) Calculate the nominal probability that the jacketing will not be intact at the next inspection



$$\overline{P}_{jacketing\ failure}(t) = \begin{cases} 0, & t < t_1 \\ d(t), & t_1 < t < (t_1 + t_2) \\ 1, & t > (t_1 + t_2) \end{cases}$$

Integral

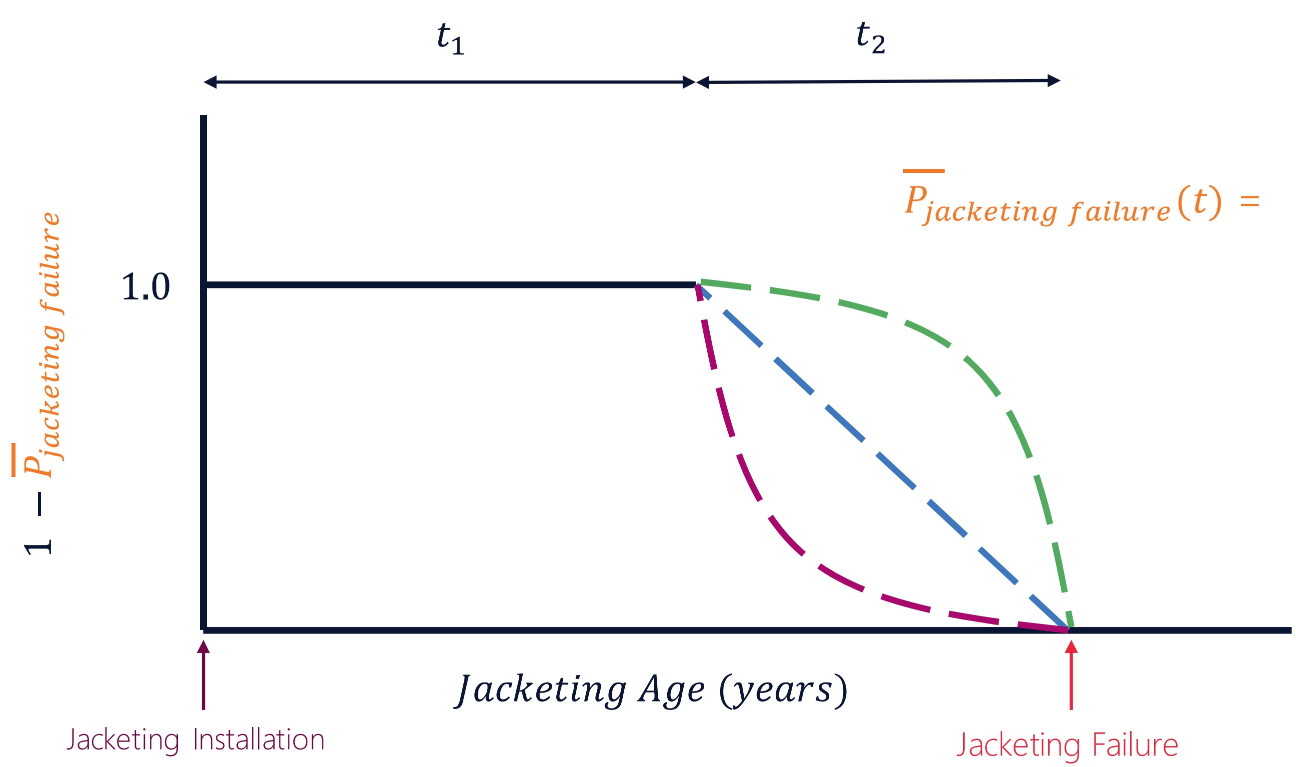
Jacketing Failure CPT

General Insulation data:

Jacketing Type	Time Before Degradation, t_1 (Years)	Degradation Time, t_2 (rate of degradation)	Degradation Over Time, $d(t)$ (linear, exponential decay, etc.)
Galvanized clad	0	1/15	linear
Aluminium	0	1/30	Linear
Stainless steel	0	1/30	Linear
FRP Jacketing	0	1/30	Linear
Venture Clad? (experimental)			
kryptonite	*10 years*	*5 years*	*Degrades linearly over time*

Jacketing Failure CPT

3) Adjust nominal probability based on environmental and operational factors

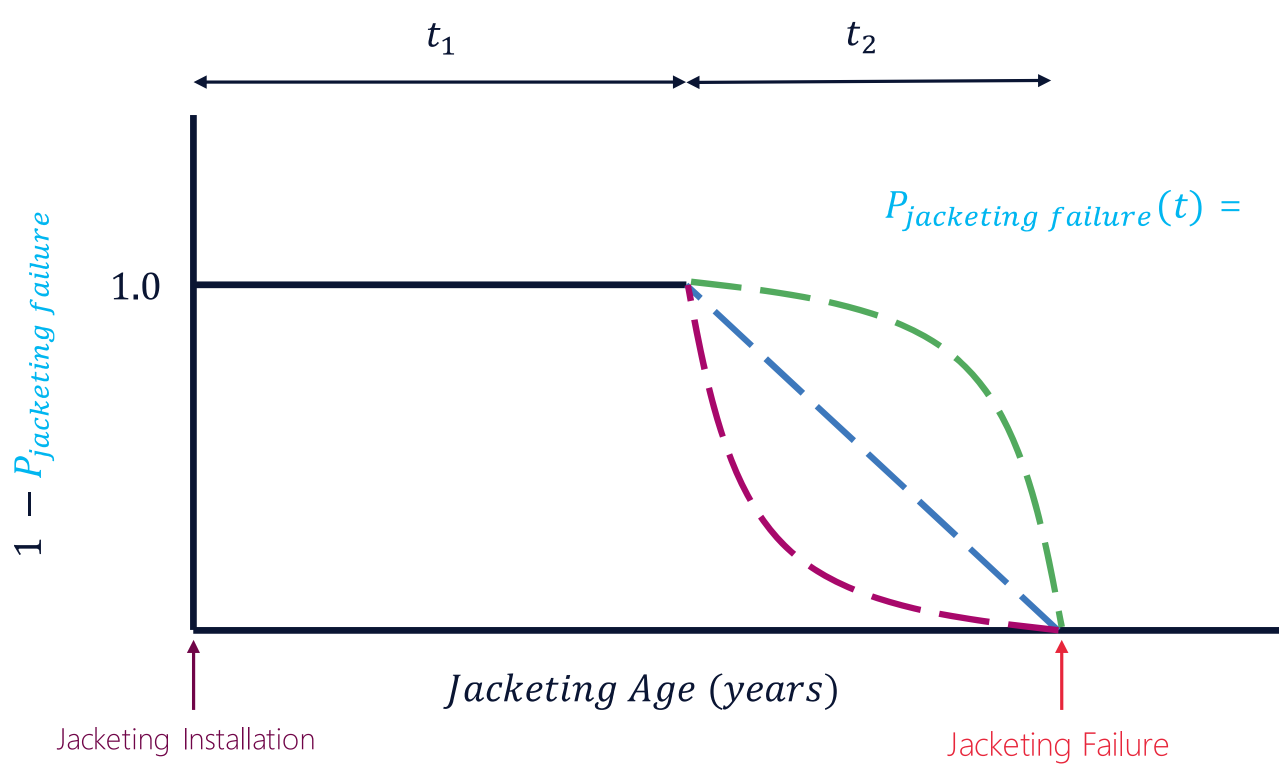


$$\overline{P}_{jacketing\ failure}(t) = \begin{cases} 0, & t < t_1 \\ d(t), & t_1 < t < (t_1 + t_2) \\ 1, & t > (t_1 + t_2) \end{cases}$$

Integral

Jacketing Failure CPT

3) Adjust nominal probability based on environmental and operational factors



$$P_{jacketing\ failure}(t) = \begin{cases} 0, & t < \frac{t_1}{F} \\ \min(1, d(t) \times F), & t > \frac{t_1}{F} \end{cases}$$

Integral

Jacketing Failure CPT

3) Adjust nominal probability based on environmental and operational factors

$$P_{jacketing\ failure}(t) = \begin{cases} 0, & t < \frac{t_1}{F} \\ \min(1, d(t) \times F), & t > \frac{t_1}{F} \end{cases}$$

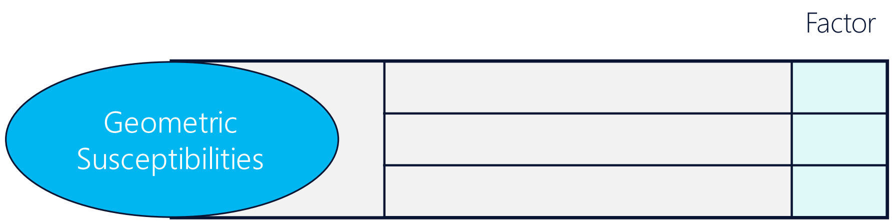
Spreadsheet

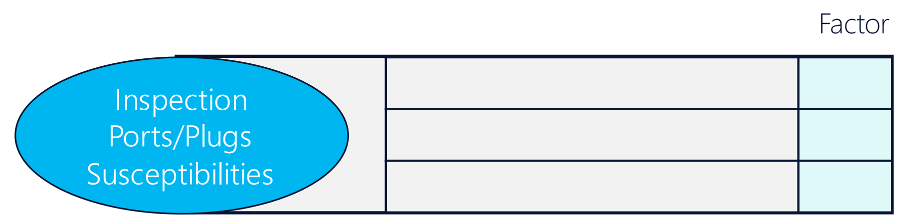
$$F = F_{geometric} \times F_{outside\ force} \times F_{insulation\ ports/plugs}$$

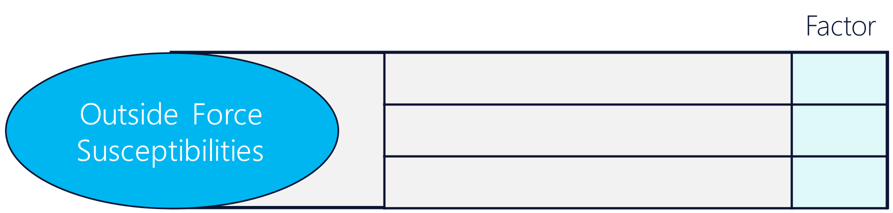
Jacketing Failure CPT

Degradation factors:

$$F = F_{geometric} \times F_{outside\ force} \times F_{insulation\ ports/plugs}$$







Spreadsheet

Insulation Failure CPT

General Insulation data:

Insulation Type	Time Before Degradation, t_1 (Years)	Degradation Time, t_2 (Years)	Degradation Over Time, $d(t)$ (linear, exponential decay, etc.)
Aerogel Blanket			
Expanded Perlite			
Cellular Glass			
Mineral Wool			
Calcium Silicate			
Fiberglass			
Ceramic Fiber Blanket			
Foam Polyolefin or Elastomeric Foam			
PUR or PIR Foam			
Cryogel Z			
Asbestos			
kryptonite	*10 years*	*5 years*	*Degrades linearly over time*

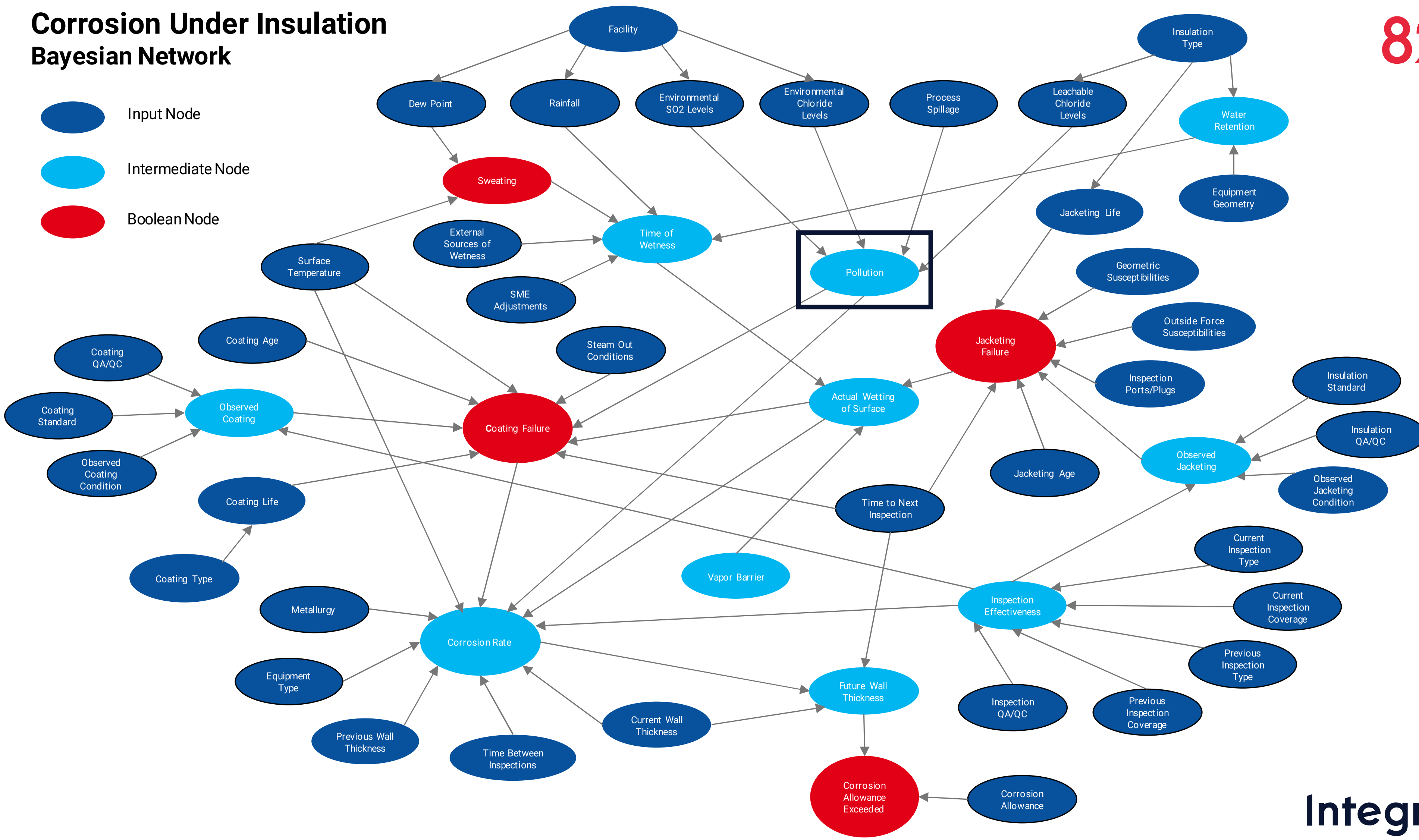

Pollution CPT

Corrosion Under Insulation
Bayesian Network

Input Node

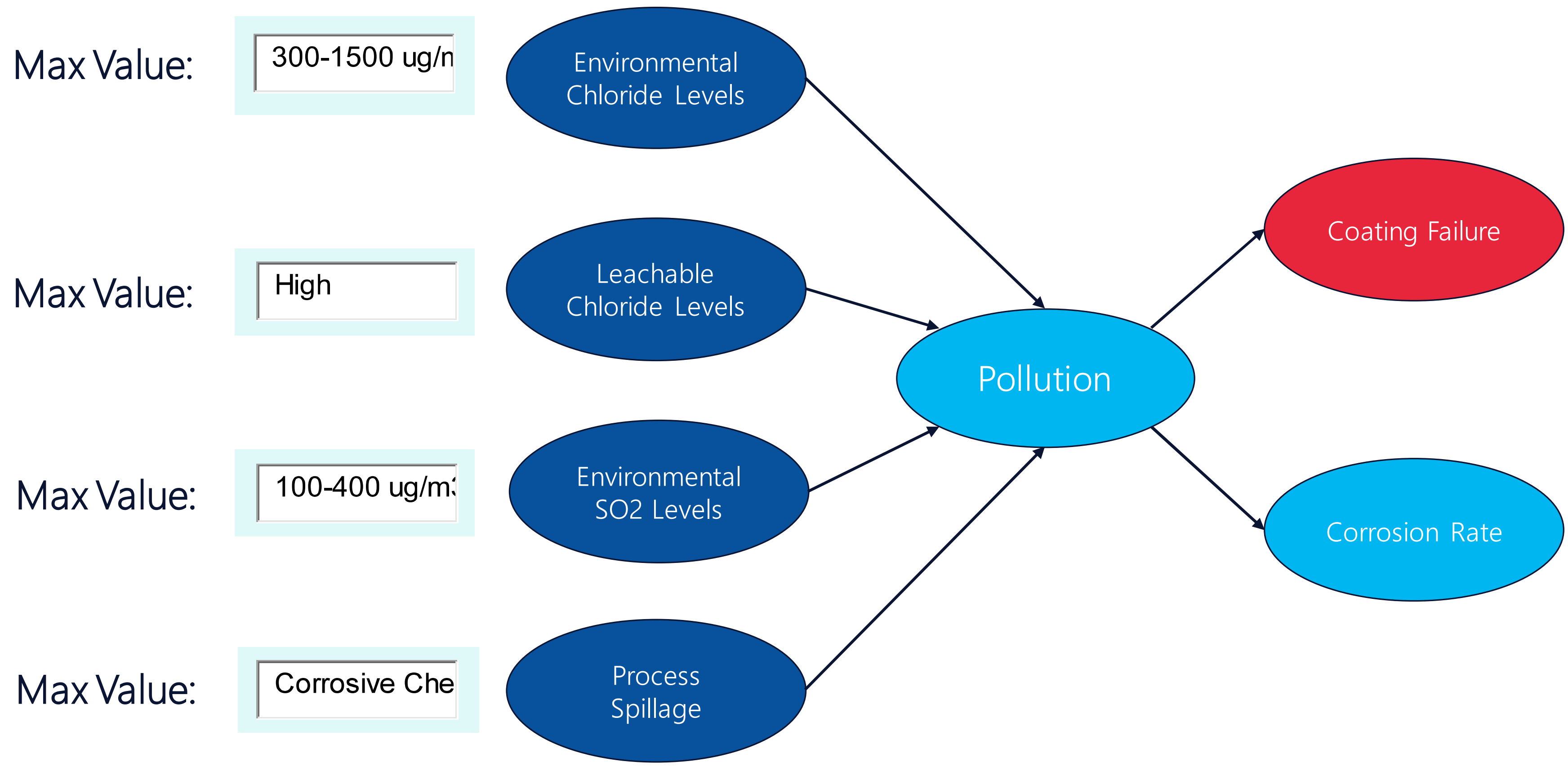
Intermediate Node

Boolean Node



Integral

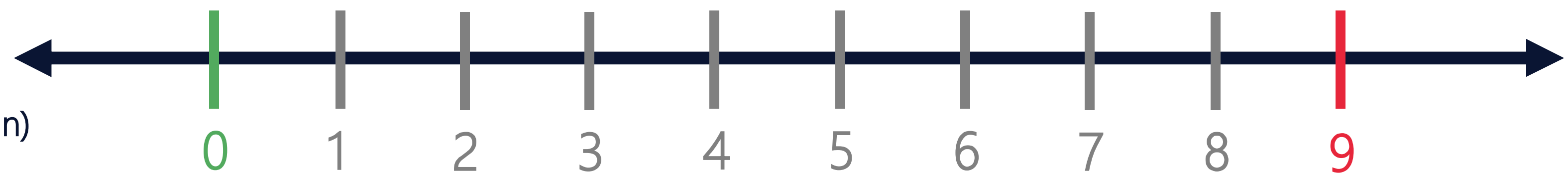
Pollution CPT



Integral

Pollution CPT

Relative Weight:
(coating degradation)



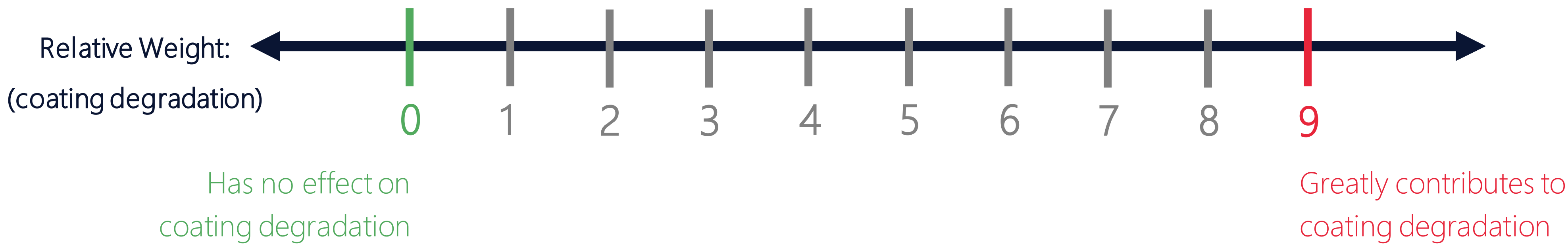
Has no effect on coating degradation

Greatly contributes to coating degradation

	Environmental Chloride Levels	Leachable Chloride Levels	Environmental SO2 Levels	Process Spillage
Max Value:				
Relative Weight for coating degradation:				

Integral

Pollution CPT



	Environmental Chloride Levels	Leachable Chloride Levels	Environmental SO2 Levels	Process Spillage
Max Value:	300-1500 ug/m3	High	100-400 ug/m3	Corrosive Chemical
Relative Weight for coating degradation:	5	5	3	7

Integral

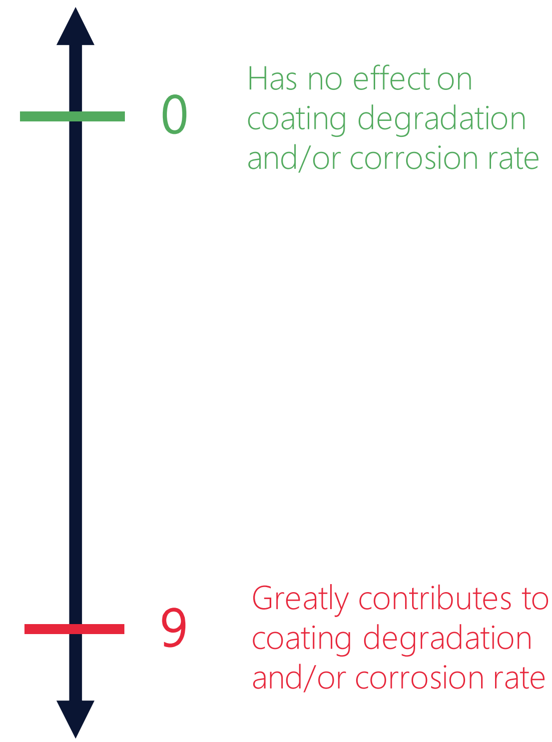
Pollution CPT

	Environmental Chloride Levels	Leachable Chloride Levels	Environmental SO2 Levels	Process Spillage
Max Value:	300 ug/m3			
Relative Weight for corrosion rate:	5			

Integral

Pollution CPT

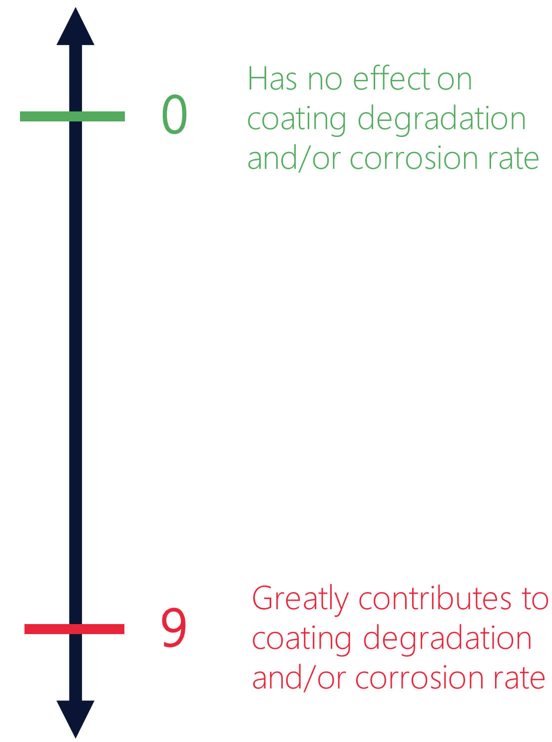
	Environmental Chloride Levels	Relative Weight for Coating Failure	Relative Weight for Corrosion Rate
Min Bin:	<50 ug/m3	0	0
	50-100 ug/m3	2	2
	100-300 ug/m3	3	3
Max Bin:	300-1500 ug/m3	5	5



Integral

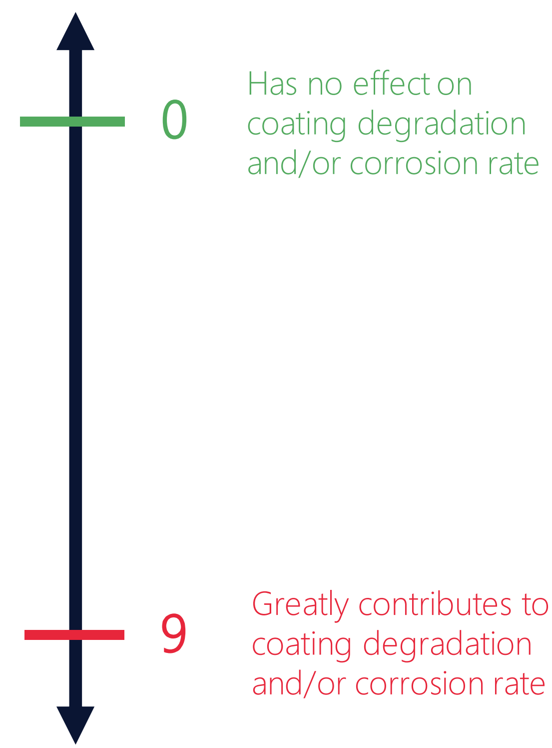
Pollution CPT

	Leachable Chloride Levels	Relative Weight for Coating Failure	Relative Weight for Corrosion Rate
Min Bin:	Low	0	0
	Medium	2.5	2.5
Max Bin:	High	5	



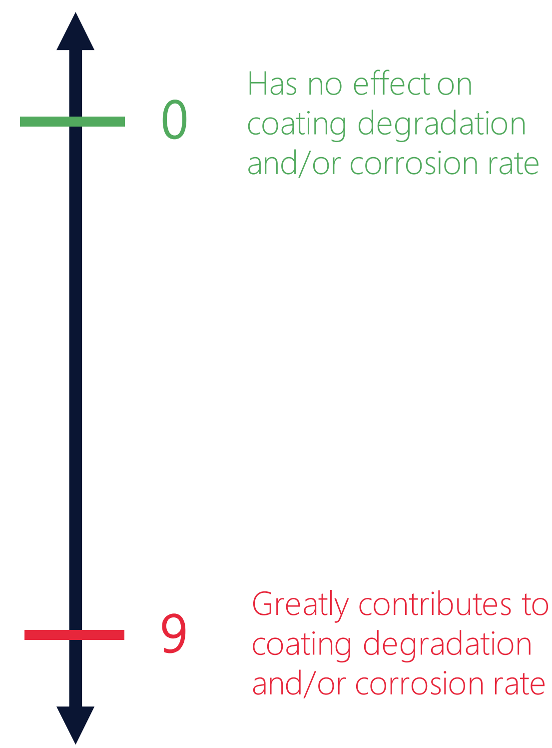
Pollution CPT

	Environmental SO2 Levels	Relative Weight for Coating Failure	Relative Weight for Corrosion Rate
Min Bin:	<15	0	0
	15-99	1.5	1.5
Max Bin:	100-400 ug/m3	3	



Pollution CPT

	Process Spillage	Relative Weight for Coating Failure	Relative Weight for Corrosion Rate
Min Bin:	Clean hydrocarbon, lube oil,	0	0
	Utilities leaks (boiler feedwater, cooling water)	2	2
	General Hydrocarbon (corrosive hydrocarbons, crude, intermediates, Sulphur compounds)	4	4
Max Bin:	Corrosive Chemica	7	



Integral

Pollution CPT

Combined Effects – Coating Degradation:

Environmental Chloride Levels	+	Leachable Chloride Levels	+	Environmental SO2 Levels	+	Process Spillage	=	Pollution Additive	Pollution Worst
0		1		0		0		1	1

Pollution CPT

Combined Effects – Coating Degradation:

Environmental Chloride Levels	+	Leachable Chloride Levels	+	Environmental SO2 Levels	+	Process Spillage	=	Pollution: Additive	Pollution: Worst
0		1		0		0		1	1
…		…		…		…		…	…
1		1		1		1		4?	1?

Pollution CPT

Combined Effects – Coating Degradation:

Environmental Chloride Levels	+	Leachable Chloride Levels	+	Environmental SO2 Levels	+	Process Spillage	=	Pollution	
								Additive	Worst
0		1		0		0		1	1
…		…		…		…		…	…
1		1		1		1		4?	1?
…		…		…		…		…	…
1		3		2		1		7?	3?

Pollution CPT

Combined Effects – Coating Degradation:

Environmental Chloride Levels	+	Leachable Chloride Levels	+	Environmental SO_2 Levels	+	Process Spillage	=	Pollution: Additive	Pollution: Worst
0		1		0		0		1	1
…		…		…		…		…	…
1		1		1		1		4?	1?
…		…		…		…		…	…
1		3		2		1		7?	3?
…		…		…		…		…	…
1		1		9		1		9?	9?

Integral

Pollution CPT

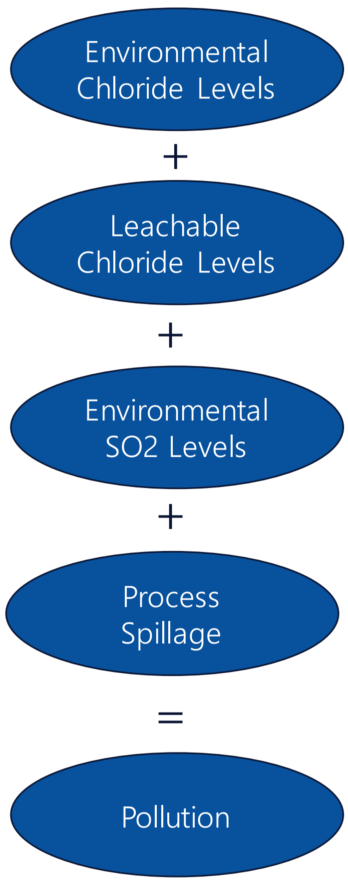
Combined Effects – Coating Degradation:

Environmental Chloride Levels	+	Leachable Chloride Levels	+	Environmental SO2 Levels	+	Process Spillage	=	Pollution: Additive	Pollution: Worst
0		1		0		0		1	1
…		…		…		…		…	…
1		1		1		1		4?	1?
…		…		…		…		…	…
1		3		2		1		7?	3?
…		…		…		…		…	…
1		1		9		1		9?	9?
…		…		…		…		…	…
5		5		5		5		9?	5?

Integral

Pollution CPT

Coating Degradation:



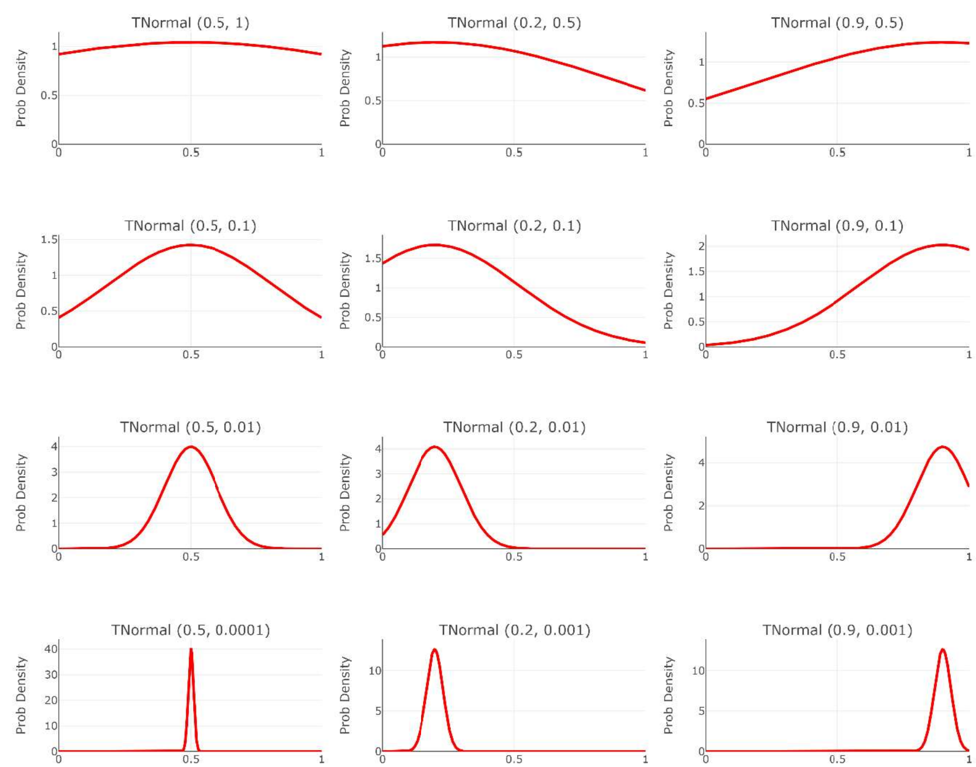
Overall, how *accurate* are these approximations? c/d

a)

b)

c)

d)



Integral

Pollution CPT

Combined Effects – Corrosion Rate:

Environmental Chloride Levels	+	Leachable Chloride Levels	+	Environmental SO2 Levels	+	Process Spillage	=	Pollution: Additive	Pollution: Worst
0		1		0		0		1	1
…		…		…		…		…	…
1		1		1		1		4?	1?
…		…		…		…		…	…
1		3		2		1		7?	3?
…		…		…		…		…	…
1		1		9		1		9?	9?
…		…		…		…		…	…
5		5		5		5		9?	5?

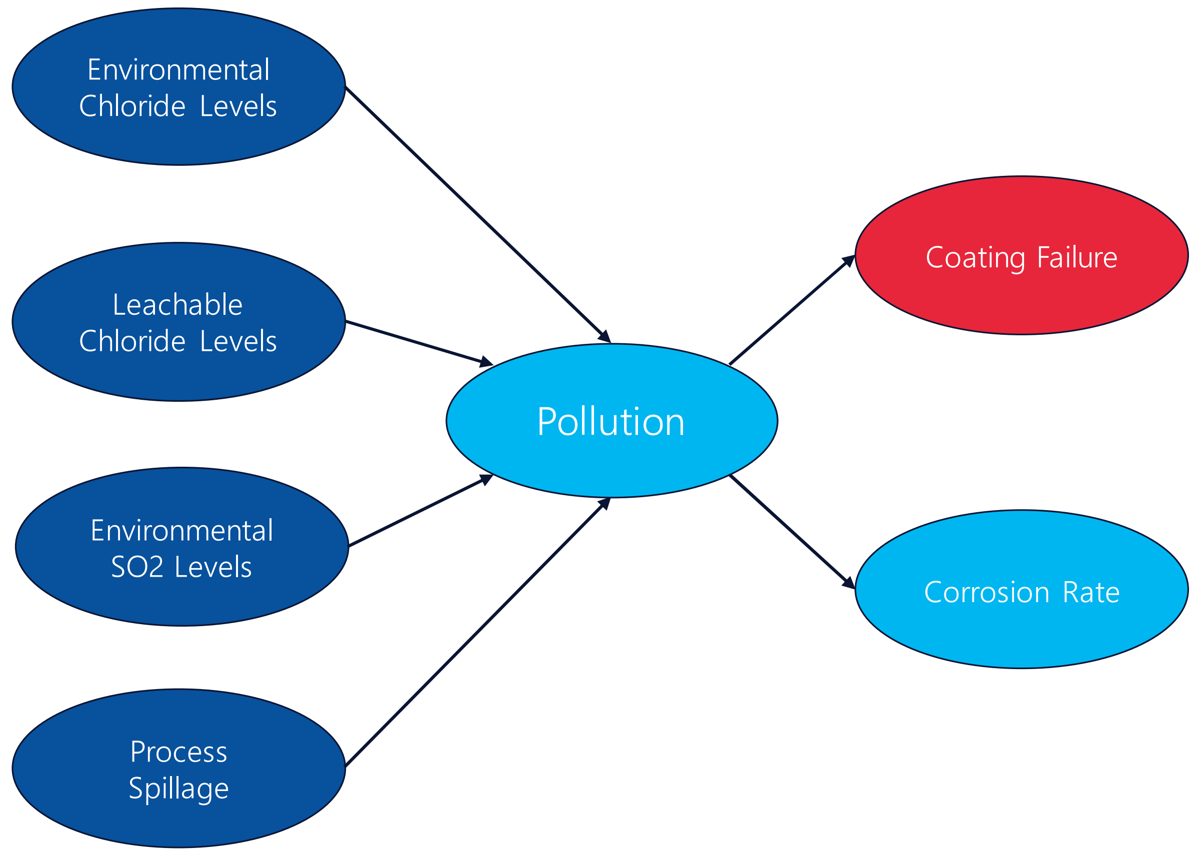
Pollution CPT

Max Value:

Max Value:

Max Value:

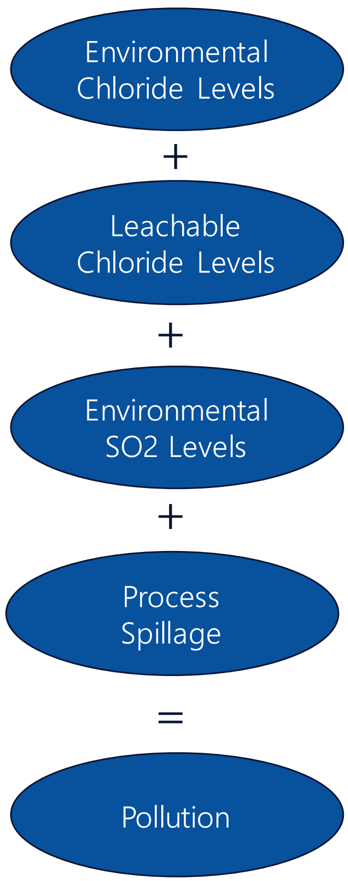
Max Value:



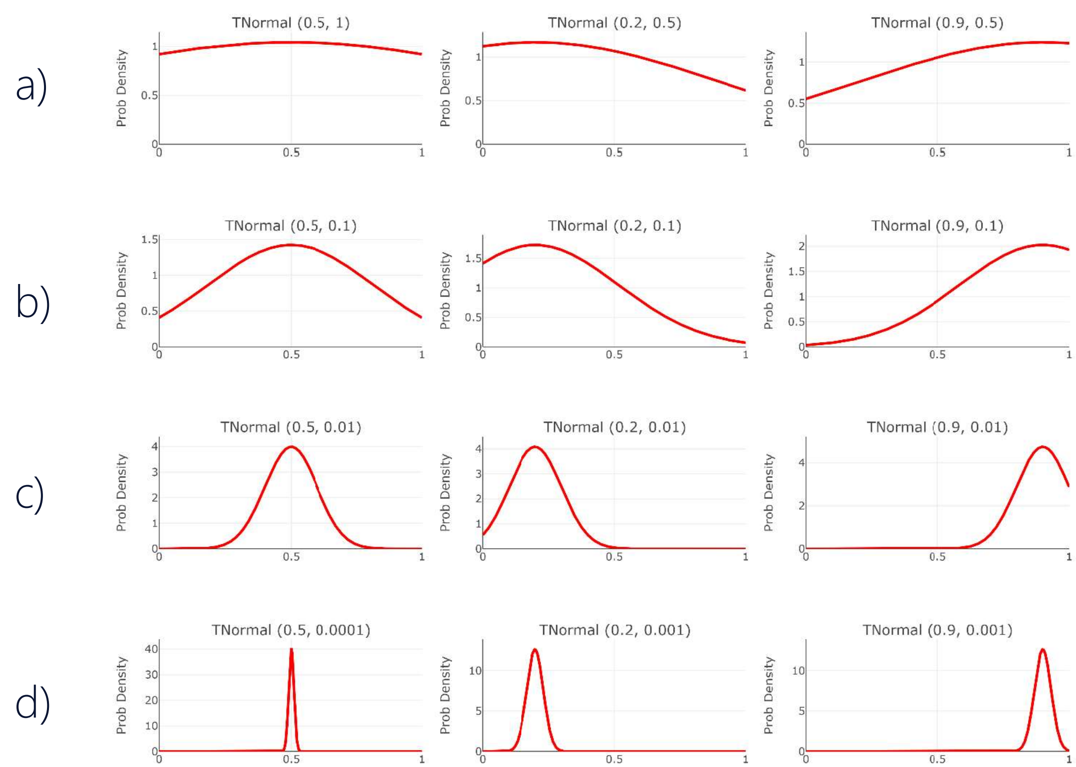
Integral

Pollution CPT

Corrosion Rate



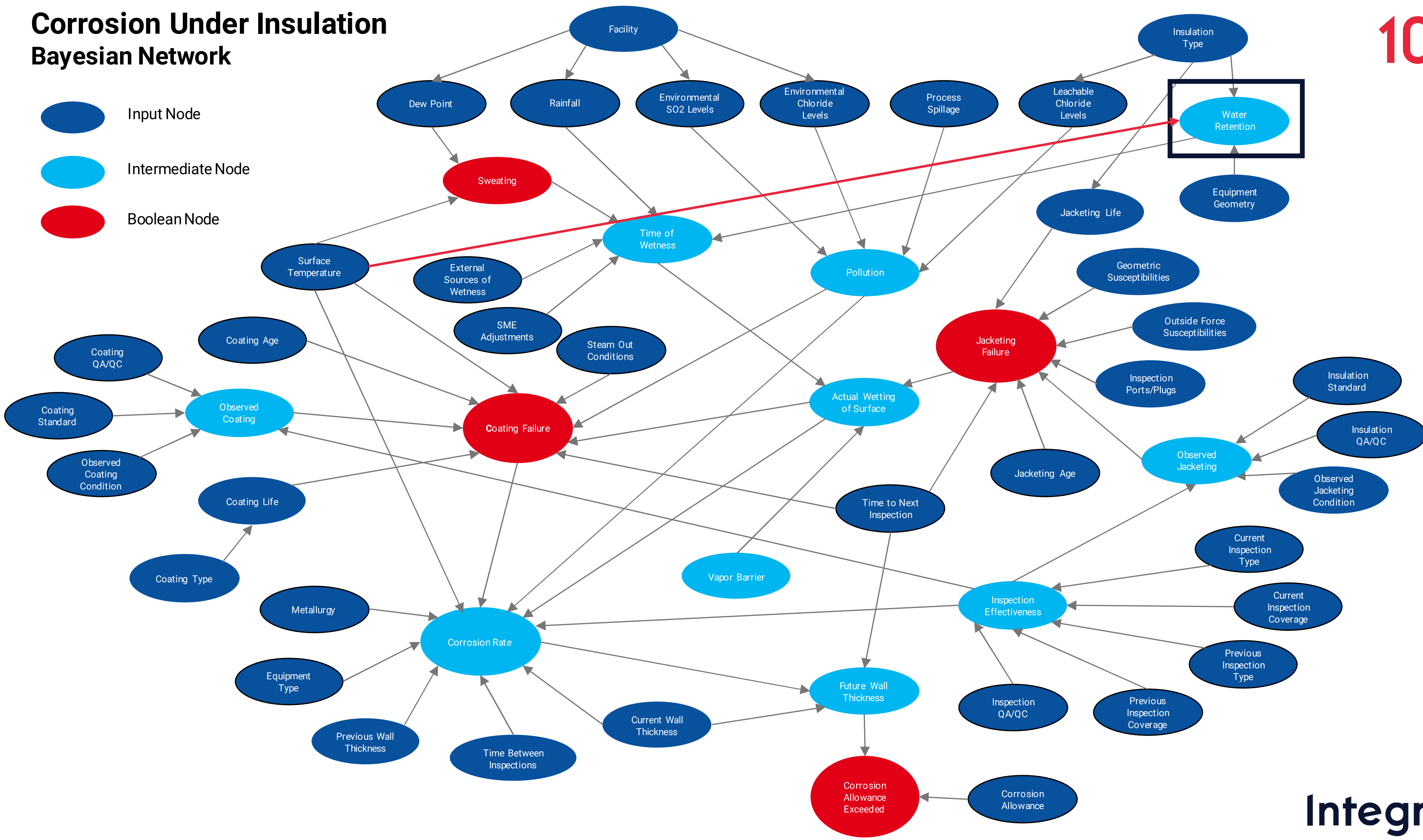
Overall, how *accurate* are these approximations?



Integral

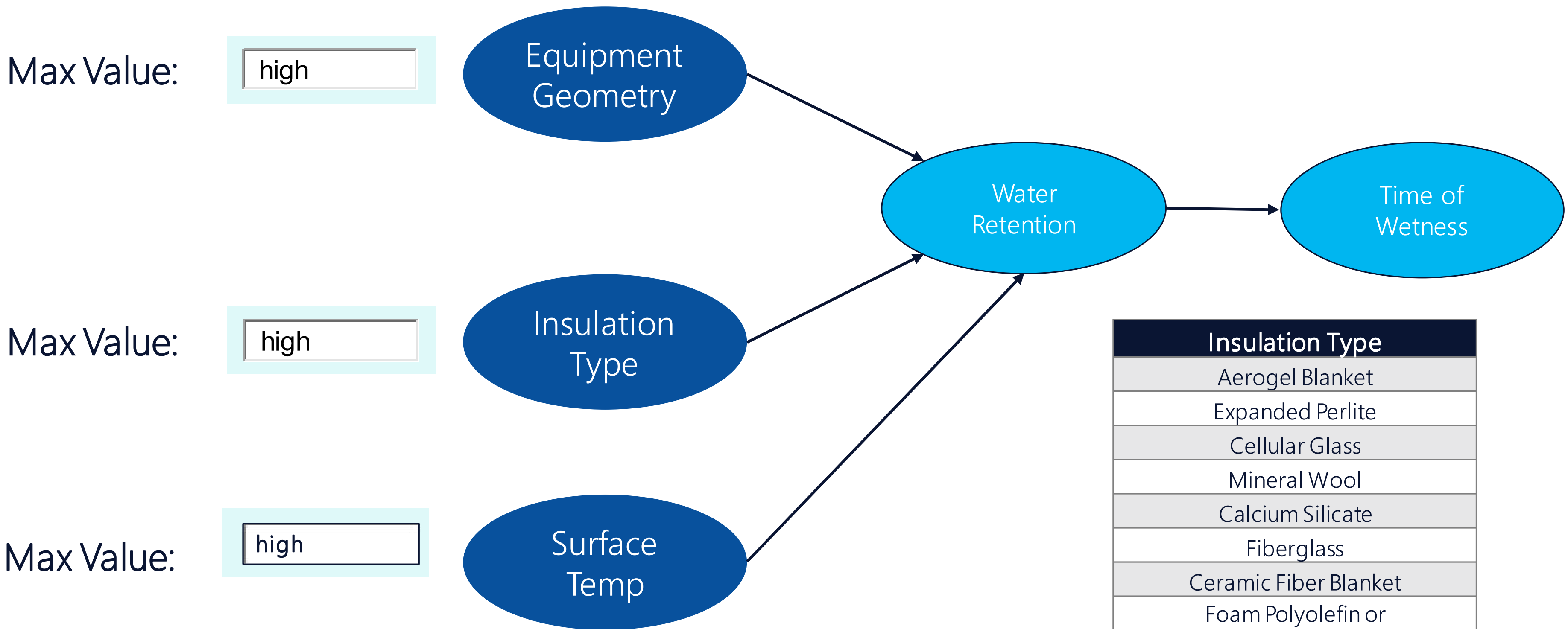
Water Retention CPT

Corrosion Under Insulation
Bayesian Network



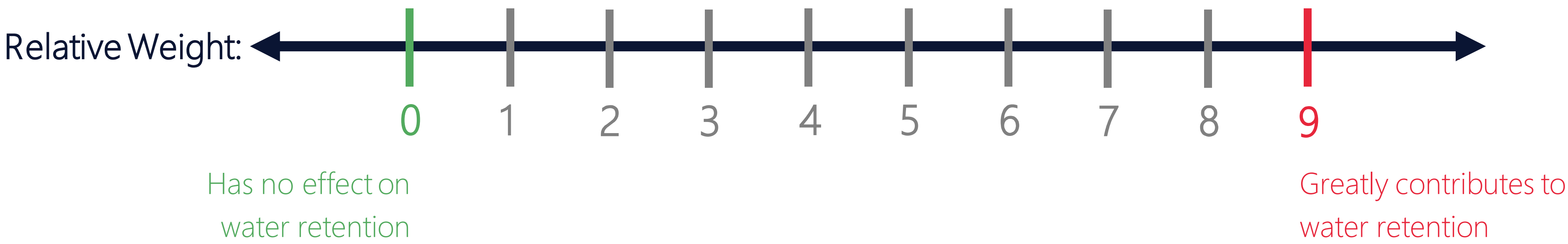
Integral

Water Retention CPT



Insulation Type
Aerogel Blanket
Expanded Perlite
Cellular Glass
Mineral Wool
Calcium Silicate
Fiberglass
Ceramic Fiber Blanket
Foam Polyolefin or Elastomeric Foam
PUR or PIR Foam
Cryogel Z
Asbestos

Water Retention CPT



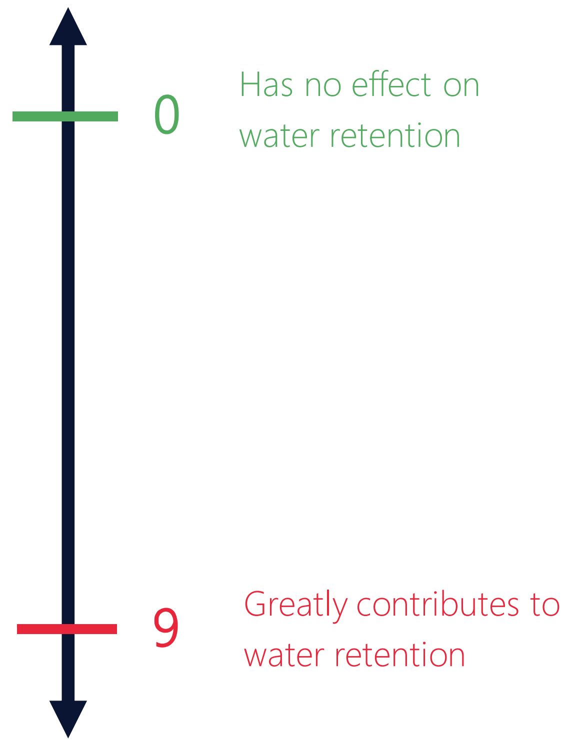
	Equipment Geometry	Insulation Type	Surface Temp
Max Value:	high	high	high
Relative Weight :	3	9	multiplier

Insulation Type
Aerogel Blanket
Expanded Perlite
Cellular Glass
Mineral Wool
Calcium Silicate
Fiberglass
Ceramic Fiber Blanket
Foam Polyolefin or Elastomeric Foam
PUR or PIR Foam
Cryogel Z
Asbestos

Integral

Water Retention CPT

	Equipment Geometry	Relative Weight
Min Bin:	Low	0
	med	5
Max Bin:	high	3



Water Retention CPT

	Insulation Type	H2O ingress resistance	H2O drain/evap	Relative Weight
Min Bin:	Aerogel Blanket	High	Low	1
	Expanded Perlite	High	Low	2
	Cellular Glass	High	Low	2
	Mineral Wool	Low	High	3
	Calcium Silicate	High	Low	2
	Fiberglass	Low	High	3
	Ceramic Fiber Blanket	Low	High	2
	Foam Polyolefin or Elastomeric Foam	Low	High	2
	PUR or PIR Foam	Low	High	2
	Cryogel Z	High	Low	1
	Asbestos	Low		1
Max Bin:			high	9

Integral

Water Retention CPT

Insulation Type	Temp Mult (<50C, 50-110C, >110C) (low, med, high)
Aerogel Blanket	1, 0.8, 0.5
Expanded Perlite	1, 0.8, 0.5
Cellular Glass	1, 0.8, 0.5
Mineral Wool	1, 0.5, 0.1
Calcium Silicate	1, 0.5, 0.1
Fiberglass	1, 0.5, 0.1
Ceramic Fiber Blanket	1, 0.5, 0.1
Foam Polyolefin or Elastomeric Foam	1, 0.8, 0.5
PUR or PIR Foam	1, 0.8, 0.5
Cryogel Z	1, 0.8, 0.5
Asbestos	1, 0.9, 0.8

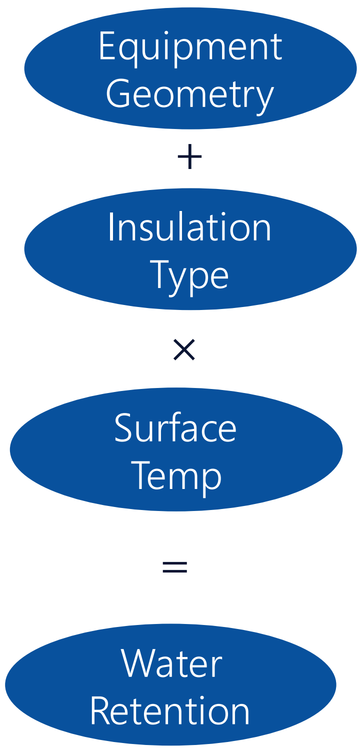
Water Retention CPT

Combined Effects:

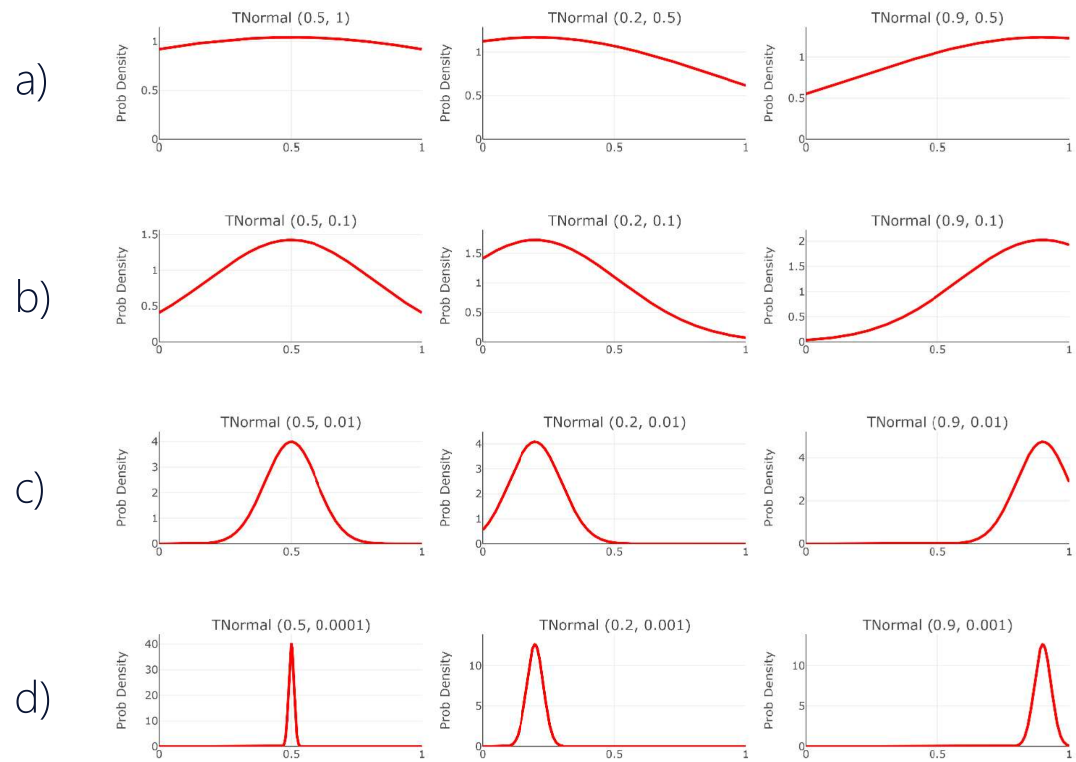
Equipment Geometry	+	Insulation Type	=	Water Retention: Additive	Water Retention: Worst
0		1		1	1
…		…		…	…
1		1		2?	1?
…		…		…	…
1		3		4?	3?
…		…		…	…
1		9		9?	9?
…		…		…	…
5		5		9?	5?

Water Retention CPT

Corrosion Rate

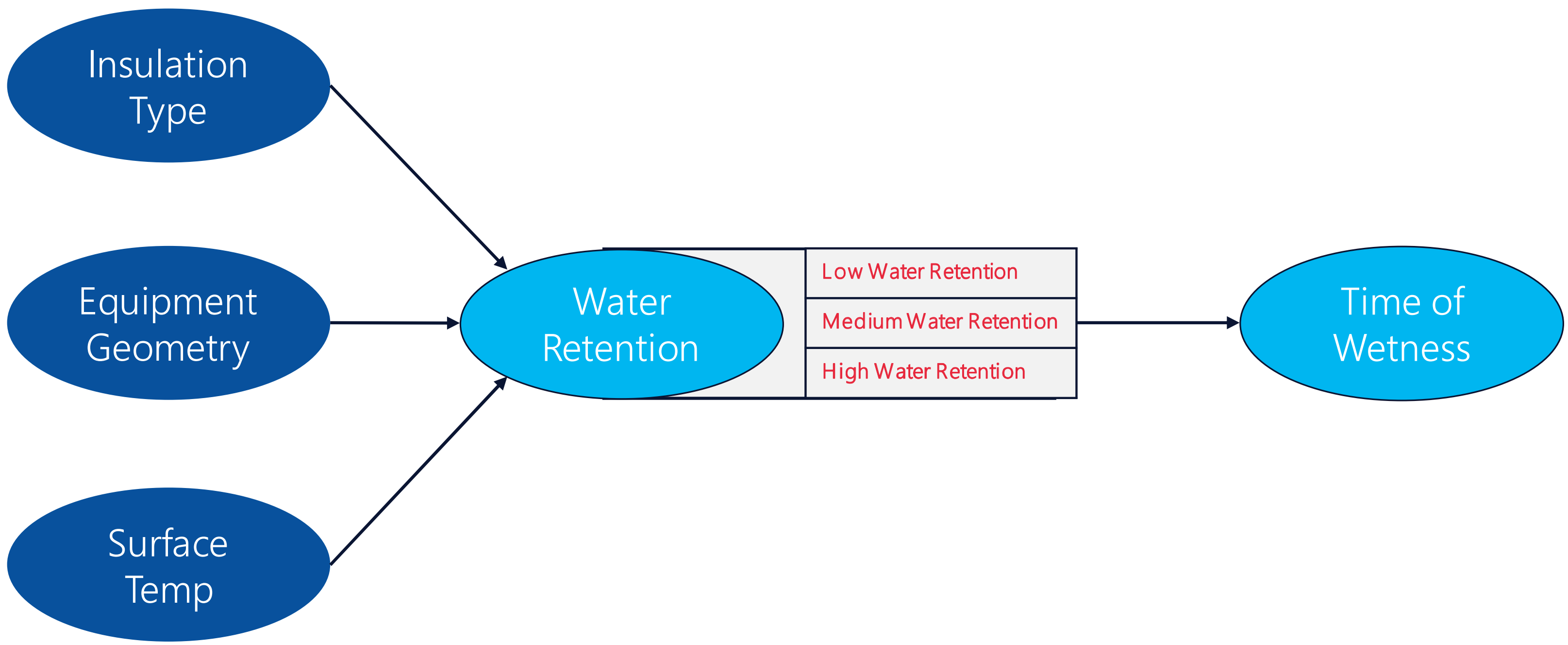


Overall, how *accurate* are these approximations? c/d



Integral

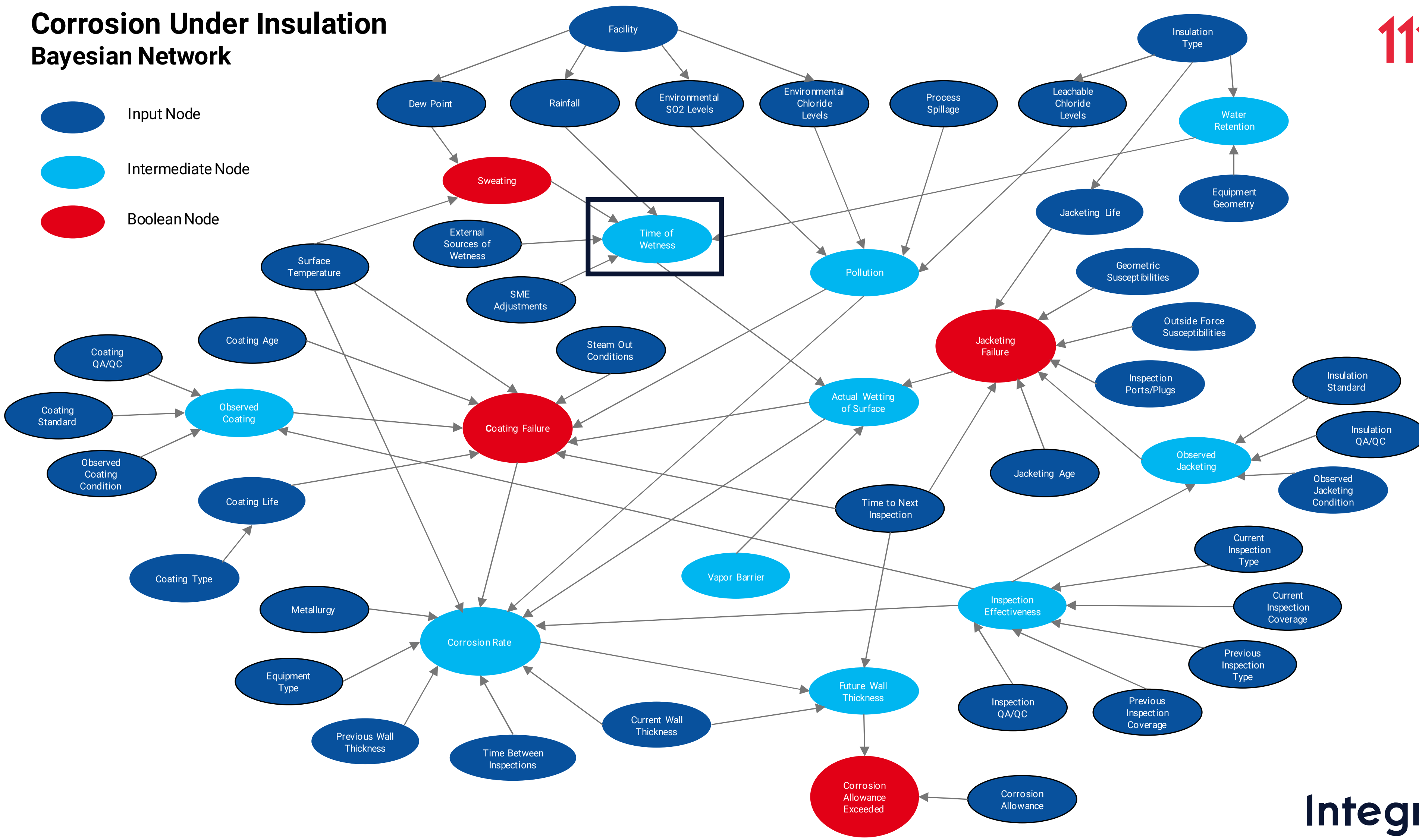
Water Retention CPT



Integral

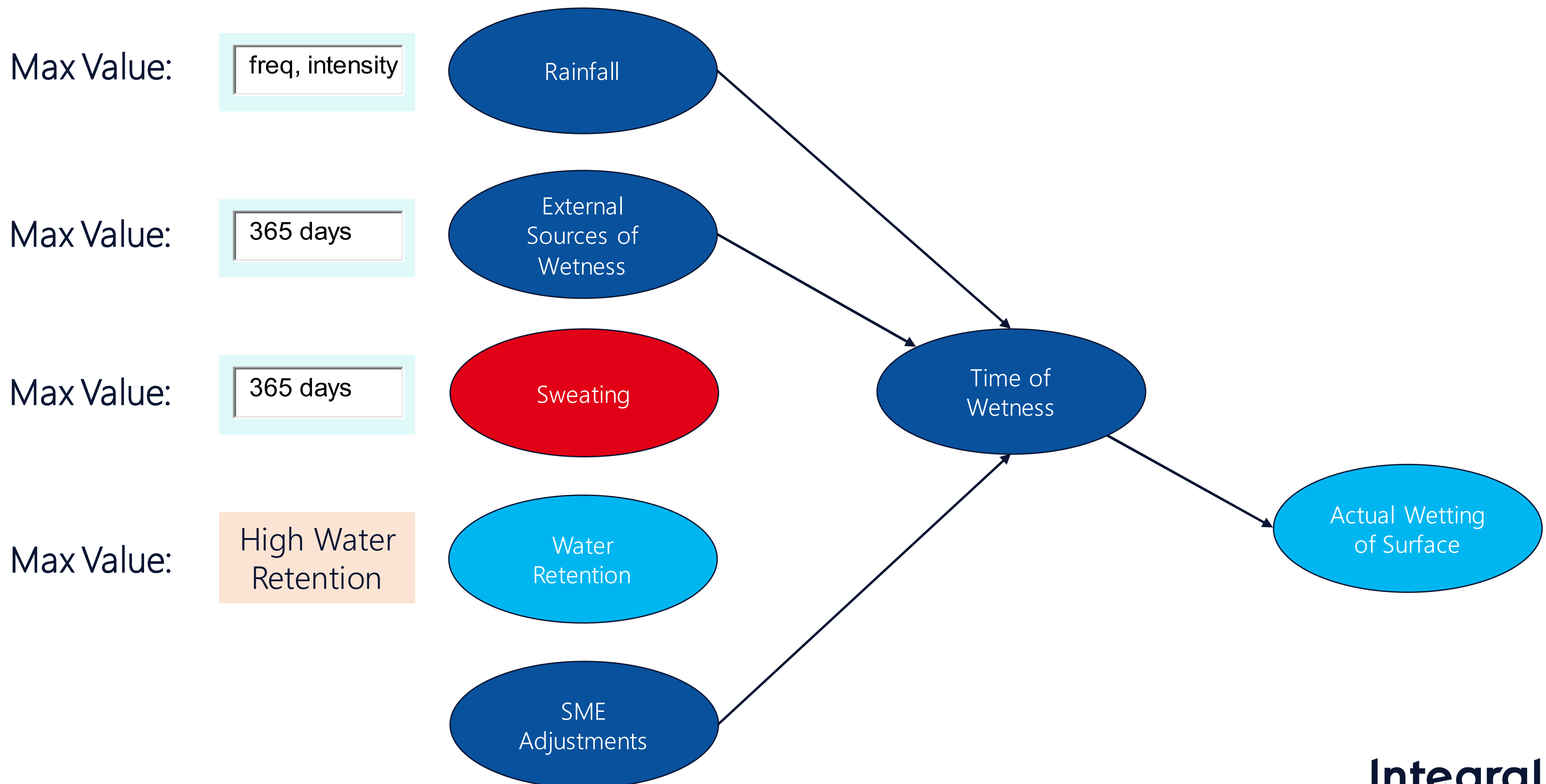

Time of Wetness CPT

Corrosion Under Insulation
Bayesian Network



Integral

Time of Wetness CPT



Time of Wetness CPT

Relative Weight:
(actual wetted surface)

0 1 2 3 4 5 6 7 8 9

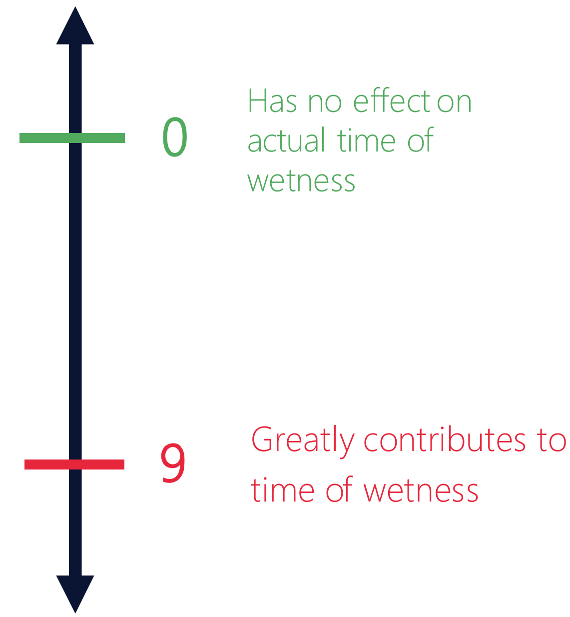
Has no effect on actual wetting of Surface

Greatly contributes to wetting of surface

	Rainfall	External Sources		
Max Value:		365 days		High Water Retention
Relative Weight for coating degradation:	10	10		1.5 x multiplie

Time of Wetness CPT

	Rainfall	Relative Weight for Wetting of Suface	
Min Bin:	5 days, y mm	0	0
	85 days, z mm	3	3
Max Bin:	freq, intensity	10	6



SME Adjustments	Relative Weight Reduction
Partial Shelter	0.75
Full Shelter	0.25
No Shelter	1.0

Integral

Time of Wetness CPT

	External Sources	Surface Wetting	
Min Bin:	No Drift	0	
	Deluge (quarterly) 10 days	2	
	Intermittent (10%), 36 days	4	
Max Bin:	365 days	10	10

Time of Wetness CPT

	Water Retention	Relative Weight for Coating Failure	Relative Weight for Corrosion Rate
Min Bin:	Low Water Retention	1.0	1.0
	-		
	Medium Water Retention	1.25	1.25
	-		
Max Bin:	High Water Retention	1.5 x multiplie	1.5 x multiplie

0 Has no effect on coating degradation and/or corrosion rate

9 Greatly contributes to coating degradation and/or corrosion rate

Time of Wetness CPT

Combined Effects – Actual wetting of surface:

Rainfall + SME Adjustment	+	External Sources	=	Overall: Additive	Overall: Worst
0		1		1	1
…		…		…	…
1		1		2?	1?
…		…		…	…
1		3		4?	3?
…		…		…	…
1		9		9?	9?
…		…		…	…
5		5		9?	5?

Time of Wetness CPT

Coating Degradation

Rainfall + SME

+

External Sources

=

Time of Wetness

Overall, how *accurate* are these approximations

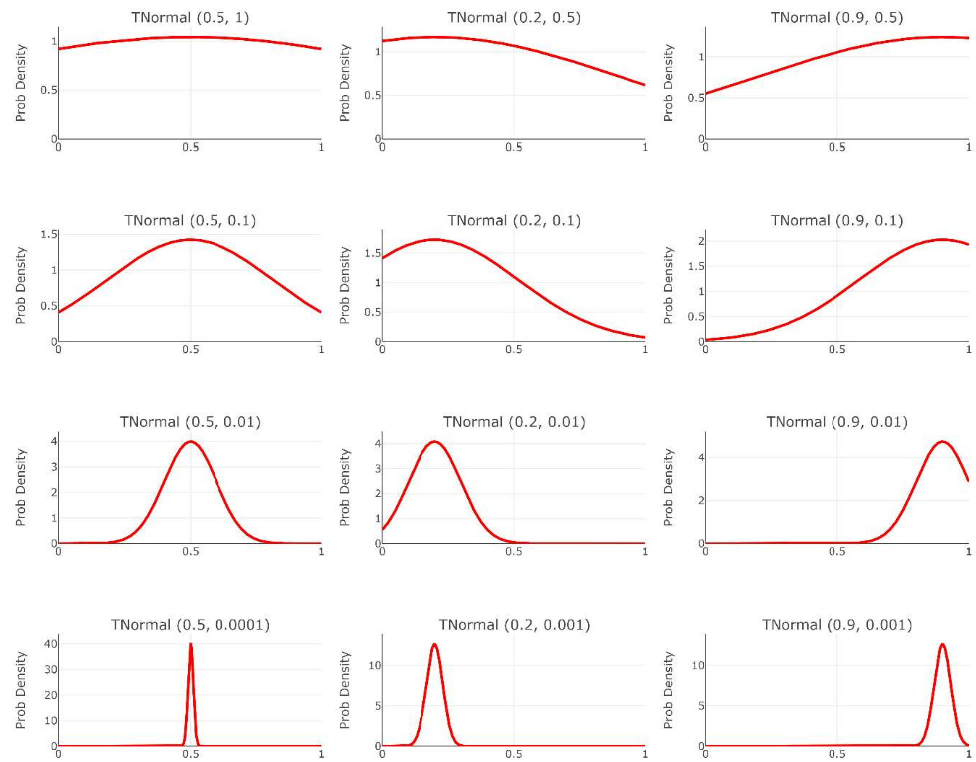
If sweating: d
If external sources: d
If rainfall: c

a)

b)

c)

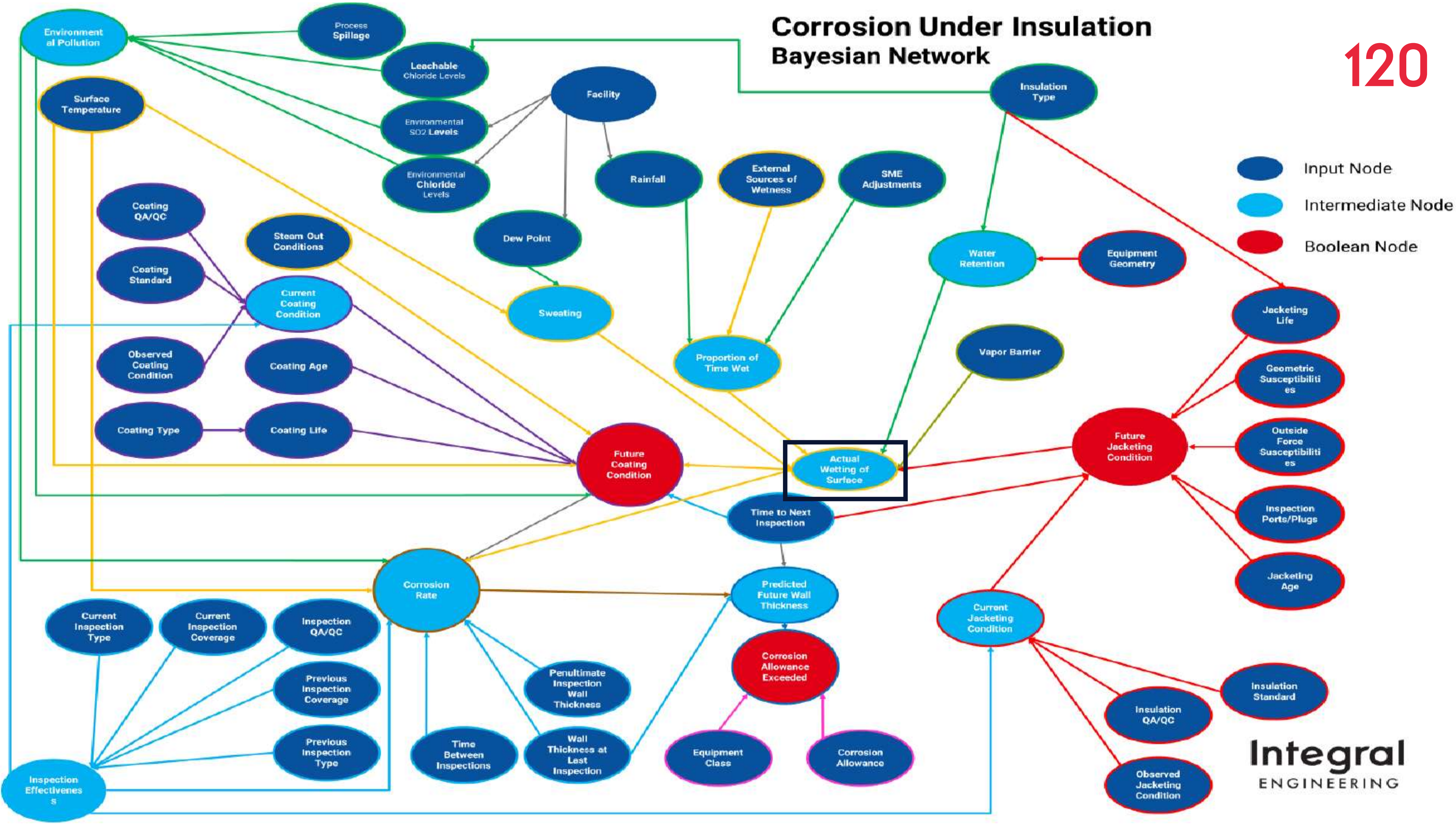
d)



Integral

Actual Wetting of Surface CPT

Corrosion Under Insulation Bayesian Network



Actual Wetting of Surface CPT

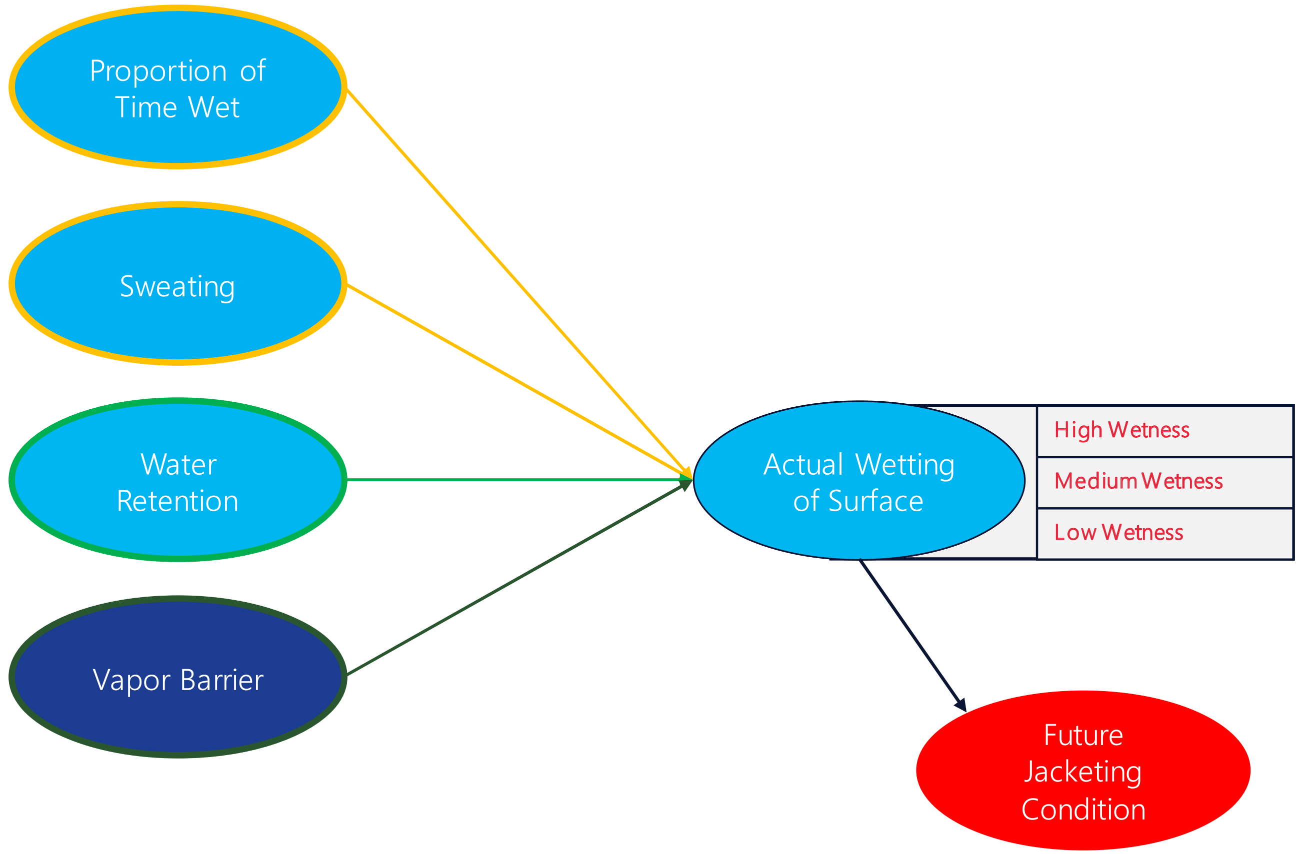
Max Value: 365 days

Values:
1. Sweating
2. Not Sweating

Values: High Water Retention

Values:
1. Not Intact
2. Intact

Values:
1. Not Intact
2. Intact



Integral

Actual Wetting of Surface CPT

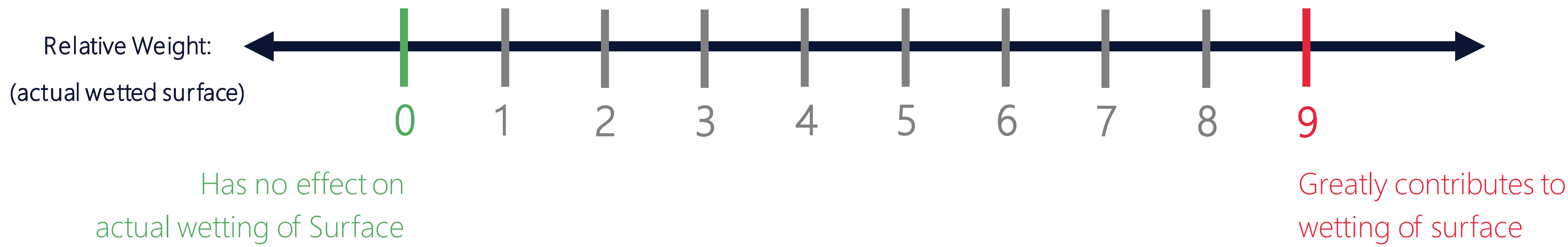
Combined Effects – Actual wetting of surface:

Proportion of Time Wet × Water Retention × Future Jacketing Condition + Sweating × Water Retention × Vapor Barrier = Actual Wetting of Surface

Water Retention	Sweating	Actual Wetting of Surface: Additive	Actual Wetting of Surface: Worst
0	0	1	1
…	…	…	…
1	1	2?	1?
…	…	…	…
1	1	4?	3?
…	…	…	…
1	1	9?	9?
…	…	…	…
5	5	9?	5?

Integral

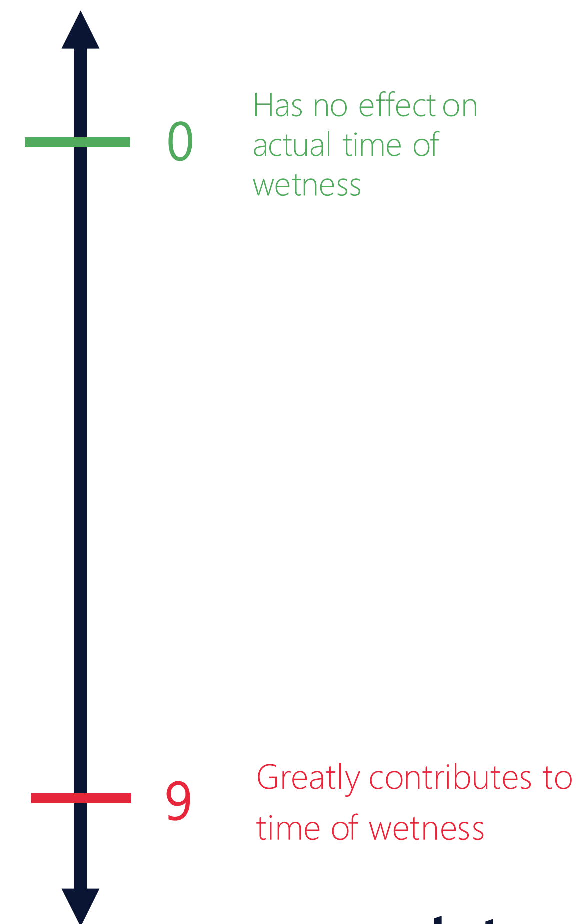
Actual Wetting of Surface CPT



Relative Weight for actual surface wetting:	Vapor Barrier	Water Retention	Sweating	Proportion of Time Wet	Future Jacketing Condition
			1	1	

Actual Wetting of Surface CPT

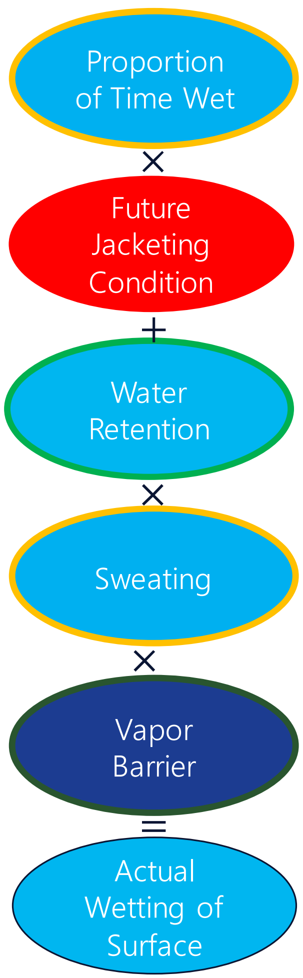
	Proportion of Time Wet	Relative Weight for Wetting of Suface
Min Bin:	0 days	0
	180 days	4
Max Bin:	365 days	9



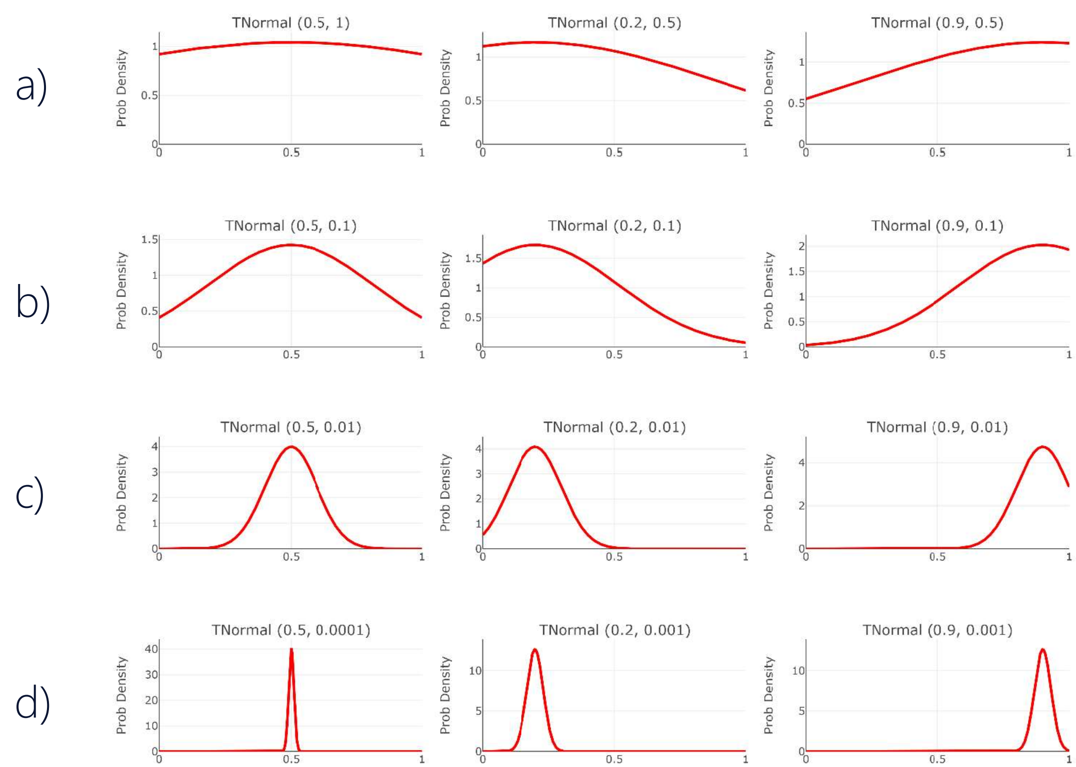
Integral

Actual Wetting of Surface CPT

Wetting of Surface



Overall, how *accurate* are these approximations? d



Integral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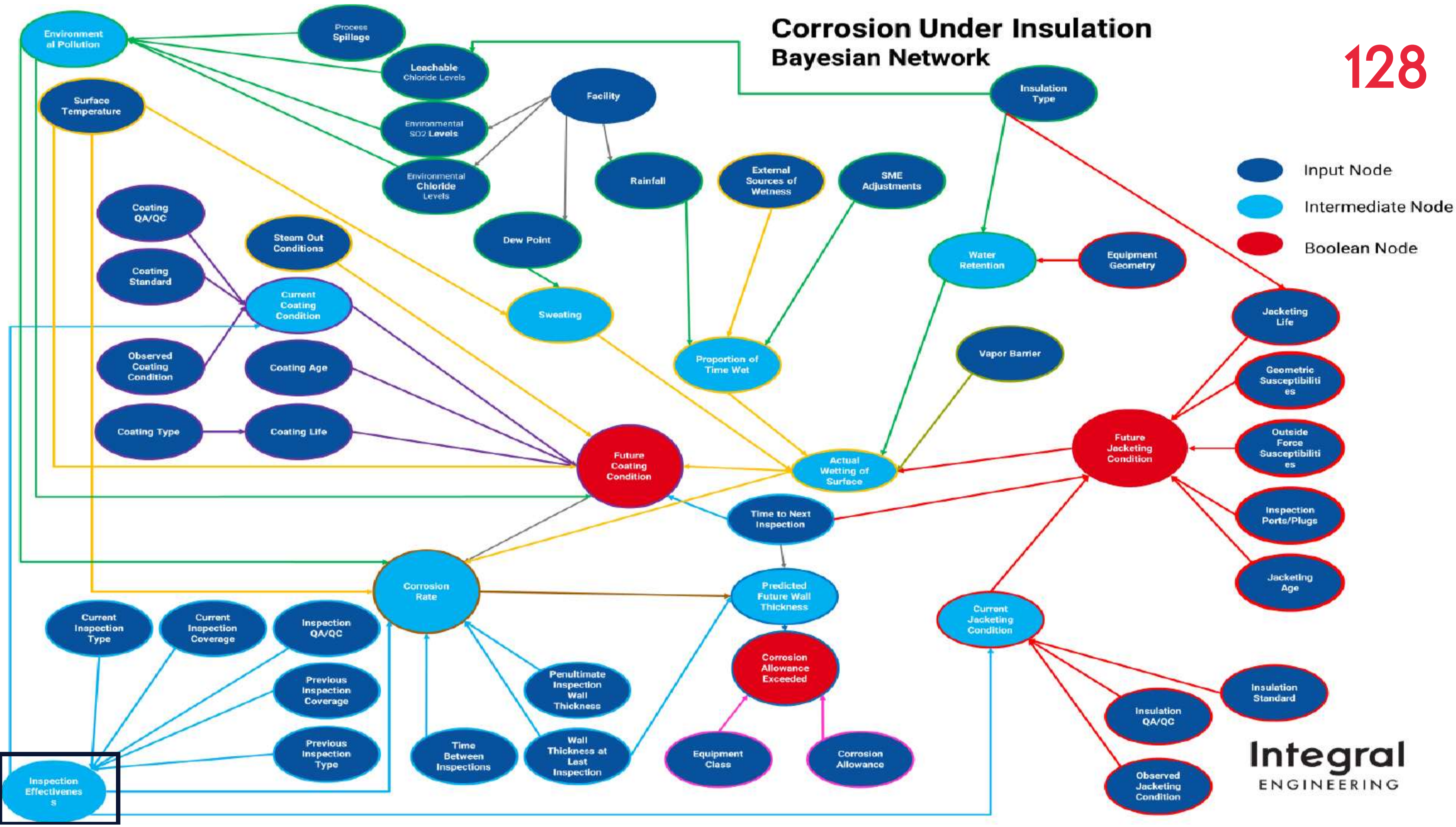
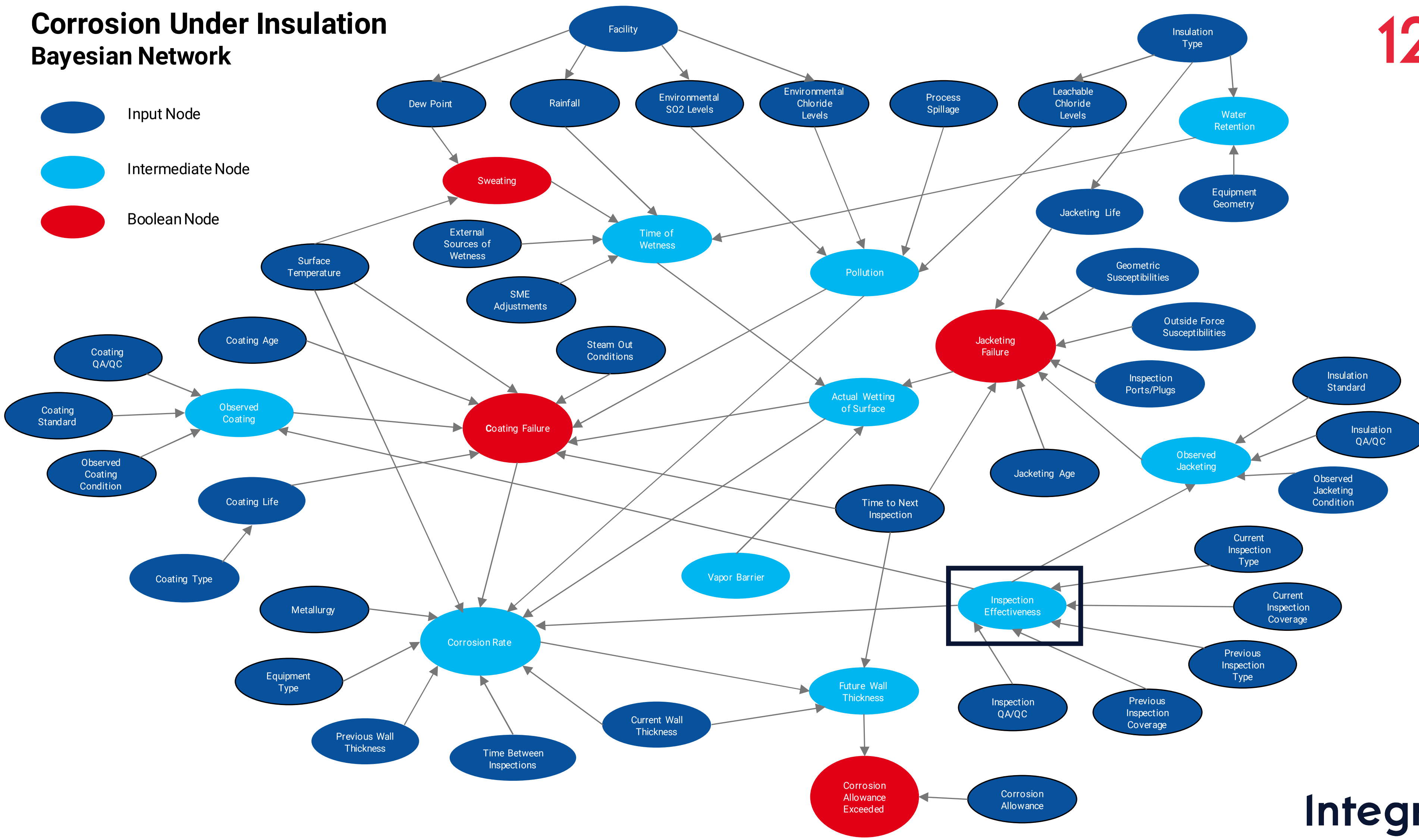
Inspection CPT

Corrosion Under Insulation Bayesian Network



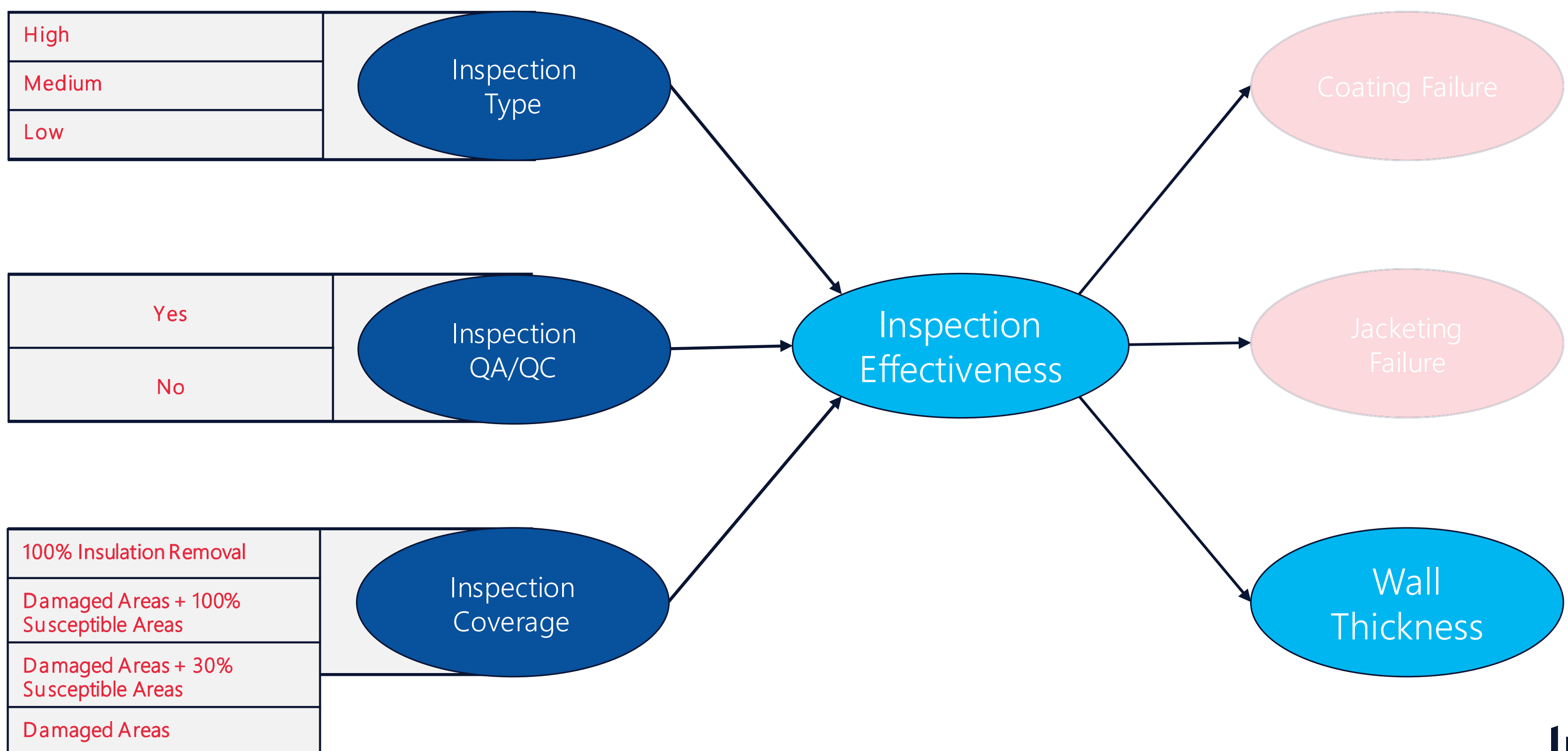
Corrosion Under Insulation
Bayesian Network



Integral

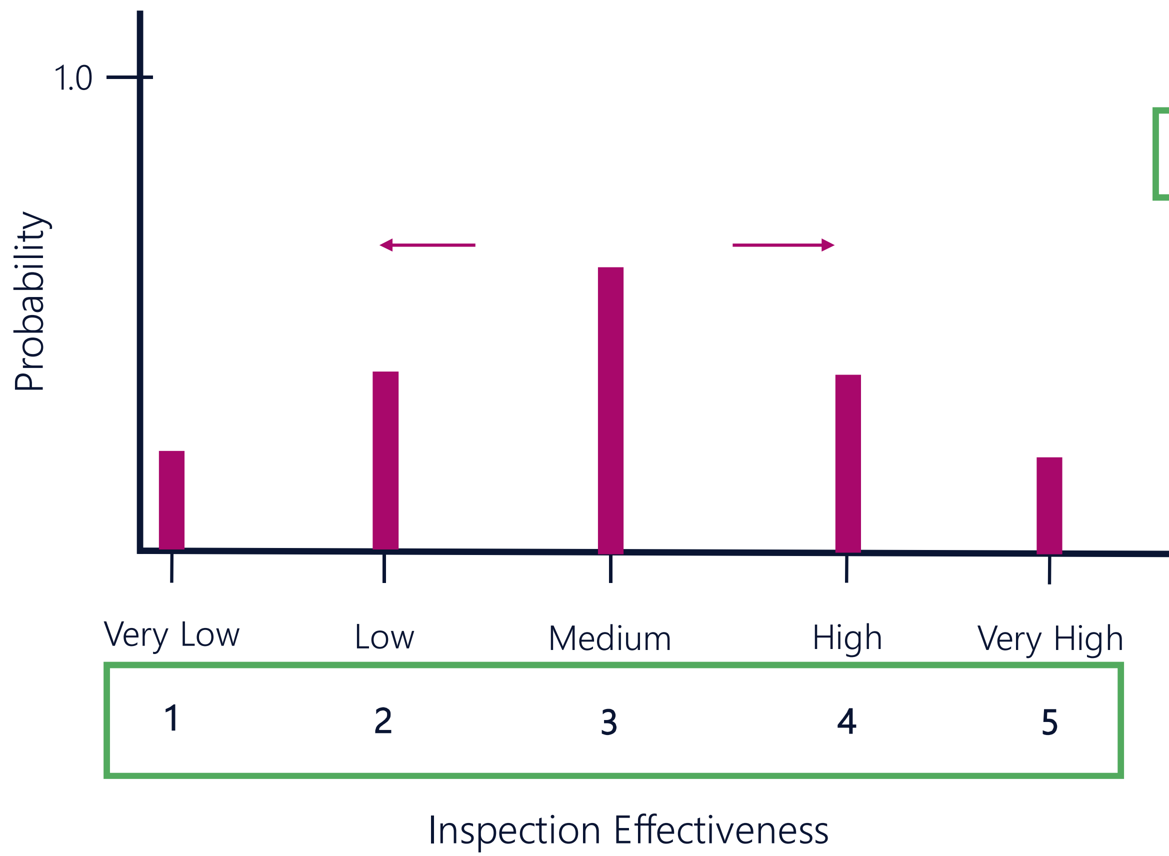
Inspection Effectiveness CPT

For a Single Inspection:

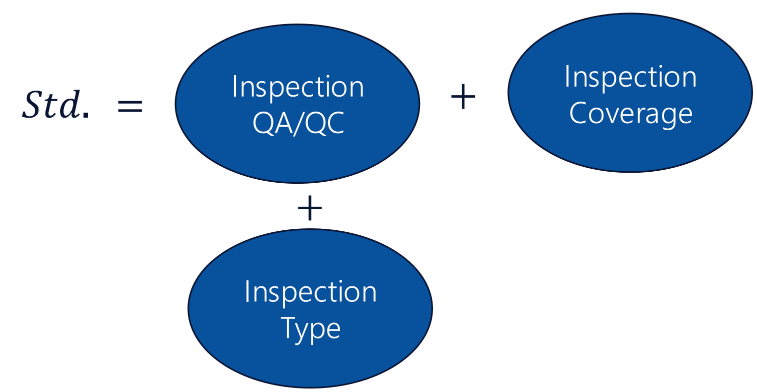


Integral

Inspection Effectiveness CPT

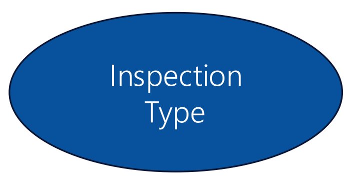


$\boxed{Mean} = Reported\ Measurements$



Inspection Effectiveness CPT

$Mean$ =

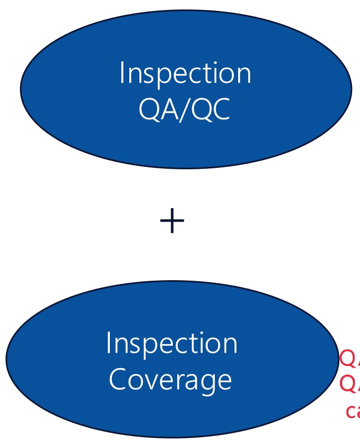


High1	5
Med	3
Low	1

Inspection Effectiveness CPT

Overall, how *accurate* are these approximatio

Inspection Effectiveness

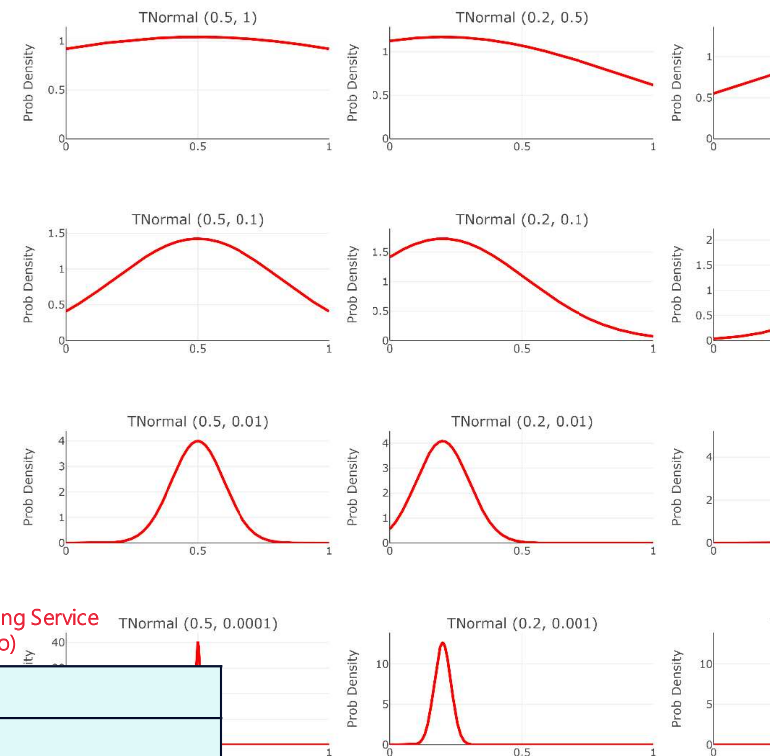


QA – scaled to account for QA/QC categories: 0/0.3/0.6/10%

a)

b)

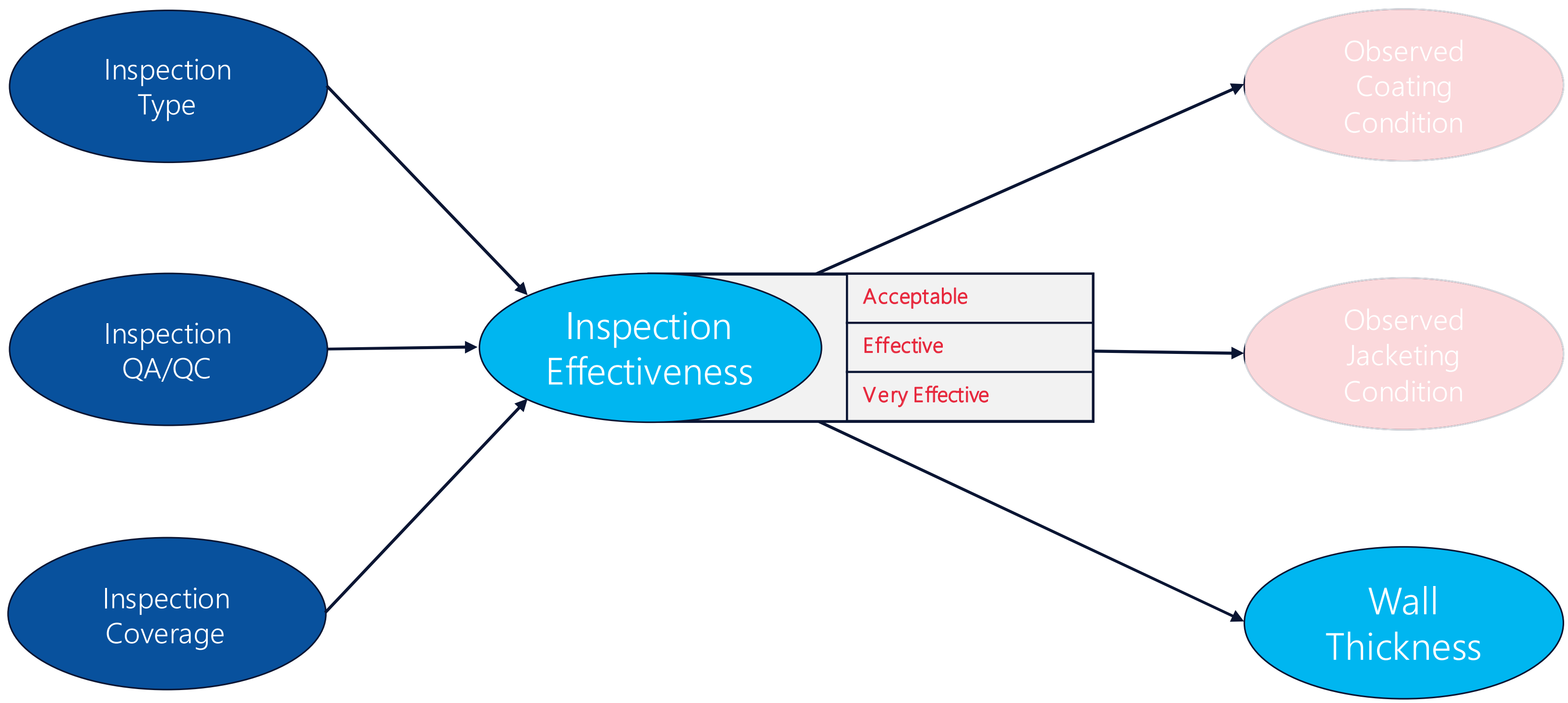
c)



	QA	Corr. found modifier?	Inspection type (sd), high, med, low	Sweating Service (yes/no)
100% Insulation Removal	0/10%	d, +10%	0.25mm, .5mm, 1mm, 15% wt	(1, 1)
Damaged Areas + 100% Susceptible Areas	0/10%	d, +10%	0.25mm, .5mm, 1mm, 15% wt	(d, c/d)
Damaged Areas + 30% Susceptible Areas	0/10%	d, +10%	0.25mm, .5mm, 1mm, 15% wt	(d, c)
Damaged Areas + 10% Susceptible	0/10%	d, +10%	0.25mm, .5mm, 1mm, 15% wt	(c/d, b/c)
Damaged Areas	0/10%	d, +10%	0.25mm, .5mm, 1mm, 15% wt	(c, b)

Integral

Inspection Effectiveness CPT



Integral